Sub-micromachining using femtosecond pulse laser interference phenomenon

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Sub-Micromachining using Femtosecond Pulse Laser Interference Phenomenon

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ABSTRACT

This research work sets out to achieve submicromachining capabilities on the femtosecond pulse laser which surpasses the conventional laser micromachining method of using the direct laser beam to machine. The aim is to achieve laser ablated features of 200nm and below with this novel research concept.

With ultrafast pulse lasers such as the femtosecond pulse laser, subspot size micromachining is possible because of their precise threshold value. However, the sub-spot size ablation mechanism has reached its lowest limit when it hit the 1/10th of the laser focal spot size range. Up to now, the smallest laser micromachined feature reported is 200nm in diameter, or approximately 8% of the original laser spot size of 2.5 μ m. The aim of this research work is to break through this limit and obtain submicron features of below 200nm with the femtosecond pulse laser.

To achieve this, a novel concept of using the phenomenon of femtosecond pulse laser interference to machine is proposed. The laser beam from the femtosecond pulse laser is first interfered to obtain a circular interference beam. The central bright fringe from the generated interference pattern which has a sharper beam profile is then used to machine. With this method, the effective ablation spot size is reduced, subsequently reducing the size of the feature size it ablates.

One of the attractive characteristics of ultrafast pulse lasers is its precise threshold value. It is this feature which enables the ablation of sub-spot size features on these lasers. And by applying this same concept, only a fraction (a part of the central bright fringe) of the interfered beam within which the fluence is greater than the threshold of the material, can be made to machine.

To obtain interference on the femtosecond pulse laser, three interferometry methods were investigated. Interference was successfully generated on a femtosecond pulse laser using 2 beam interference method (Mach-Zehnder and Newton's Ring interferometry setup) and multiple beam interference method (Fabry Perot etalon setup). One of the limitations encountered is that it is difficult to obtain stable, sharp interference fringe patterns on the 150fs ultrafast pulse laser because of its very short coherence length of $45\mu\text{m}$. Therefore, the interferometer and the experimental setup must be designed to be able to maintain the small OPD required in order to obtain the sharp interference fringes required for this micromachining concept to work.

From experimental work and supported by theoretical analysis, it was found that by using the centre bright fringe of the laser beam to machine, a smaller feature could be obtained. With the Mach-Zehnder setup, a 600nm feature was obtained on a gold specimen using the interfered laser beam compared to a $1.1\mu\text{m}$ feature obtained with the direct laser beam at the same laser fluence.

With the Newton's Ring setup, a 350nm feature was obtained by using the interfered laser beam compared to a $1\mu\text{m}$ feature using the direct laser beam at the same laser fluence for both gold and platinum specimen.

And with the Fabry-Perot etalon setup, a 105nm feature was obtained using the multiple interfered laser beam compared to a 938nm feature using the direct laser beam at the same laser fluence on the gold specimen.

Therefore, it can be concluded that with this research concept of using the central bright fringe of the interfered femtosecond laser beam instead of the direct beam to machine, a smaller machining feature can be obtained. A laser ablated feature of unprecedented 100nm was obtained, an almost 89% decrement in feature size compared to the feature machined using the conventional direct beam method.

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- was awarded the SMTA (Surface Mount Technology Association) Best Student Paper Award

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LIST OF SYMBOLS

F	laser fluence
F_0	peak laser fluence
F_{th}	ablation threshold fluence
E_0	peak pulse energy
E_{th}	ablation threshold energy
D	diameter of laser beam
f	focal length of lens
$f\#$	f-number
k	function of the index of refraction
MTF	modulation transfer function
n	refractive index
α_{eff}	effective target absorption coefficient
α	linear absorption coefficient
$\mathbf{E}$	electric field
A	amplitude
P	power
I	beam intensity/irradiance
λ	wavelength of laser light
$\Delta\lambda$	bandwidth of the laser spectrum
τ	pulse width of the laser
TEM ₀₀	Gaussian transverse mode
OPD	optical path difference
w	Gaussian beam radius
r	spot size radius

d	diffraction limited focused spot size
$\varnothing$	ablated feature diameter
e	ablation depth
d	thickness/separation gap
a	beam area
δ	phase difference
$\mathcal{R}$	radius of curvature
t	time interval
m	order number
N	number of rings/fringes
θ	angle of incidence
FWHM	full width at half maximum
Φ	finesse
FSR	free spectral range
R	reflectance/ coefficients of reflection
T	transmissivity/ coefficient of transmission
c	speed of light (3×10^8 m/s)
L	lens
BS	beamsplitter
CPA	chirped pulse amplification
M	mirror
CP	compensation plate
AOD	acousto-optic deflector
P	point of observation
S	point source

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Present research trend in many of today's technologies such. biotechnology, material technology and microelectronics is accelerating towards miniaturisation [1]. The demand for smaller, more compact, more efficient and cheaper devices has spurred the field of miniaturisation. Micromachining technology is the foundation to the realisation of these miniaturised products.

The ultrafast pulse laser ablation technology opens the door to a whole new prospect for micromachining and submicromachining. With the advent of femtosecond pulse lasers, ablation features of micron size and below, of high precision and exceptional machining quality can now be achieved. The precise threshold value characteristic of the ultrafast laser pulses allows it to perform sub-spot size micromachining, overcoming previous notions that the minimum achievable ablation feature is limited to the laser wavelength. Features as small as approximately 1/10th of the laser focus spot size has been achieved by precisely controlling the laser fluence so that only a portion of the central part of the laser beam is above the breakdown threshold of the specimen. The smallest ablation feature reported to date, is an amazing 200nm in diameter [2,3,4].

However, the consumer demand for smaller, smarter and faster technology calls for ever increasingly smaller and finer micromachining requirement. At the moment, direct laser micromachining technology has reached its limits at the 1/10th of the laser spot size. Much research work in the ultrafast pulse laser micromachining field has been dedicated to finding new methods and technologies which can overcome this limit, notably near field optics with NSOM [5,6].

In this research work, a novel method for overcoming this limit by first interfering the laser light, and then using the sharper central bright fringe of the interfered beam to machine, effectively reducing the effective machining spot size and subsequently the size of the ablated features, is introduced. This method is relatively simpler and cheaper compared to near field technology and can be easily adopted on most commercially available ultrafast pulse laser setup.

The phenomenon of light interference is not a new observation and its importance is well recognised. It has spawned the subject of interferometry, allowing the measurements of very small lengths or angles with extraordinarily high degree of accuracy, and which has exceedingly important uses in the fields of spectroscopy and metrology.

Light interference has also been applied in the fabrication of fibre Bragg gratings (FBGs) and long-period fibre gratings (LPEGs) on optical fibres by interference lithography [7] and by induced holographic writing or line irradiation method with ultrafast pulse lasers [8,9,10]. Ultrafast pulse laser interference has also been reported in the formation of periodic structures in transparent material [11,12] and in the fabrication of array microstructures [13,14].

However till date, nobody has thought to combine the effect of laser light interference and the sub focal spot machining ability at near threshold fluence of ultrafast pulse lasers and garner this phenomenon for the use in submicromachining. In this report, the principles of this research concept, the experimental work and the theoretical calculations and analysis done, the observations made, the results obtained and the conclusion of this research work shall be presented.

1.2 OBJECTIVES

The objective of this research work is to employ the phenomenon of femtosecond pulse laser interference for the machining of submicron features which surpasses conventional femtosecond laser micromachining capabilities.

Through the above-mentioned objective, this research work seeks:

- to develop a femtosecond pulse laser optical system and experimental setup which can garner the advantages of laser light interference and channel it for submicromachining
- to achieve machining features of 200nm and below
- to achieve better machining quality: higher aspect ratio, better edge quality and smaller taper

1.3 SCOPE

The scope of this research work centres on the utilisation of the central bright fringe of the interfered femtosecond pulse laser beam in micromachining and sub-micromachining.

The first challenge in this research work will be to obtain sharp circular interference with the ultrashort pulse laser system, a tall task considering the fact that a femtosecond pulsed laser with a pulse width of only 150fs is used. The profile of the interfered laser beam envelope shall also be investigated and ascertained.

The second challenge is to develop the experimental setup and identify the equipment and support needed for the conceptualism of the system. The system will then be tested, modified and fine tuned to identify the best setup configuration to be adopted.

The third challenge is to support the feasibility of the concept of combining the effect of laser light interference and the sub focal spot machining ability at near threshold fluence of the ultrafast pulse laser for submicromachining by theoretical analysis and

calculations. Visualisation and simulation have to be done in order to predict and anticipate the results that can be achieved through the experimental work later.

The fourth challenge will be to perform the methodical experiments to support the concept. Experiments will be repeated for the different machining parameters to ascertain the best range and balance of parameters. The experiment will also be repeated for the different specimen material used. Problems with the setup and concept and the modifications and countermeasures to address these problems will need to be identified. Further improvement to the system will also be ongoing.

Lastly, the results obtained from the theoretical analysis and calculations will be compared with the results obtained through experimental work. Results will be compared to the objective and aim of this research work. A conclusion will then be summed up based on the results and observations.

1.4 ORGANISATION

This report will begin with an introduction to the principles and aims of this research work followed by a detailed précis of the ultrashort pulse laser ablation technology, the comparison and its advantages over conventional long pulse industrial lasers and its applications in Chapter 2.

In Chapter 3, the light interference phenomenon is described. Some of the interferometric methods for obtaining interference on the femtosecond pulse laser will be discussed. The Newton's Ring interferometer and the Fabry-Perot etalon will be particularly highlighted

Chapter 4 introduces the equipment and systems used in the experimental setup of this research work. The femtosecond pulse laser system, the beam scanning system and the various equipment that constitutes the experimental setup will be listed together with their specifications, their attributes and limitations. The specimen and the type of material used in this research work will also be identified.

In Chapter 5, the concept of combining the effect of laser light interference and the sub focal spot machining ability at near threshold fluence of the femtosecond pulse laser for the use in submicromachining, its advantages and also its limitations will be discussed. The problems & limitations with regard to this research concept and the countermeasures needed to tackle and solve these problems will be identified. The reader will be guided through the step-by-step changes and tweaking to the experimental setup, their reasons and the results obtained along the way.

In Chapter 6, the Mach-Zehnder interferometry setup will be introduced into the experimental setup. The equipment and optical components used and the concept of the interferometer setup will be explained. The methodology of the experimental work and the results obtained will also be presented.

In Chapter 7, the Newton's Ring setup will be introduced. The principle and concept of this interferometry method will be explained. The experimental setup and the methodology of the experimental work will also be presented. The experimental results will then be compared with the results obtained through theoretical calculations and MATLAB[®] analysis.

Chapter 8 introduces the Fabry-Perot etalon setup, its concept and its role in the experimental setup. The methodology of the experimental work and the experimental setup and equipment used will be presented. Theoretical analysis and calculations work will be performed and the results obtained will then be compared to the experimental results for qualification and justification.

In Chapter 9, the proposed micromachining technique using the central bright fringe of the femtosecond laser interference beam is compared with current nanofabrication technologies in the market today. The advantages and significance of this research work is highlighted together with its importance and contribution to current laser micromachining technology.

Lastly, the results and conclusions obtained will be presented, compared and aligned with the objective of this research work in Chapter 10 follow by the recommendations for future development of this research concept.

CHAPTER 2

ULTRASHORT PULSE LASER ABLATION

2.1 INTRODUCTION

Current research trends in most of today's technologies such as in biotechnology, material technology and microelectronics is accelerating towards miniaturisation [1]. The demand for smaller, more compact, more efficient and cheaper devices has resulted in the need for higher precision and finer machining technologies. Micromachining/sub-micromachining is the foundation of the technology to realise such miniaturised products. Literally, 'micro' in micromachining indicates 'micrometer'. Therefore, 'micromachining' refers literally to the machining of a material in the 'micro' range of $1\mu\text{m}$ to $500\mu\text{m}$. Submicromachining will therefore refer to machining in the submicrometer ($<1\mu\text{m}$) ranges.

The ultrafast pulse laser ablation technology opens the door to a whole new prospect for micromachining and submicromachining. With the advent of femtosecond pulse lasers, ablation features of micron size and below, of high precision and exceptional machining quality can now be achieved. This exciting technology shall be the forerunner of tomorrow's machining trends in the industries.

2.2 WHY LASER MICROMACHINING?

Among the positive attributes of laser micromachining which makes it the preferred technology for many industrial applications are:

- it is a direct, single step process
- it is a non-contact process. Therefore, no tool wear and minimal chance of damage to process material due to shock or handling
- selective material removal. Proper selection of laser fluence allows the removal of one type of material without affecting the underlayers. E.g. wire stripping, skiving
- very minimal or no heat affected zone (HAZ)
- high precision and repeatability
- flexible feature size and shape
- can machine almost all materials, both conductive and non-conductive
- environmental friendly; does not use, nor emits high-toxicity and environmental harmful chemicals or gases. Also, reduced waste handling costs

2.3 ULTRASHORT PULSE LASER VS. CONVENTIONAL INDUSTRIAL LASERS

Pulse width, or the duration of the pulse, greatly affects the peak power of a laser because it defines the amount of time the material being machined interacts with the light. Pulse widths of longer duration are generally associated with lower intensity lasers and longer periods of light exposure, while pulse widths of shorter duration are associated with higher intensity lasers and shorter light exposure, characteristics essential for high-precision laser machining.

The ultrashort pulse laser (with pulse width of less than 1ps [15]) represents a major advancement in precision machining technology. Conventional industrial lasers such as the continuous wave (CW) lasers and long pulse lasers such as the nanosecond and picosecond lasers, first heat the target surface to the melting point into the liquid phase, and then into the vapour phase, resulting in the expansion and subsequently, the expulsion of the desired target material [3,16]. The heat and shock subsequently produced can cause considerable damage to the areas surrounding the machining spot

that can range from changes in the grain microstructures to cracking. Even the slightest thermal stress or shock can create intolerable collateral damage to very tiny structures only a few tens of micrometers in size, such as biological tissues or semiconductor devices [17].

The diffused heat will also result in the formation of a heat-affected zone (HAZ) around the machining spot [18,19]. The HAZ will have a different physical and/or chemical structures from the original parent material and as a result, is mechanically weak because of its inhomogeneity. The heating (and subsequent cooling) waves from subsequent laser pulses may cause mechanical stress which can cause microcracks in the surrounding material.

As the material is vaporised in conventional laser machining, some of the vaporised material will be deposited on the walls or the upper surface of the cut, resulting in the formation of slag and leaving residues on the edges. Heat diffusion also reduces the efficiency of the micromachining process by taking energy away from the work spot, energy that would otherwise go into the material removal process [18].

However, in the case of ultrashort femtosecond pulse laser ablation, material is heated to temperatures far beyond its boiling point, thus ionising the material, removing it atom by atom [20], allowing precise machining of everything from diamond [21,22] and the hardest steels to very soft materials such as heart tissues.

Each pulse is extremely short, lasting just 10 to 1000 femtoseconds, too brief to transfer heat or shock to the material machined, which means that the cutting, drilling, and machining occur with virtually no damage to the surrounding material [16,20,23]. The pulse deposits its energy so quickly that it does not have the chance to interact at all with the plume of vaporised material from the shot before, which would distort and bend the incoming beam and produce a rough-edged cut. The plasma plume leaves the surface very rapidly, ensuring that it is well beyond the machined edges before the arrival of the next laser pulse. And as only a very thin layer of material is removed during each pulse of the laser through a non-thermal mechanism, the machined surface is very smooth and does not require a subsequent cleanup process.

The laser-induced breakdown process takes time to build up and depends on the laser field strength. It exhibits a threshold behavior: at a given laser pulsewidth, only when the laser field strength exceeds a certain threshold can the plasma density grow to the critical value where irreversible breakdown takes place [3,24]. The threshold is customarily expressed as a laser fluence threshold (in unit of energy per unit area) as a function of pulse width.

For long pulses, the fluence breakdown threshold has a large deviation. Some pulses with fluences way below the threshold value can cause breakdown, while some pulse with fluences far above the threshold will not cause breakdown. However, the situation changes drastically when ultrashort laser pulses are used: the deviation in breakdown threshold is confined in a very narrow range [3,24]. More importantly, the large statistical variation of breakdown events near the threshold at long pulsewidths has disappeared at ultrashort pulses. In other words, the breakdown threshold becomes precise at ultrashort pulse widths.

Also, when machining with long pulse lasers, heat diffusion dominates the material removal process [2,15,18]. Heat diffusion reduces the efficiency of the laser machining process by taking energy away from the work spot, energy that would otherwise go into removing material. Therefore, a greater amount of energy, and hence fluence, will be needed to raise the machining temperature above threshold.

However, with ultrafast pulse lasers, the duration of the laser pulse is shorter than the heat diffusion time. As the energy does not have time to diffuse away, the efficiency of the machining process is high and there are no thermal losses due to heat diffusion. Therefore, the threshold fluence for ultrafast pulse lasers is lower than for long pulse lasers. This is relevant for certain machining situations such as in medical surgeries, where low fluences are desirable to reduce the effect of collateral damage, that is, damage to tissue located outside the desired region [2,3].

In a nutshell, the main advantages of ultrashort pulse laser material processing over conventional industrial laser material processing are:

- ultrashort laser ablation is a “nonthermal process”. Therefore, it will not cause thermal shock or damage to the areas surrounding the machining spot
- no heat-affected zone (HAZ)
- better control during the machining process
- very good reproducibility
- machined surface is very clean and smooth, and does not require a subsequent cleanup process
- can machine any materials from diamond and the hardest steels to very soft materials such as heart and corneal tissues
- lower fluence threshold
- the ability to perform sub-spot size micromachining

2.4 ULTRASHORT PULSE LASER ABLATION TECHNOLOGY

Laser ablation implies the removal of macroscopic amounts of matter from the surface of solid material using very short laser pulses in the sub-picosecond or femtosecond range, where the photon energy is high enough to break atomic bonds, resulting in ‘cool’ laser processing [25]. Usually, the material must undergo a change of the fundamental state of aggregation and transform into some volatile phase, e.g., a gas or a plasma [24].

Ablation occurs when the laser beam’s intensity passes a threshold value that depends on the material to be ablated and the wavelength of the laser [19]. Whenever the energy density, or fluence, exceeds the ablation threshold value for the material, chemical bonds are broken, fracturing the material into energetic fragments. The fragments are atoms, groups of atoms, ions, and electrons. Because the fragments leave the reaction zone as an energetic gas and solid debris, the ablation process resembles explosive evaporation of the material [26].

Figure 2.1: Typical Ablation Curve of Etch Rate vs. Fluence. [24]

Figure 2.1 shows a typical ablation curve for pulsed lasers. At low target energy density (fluence), there is no material removal. As the energy density is increased, it will eventually reach the ‘ablation threshold’ point, where material removal will begin. As the fluence increases, there is more material removed per volume of photons until the point where the curve plateaus. Once the curve has reached this plateau, the amount of removed material is not further increased with increasing fluence, so it is generally not beneficial to run at laser fluences much beyond this point, as thermal side effects will become more pronounced. The energy of the additional photons, since it is not being used to eject material, therefore transforms to heat and can cause secondary thermal effects [3,18,24].

The transition from the solid phase to the gas phase can occur in a stepwise fashion by the melting of the solid and evaporation of the liquid. Otherwise, a direct transition to a plasma (gas) phase can be accomplished by laser radiation of sufficiently high intensity which leads to the ionisation of the solid material, transforming it into dense plasma. When the laser fluence is kept constant while the pulse duration is decreased, the optical electric field strength will at some point exceed the breakdown threshold of the material. Therefore, plasma formation is expected to become the dominant mode of laser ablation when the pulse duration is made shorter and shorter.

Transportation of the energy in the ultrafast pulse laser ablation process can be divided into two stages: (1) the photon energy absorption, mainly through free electron generation and heating, and (2) the redistribution of the absorbed energy to lattice leading to material removals [3,27,28]. This stage separation is based on the assumption that free electron generation and heating are completed in such a short time that the lattice temperature remains unchanged during the duration of a femtosecond laser pulse [24,29]. Therefore, ablation with ultrashort pulse lasers is considered a “nonthermal process”.

The laser-material interaction is also separated in time from the actual removal of material. Therefore, heat conduction is negligible, allowing for better control during the machining process. Hence, the reproducibility with femtosecond laser machining is very good.

The particular nature of the ablation process is strongly dependent on the type of material machined and on the laser intensity, wavelength, energy on target, pulse length and the number of pulses (repetition rate) [25,30,31]. The most important consideration however, is the peak intensity which is dependent on the temporal beam profile and therefore, the laser pulse length [25]. In general, a shorter pulse length will produce less thermal effects. Short pulse lasers can have very high peak powers even though the total output energy is low due to the short pulse length. Basically, the peak power (in Watts) is equal to the energy (Joules) divided by the pulse length (seconds). Therefore, either an increase in energy or a decrease in pulse length will increase the peak power.

2.5 MECHANISM OF SUB SPOT SIZE ABLATION PHENOMENA

First demonstrated by Pronko P.P. et al. in 1995, sub-spot size micromachining by ultrafast lasers has been proven possible, overcoming previous notions that the minimum achievable machining spot size is dependent and limited by the smallest focal spot size given by the laser wavelength [2,3].

One of the amazing characteristics of ultrashort pulse laser ablation is that the threshold value can be precisely determined, in contrast to the broad threshold bandwidth of long pulse laser ablation. This is because the duration of the laser pulses of ultrafast pulse lasers are shorter than the heat diffusion time [2]. As the energy does not have time to diffuse away, the efficiency of the machining process is very high and hence, the threshold value of the material machined can be determined very accurately.

As the threshold fluence can be precisely determined, the input beam intensity profile can be controlled as such that only a small portion of the focussed laser spot is above the ablation threshold. This enables ultrafast pulse lasers to create features substantially below that of the minimum focal spot size.

The ultrafast laser pulse has a Gaussian beam profile which has a peak intensity in the center of the beam which smoothly decreases radially outward from the centre. By properly choosing the incident laser fluence, it is possible to control and make only a fraction (the central peak region) of the focused Gaussian beam within which the fluence is greater than the threshold of the material, to machine. Therefore, the ablated region can be restricted to a very small area, much smaller than the diameter of the focal spot size [2]. This limited area of ablation can be as small as 1/10th of the focal spot size itself. The principle of this technique is illustrated in Figure 2.2 and Figure 2.3.

Figure 2.2: By controlling the peak fluence F_0 , to be just above the threshold fluence F_{th} , ablation can be confined to a much narrower bandwidth, thus greatly reducing the effective ablation spot size from D_0 to D .

Figure 2.3: The intensity profile of the laser focus spot can be controlled so that only a small portion at the center part of the beam is above the breakdown threshold. Using this geometry, subfocal spot size ablation features can be obtained. [3]

2.5.1 Ablation Threshold

The process of laser ablation has a threshold fluence. Fluence is the laser pulse energy per unit area and it can be changed either by changing the laser pulse energy or by changing the ablation area. Threshold, which is usually expressed as the laser fluence threshold, is a function of the absorbed energy.

At fluences below the threshold, only miniscule etching (<0.005 μm per laser pulse) is observed, if at all. But when laser fluence is above the threshold, the etch depth per pulse increases rapidly with increasing laser fluence. The threshold fluence depends mainly on the target material structure and effective target absorption coefficient, α_{eff} at the laser wavelength. Absorption of laser radiation leads to a temperature increase in the target material.

For the quantification of the ablation threshold fluence, F_{th} , the utilization of a semi-logarithmic plot of ablation depth, d vs peak laser fluence, F_0 is shown [32].

$$d = \frac{1}{\alpha_{eff}} \ln \left(\frac{F_0}{F_{th}} \right) \quad \text{Equation 2.1}$$

α_{eff} represents the effective absorption coefficient that includes to a certain extent the incubation phenomena (the occurrence when a minimum number of pulses have to be applied to the material before macroscopic material removal occurs) and nonlinear absorption phenomena. However, it was observed that experimentally, for opaque materials such as metals (Ni, Cu, Mo), $\alpha_{ef} \approx \alpha$ with α as the linear absorption coefficient at the laser wavelength [33,34,35]. It has also been observed that the effect of incubation is virtually absent in metals [36]. For weaker absorbing samples such as dielectrics and wide bandgap materials, $\alpha_{eff} > \alpha$ is normally obtained [34].

To measure the ablation threshold fluence, F_{th} , the laser beam is sent through a telecentric lens of $f=100\text{mm}$ and onto the specimen. The peak pulse energy taken right after the lens is maintained at 500nJ (Peak energy is used rather than the average laser energy taking into consideration that there will be some instances where only the

upper part of the energy distribution of the Gaussian beam will be able the ablation threshold and so only this part of the beam will actually cause ablation, therefore the peak value is a more meaningful quantity). The metallic thin film specimen is placed on a translation stage located behind the focal point of the beam. The specimen is placed far enough away from the focal point to avoid breakdown, and then moved incrementally closer to the focal point using the translation stage. The number of pulses is controlled at 100 shots per point.

Breakdown is determined when the laser light penetrates through the metallic thin film coated fused silica glass specimen (a CCD camera is placed behind the specimen to observe this phenomenon) indicating that ablation has been initiated and material has been removed. In addition, when breakdown occurs, plasma emission will take place and a spark will be observed in the darkened room.

At the breakdown point, the location of the specimen surface to the lens is recorded and maintained. Pulse energy is reduced to 50nJ, and then slowly increased (incremental step of 50nJ) till 500nJ.

Peak laser fluence, F_0 and peak pulse energy, E_0 are directly related by,

$$F_0 = \frac{2E_0}{\pi w^2} \quad \text{Equation 2.2}$$

where,

w = Gaussian beam radius

Assuming a Gaussian spatial beam profile, the relation between the feature diameter ablated, D and the respective peak laser fluence, F_0 can be written as [35,37],

$$D^2 = 2w^2 \ln \left(\frac{F_0}{F_{th}} \right) \quad \text{Equation 2.3}$$

By plotting the squared diameters versus the peak laser fluence, F_0 , and then extrapolating the D^2 values back to zero, the ablation threshold fluence, F_{th} can be determined. Equation 2.3 is also valid when the laser fluences F_0 and F_{th} are replaced by the pulse energies E_0 and E_{th} respectively.

The breakdown threshold for platinum and gold is calculated to be 132 mJ/cm^2 and 158 mJ/cm^2 respectively. Several researchers have investigated the breakdown threshold for these materials (Gold 118 mJ/cm^2 [38], 170 mJ/cm^2 [39]; Platinum 112 mJ/cm^2 [40]) and the reported values from these literature are in good agreement with the calculated values from this work.

2.6 APPLICATIONS

2.6.1 Ultrafast Laser Micromachining Technology

Laser micromachining is an increasingly important production method and is used in the automotive, aerospace, electronics, telecommunications and medical device industries. Laser micromachining offers the advantage of being a direct, single step process and can work with almost all materials, both conductive and non-conductive, and without the need for a vacuum chamber. In laser micromachining, laser ablation is the dominant mechanism for material removal [22].

Laser micro-ablation has become a dominant technology for such applications as the production of nanomaterials, deposition of thin metal and dielectric films, welding and bonding of metal parts, micromachining of semiconductor materials and chemical analysis [22,41,42,43]. It plays an important role in laser processing and structuring of materials. The applications range from high precision drilling and cutting to fabrication of complex surface patterns or highly controlled changes of the physical and chemical microstructure. By choosing the proper laser parameters such as the wavelength, intensity, and pulse duration, great flexibility is available to tailor laser ablation to suit specific task.

During the last few years, results have been reported which indicate that the use of very short laser pulses such as picosecond pulses and femtosecond pulses provides distinct advantages over laser pulses of longer duration [22]. Tiny structures with extremely complex geometry and small kerf widths can be machined [44]. The high quality beam of ultrashort pulse lasers make the precision machining of almost all materials possible.

2.6.2 Ultrafast Lasers in Industrial Micromachining

2.6.2.1 Laser Cutting

The ultrashort pulse laser represents a major advancement in micro-cutting technology. The high beam quality of ultrashort pulse lasers enables it to be focused to a very small spot size. Coupled with the high peak power inherent to ultrashort pulse lasers, very high focal intensities ($1\text{-}1000\text{ GW/cm}^2$) can be obtained, which are ideal for ablating a wide variety of materials from diamond and the hardest steels and brittle ceramics to very soft materials such as heart and ocular tissues [21,22,45,46].

Conventional methods such as continuous and long pulse lasers, diamond saws, water jets and EDM are only able to meet the demand for increasingly finer and more precise structures to a limited extent [44]. None of them can achieve the precision of the femtosecond laser machine tool (0.1mm) [17], and most of them cause collateral damage to the areas surrounding the cut to varying degrees.

Removal of minimal amounts of material makes the ultrashort pulse laser cutting system useful for processing extremely valuable or hazardous materials. The high precision of the laser cutting minimises the amount of waste generated during the cutting process. If the cutting is done in a vacuum, better than 95% of the removed material can be recovered [17].

The femtosecond laser can also be used to machine high explosives and volatile materials. Because so little energy or mechanical shock is transferred to the part being machined, materials such as high explosives or parts containing high explosives can be cut without danger of detonation [17].

Also, by using CNC or scanning optics, complex patterns can be formed by direct-writing. The direct-write capability of the laser makes it an advantage over other machining methods as it is a single step process. This is especially advantageous when the production volume is low because of the low set-up times and costs [22].

2.6.2.2 Laser Drilling

Microdrilling is an enabling technology for several important manufacturing processes. One very important example is the drilling of microvias in printed circuit boards/ printed wire boards (PCB/PWB) and flex industries. These microvias enables the electrical connections between the different insulating layers. Among the many consumer products requiring microvia technology are cellular phones, internet devices, personal computers, personal global positioning systems, digital cameras, medical devices, etc. Currently, laser-drilled vias range from 100 to 200 μm in diameter, with some speciality items requiring vias down to 25 μm in diameter [47].

However, the rapid trend for miniaturisation has led to the need for even smaller and finer drilling capabilities. For example, the miniaturisation in portable electronics devices resulted in the need for smaller high-density interconnects (HDI) for packaging and printed circuit boards. And driven by the increasingly high I/O chips, the number of interconnects per layer continually rises resulting in the demand for smaller and finer vias.

Currently, the number of microvias exceeds 10,000 per substrate. But with the continued growth of silicon chip capabilities, this requirement will move upward to the range of 40,000 to 80,000 microvias per substrate in the near future [48]. Therefore, there is a need for a laser-drilling technology that can produce fine holes into the sub-micron ranges with high aspect ratios and good reproducibility.

Another very good example is in the manufacturing of microscale fluidic devices. Among the most widely known applications is the production of ink-jet printer nozzles. This family of products also includes drug-delivery systems, microscale heatpipes and heat exchangers, fuel injectors, chemical-reactor networks, and chemical-analysis tools [22,49]. Precise control of small quantities of fluid is important for all these devices, and depending on the working fluid and desired flow rates, diameters ranging from 100 μm to less than 1 μm are required with diameter tolerances of less than 0.5 μm [19].

2.6.3 Medical and Biology Applications

Ultrashort pulse lasers are finding increasing applications in biology and medicine. Direct utilisation includes propagation studies in scattering media with applications in optical mammography, dosimetry for photodynamic therapy and species concentration assessment [50].

2.6.3.1 Surgery/ Microsurgery

Ultrashort pulse lasers have an important niche in microsurgery. According to theory, subpicosecond durations are far too short for appreciable electron energy to be transferred to the surrounding material. For ultrashort pulses, tissue ablation occurs through a photoacoustic mechanism instead of a photothermal mechanism [51]. As a result, very little laser energy is absorbed by the tissues ablated, enabling material to be removed with essentially no collateral damage [52,53]. In addition, the fluence at threshold of the ablation was found to be reduced for shorter pulse durations. Therefore, lower pulse energies can be used for the removal of tissues resulting in reduced shockwave effects and higher efficiency [54].

The precision ablation of these lasers allows microsurgeons to perform intricate operations, such as drilling holes through small middle ear bones, angioplasty and corneal sculpting. Likewise in brain surgery which also puts a premium on accuracy and control and on minimising thermal collateral damage, a system with a high pulse-repetition rate could allow surgeons enough speed and control to virtually “sculpt” the tissues [55]. In microvascular surgery, an ultrashort pulse laser can be used to drill small holes in the walls of the heart to supply oxygenated blood to cardiac muscles with irreparably blocked blood vessels.

Ultrashort pulse lasers are also being used for eye surgery and LASIK (laser-assisted in situ keratomileusis) procedures. INTRALASETM has developed a femtosecond pulse laser system for microkeratome surgery which is painless and offers a higher degree of accuracy over the traditional LASIK systems which uses a blade to create the flap.

Among the advantages of tissue ablation with ultrashort pulse laser are:

- It is efficient. With decreasing pulse width, the energy density needed to ablate material decreases.
- Minimal collateral damage to the tissues because ablation is efficient with the short pulse and because the ablated tissues carry away a large fraction of the deposited energy from the laser.
- The ablation threshold and ablation rates vary only slightly as tissue type changes.
- Ablation depth can be controlled with extreme precision because a small amount of tissue is ablated per pulse and because the number of pulses can be controlled.

An added benefit of lasers to surgery is the fact that the pulses can be transmitted by fibre optics. Laser energy can be delivered to many remote locations within the body through fibre-carrying catheters. In the future, instead of making large incisions to gain access to certain organs or cavities, surgeons will be able to use more endoscopic and laproscopic techniques.

2.6.3.2 Dentistry

Ultrashort pulse laser systems also have great potential in dentistry to replace the dentist's drill for cavity and root canal work. The drill produces pain chiefly by heat (the drill can get the tooth very hot), and secondarily by mechanical vibration. Ultrashort pulse lasers produce minimal heat and vibration and virtually no collateral damage to the surrounding enamel due to their precise and highly effective ablation capabilities and minimal thermal and shock wave [56].

2.6.3.3 Medical Implants

A typical medical application for ultrafast pulse laser machining is in the production of intra-coronary stents, which are used in angioplasty (Figure 2.4). The advantages of implants machined by laser are their high contour accuracy (better than 5 μ m) and the fact that the production method is gentle even on extremely fragile tubes. It can also produce stents in biodegradable polymers which are very difficult to micromachine using other micromachining methods [57,58,59].

Figure 2.4: A medical stent micromachined from a biodegradable polymer using a femtosecond laser (Courtesy of LZH/Cortronik).

Another important medical application of laser micromachining is in the microdrilling of catheters for controlled drug delivery [57,60]. Very precise holes of less than 0.004 inches in diameters are often required for precise metering and distribution of drug delivery to locations within the body.

2.6.3.4 Micro-fenestration of Contact Lenses

Contact lens discomfort is caused primarily by a lack of oxygen at the cornea surface. The addition of micro-fenestration to the lenses can increase oxygen permeability [61].

2.6.3.5 Diagnostic Utilisation

During the last 15 years, laser spectroscopic techniques have been developed providing powerful means for non-intrusive real time medical diagnostics of tissue. The field encompassed the early diagnostics and demarcation of malignant tumours, the characterisation of blood vessels for guiding interventional angioplastic procedures and scattering spectroscopy for optical mammography, etc [62,63].

However, with the advent of ultrafast pulse lasers, a new domain of ultrafast spectroscopy has been uncovered [64]. The field of femtochemistry has allowed the

study of many fundamental processes in biology and medicine such as photosynthesis and vision.

2.7 CONCLUDING REMARKS

The ultrafast pulse laser represents a major advancement in precision machining technology. Ultrafast pulse laser technology offers the advantages of being a nonthermal process, therefore eliminating thermal damages such as residual stress and a heat-affected zone layer. Therefore, it can give very good reproducibility and exceptional machining quality.

However, the most important feature of the ultrashort pulse laser is its ability to perform sub-spot size micromachining, overcoming previous notions that the minimum achievable ablation feature is limited to the laser wavelength. Features as small as 1/10th of the laser focus spot size has been achieved with this phenomenon.

Ultrashort pulse laser ablation is the future enabling technology in many industries such as in the automotive, aerospace, electronics, telecommunications and medical device industries. Laser micromachining offers the advantage of being a direct, single step process and can work with almost all materials, both conductive and non-conductive, and without the need for a vacuum chamber. Key applications include the drilling of microvias in the semiconductor industry and the manufacturing of catheters and heart stents in the biomedical industry, the micro-drilling of microscale fluidic devices such as ink-jet printer nozzles and drug-delivery systems and in microsurgery.

CHAPTER 3

INTERFERENCE OF LIGHT

3.1 INTRODUCTION

As light has wave properties, these light waves can interact to interfere with one another. When the waves are propagating in the same direction and overlaps, the amplitude, wavelength and phase angle will interact and produce either an addition or subtraction of amplitude in the resultant wave. This phenomenon is called light interference [65].

Interference of light shows itself as regular ‘fringe patterns’, a series of light and dark bands of illumination. These bands of fringes can be linear, circular or wiggly. The spacing between these alternating bands of light and dark fringes can be of equal spacing and can be of variable spacing.

3.2 CONSTRUCTIVE AND DESTRUCTIVE INTERFERENCE

Constructive interference happens when two or more waves come together to form a larger and stronger wave. If the crests of one of the waves coincide with the crests of the other, the amplitudes are additive.

Figure 3.1: Example of constructive interference. [66]

Destructive interference is when two or more waves come together and cancel each other out to make a weaker wave. If the crests of one wave coincide with the troughs of the other wave, the resultant amplitude is decreased or may even be completely cancelled. The result is a drop in intensity, or in the case of total cancellation, zero intensity.

Figure 3.2: Example of destructive interference. [66]

At the two extreme instances for two waves of equal amplitude and intensity (only), when [65,67]:

- i) the light waves are in exactly the same phase; the 2 waves will constructively interfere to give a resultant amplitude of two times the amplitude of the original waves. It is known that light intensity varies directly as the square of the amplitude. Therefore, when amplitude is doubled, the intensity will be quadrupled producing light of four (4) times the intensity of either wave.
- ii) the light waves are 180° (π radian) out of phase, the 2 waves will completely destruct each and other resulting in no intensity at all.

3.3 THE PRINCIPLE OF SUPERPOSITION

The phenomenon of interference is a consequence of the Superposition Principle. The Principle of Superposition states that when two or more waves are superimposed, the total net wave displacement at any point is equal to the vector algebraic sum of the displacements of the individual waves at that point [68]. Since these displacements can be positive or negative, the net displacement can either be greater or less than the individual wave displacements. The former case is called *constructive interference*, while the latter is called *destructive interference*.

As illustrated in Figure 3.3, the two darker waves, A and B, "add together" to give the third, brighter wave, C. At any point along the graph, $A + B = C$.

Figure 3.3: The Principle of Superposition.

3.4 THE LIGHT INTERFERENCE TERM

In accordance with the Principle of Superposition, the electric field $\vec{E}$, at a point in space, arising from the separate fields $\vec{E}_1, \vec{E}_2, \dots$ of various contributing sources is given by

$$\vec{E} = \vec{E}_1 + \vec{E}_2 + \dots \quad \text{Equation 3.1}$$

The light field $\vec{E}$, varies in time making the actual field an impractical quantity to detect. On the other hand, the intensity or irradiance I , can be measured directly with a wide variety of sensors (e.g., photocells, bolometer, etc). Therefore, the study of light and light interference is best approached by way on the intensity measure.

Consider two point sources, S_1 and S_2 , emitting monochromatic waves of the same frequency in a homogenous medium. Let their separation a , be much greater than the light wavelength, λ .

Figure 3.4: Waves from two point sources overlapping in space. [65]

Locate the point of observation, P far enough away from the sources so that at P , the wavefronts will be planes (Figure 3.4). Consider

$$\vec{E}_1(\vec{r}, t) = \vec{E}_{01} \cos(\vec{k}_1 \cdot \vec{r} - \omega t + \phi_1) \quad \text{Equation 3.2}$$

and

$$\vec{E}_2(\vec{r}, t) = \vec{E}_{02} \cos(\vec{k}_2 \cdot \vec{r} - \omega t + \phi_2) \quad \text{Equation 3.3}$$

Intensity at P is given by

$$I = \left\langle \vec{E}^2 \right\rangle_T \quad \text{Equation 3.4}$$

It is known that

$$\vec{E}^2 = \vec{E} \cdot \vec{E} \quad \text{Equation 3.5}$$

where now

$$\vec{E}^2 = (\vec{E}_1 + \vec{E}_2) \cdot (\vec{E}_1 + \vec{E}_2) \quad \text{Equation 3.6}$$

and thus

$$\vec{E}^2 = \vec{E}_1^2 + \vec{E}_2^2 + 2\vec{E}_1 \cdot \vec{E}_2 \quad \text{Equation 3.7}$$

Taking the time average of both sides, intensity will then becomes

$$I = I_1 + I_2 + I_{12} \quad \text{Equation 3.8}$$

with

$$I_1 = \left\langle \vec{E}_1^2 \right\rangle_T \quad \text{Equation 3.9}$$

$$I_2 = \left\langle \vec{E}_2^2 \right\rangle_T \quad \text{Equation 3.10}$$

and

$$I_{12} = 2 \left\langle \vec{E}_1 \cdot \vec{E}_2 \right\rangle_T \quad \text{Equation 3.11}$$

The latter expression is known as the interference term. To evaluate it in this specific instance,

$$\vec{E}_1 \cdot \vec{E}_2 = \vec{E}_{01} \cdot \vec{E}_{02} \cos(\vec{k}_1 \cdot \vec{r} - \omega t + \phi_1) \times \cos(\vec{k}_2 \cdot \vec{r} - \omega t + \phi_2) \quad \text{Equation 3.12}$$

or equivalently,

$$\begin{aligned} \vec{E}_1 \cdot \vec{E}_2 &= \vec{E}_{01} \cdot \vec{E}_{02} [\cos(\vec{k}_1 \cdot \vec{r} + \phi_1) \cos \omega t + \sin(\vec{k}_1 \cdot \vec{r} + \phi_1) \sin \omega t] \\ &\times [\cos(\vec{k}_2 \cdot \vec{r} + \phi_2) \cos \omega t + \sin(\vec{k}_2 \cdot \vec{r} + \phi_2) \sin \omega t] \end{aligned} \quad \text{Equation 3.13}$$

The time average of function $f(t)$, taken over an interval, t is

$$\langle f(t) \rangle_t = \frac{1}{t} \int_t^{t+t} f(t') dt' \quad \text{Equation 3.14}$$

After multiplying out and averaging Equation 3.13,

$$\left\langle \vec{E}_1 \cdot \vec{E}_2 \right\rangle_t = \frac{1}{2} \vec{E}_{01} \cdot \vec{E}_{02} \cos(\vec{k}_1 \cdot \vec{r} + \phi_1 - \vec{k}_2 \cdot \vec{r} - \phi_2) \quad \text{Equation 3.15}$$

The interference term is then,

$$I_{12} = \vec{E}_{01} \cdot \vec{E}_{02} \cos \delta \quad \text{Equation 3.16}$$

with δ equal to $(\vec{k}_1 \cdot \vec{r} - \vec{k}_2 \cdot \vec{r} + \phi_1 - \phi_2)$ is the *phase difference* arising from a combined path length and initial phase-angle difference.

In most situations, $\vec{E}_{01}$ is parallel to $\vec{E}_{02}$. Therefore, the intensity becomes

$$I_{12} = E_{01}E_{02} \cos \delta \quad \text{Equation 3.17}$$

This can be written in a more convenient way by noticing that

$$I_1 = \left\langle \vec{E}_1^2 \right\rangle_t = \frac{E_{01}^2}{2} \quad \text{Equation 3.18}$$

and

$$I_2 = \left\langle \vec{E}_2^2 \right\rangle_t = \frac{E_{02}^2}{2} \quad \text{Equation 3.19}$$

The interference term then becomes

$$I_{12} = 2\sqrt{I_1 I_2} \cos \delta \quad \text{Equation 3.20}$$

whereupon the total intensity is

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta \quad \text{Equation 3.21}$$

At various points in space, the resultant intensity can be greater, less than, or equal to $I_1 + I_2$, depending on the value of I_{12} , that is depending on δ . A maximum intensity is obtained when $\cos \delta = 1$, so that

$$I_{\max} = I_1 + I_2 + 2\sqrt{I_1 I_2} \quad \text{Equation 3.22}$$

when $\delta = 0, \pm 2\pi, \pm 4\pi, \dots$

In this case of *total constructive interference*, the phase difference between the two waves is an integer multiple of 2π , and the disturbances are in-phase.

A minimum intensity occurs when the waves are 180° out-of-phase when the troughs overlaps the crests, $\cos \delta = -1$, and

$$I_{\min} = I_1 + I_2 - 2\sqrt{I_1 I_2} \quad \text{Equation 3.23}$$

when $\delta = \pm\pi, \pm 3\pi, \pm 5\pi, \dots$

This is referred to as *total destructive interference*.

3.5 CONDITIONS FOR INTERFERENCE

Interference of light is not a common occurrence because of the small wavelength (400nm to 700nm) and the high frequency. For interference to be observable, three conditions must be met:

- i. The sources must be *coherent*, that is they must maintain a constant phase with respect to each other
- ii. The sources must have identical wavelengths (monochromatic)
- iii. The Principle of Superposition must apply

3.6 NEWTON'S RING

Newton's Ring is a type of interference by division of amplitude (IDA). They are Fizeau fringes or fringes of constant thickness [69]. First observed by Robert Hooke [70] as rings of rainbow colours in a flake of mica in 1665, it was later studied and written in more depth by Sir Isaac Newton in his book "Opticks" [71].

In its simplest, Newton's Rings can be observed by placing a long focal length convex lens of shallow spherical curve in contact with an optical flat or glass plate and viewing the reflected light [72] (Figure 3.5(a)).

Figure 3.5: (a) General set-up for observing Newton's Ring; (b) Interference fringe pattern of Newton's Ring. [73]

The enclosed air film will then be extremely thin at the point of contact and will gradually increase in thickness with increased distance from this point [74]. If illuminated with monochromatic light, alternate bright and dark concentric fringes of equal thickness can be observed, being circles with the point of contact as centre. On transmission, the centre of the concentric fringes at the contact point will be black [75].

For monochromatic light, an extensive fringe system such as that shown in Figure 3.5(b) is observed. This is because the ring diameters of the fringes depend on the wavelength of the light used.

Referring to the set-up in Figure 3.5(a), the wavefront of the illuminating light travelling downwards is partially reflected at each boundary of the lens and plate. The two wavefronts that interfere to cause Newton's Rings arise from the partial reflection at the lower surface of the lens and the upper surface of the glass plate/ optical flat. As they are both derived from the same source, the two waves can interfere with each other. Their relative phases are determined by two factors:

- i) the reflection coefficients of the two boundaries are of opposite sign,
- ii) there is an extra path traversed by the wave reflected by the flat surface.

The first factor provides a phase difference of π , so that the centre of the pattern is dark, with the two reflections in antiphase as would be expected when the glass is in contact and effectively continuous (no reflection at a boundary can take place if there is no boundary). Succeeding rings are light and dark as the extra path length is $(N - \frac{1}{2})\lambda$ or $N\lambda$.

If the radius of curvature of the bottom face of the lens is R , the condition for a bright fringe at r from the axis in *reflection* is

$$\text{Path difference} = 2d = (m + 1/2)\lambda \quad \text{Equation 3.24}$$

with

- m = the order of the rings
= 0, 1, 2, 3...
- λ = wavelength of the laser light in air

where the value of d in terms of $\mathcal{R}$ and r can be determined approximately by an

$$d = \mathcal{R}(1 - \cos \theta) = \mathcal{R}\left(\frac{\theta^2}{2} + \dots\right) \approx \frac{r^2}{2\mathcal{R}} \quad \text{Equation 3.25}$$

Therefore, the radius of the bright ring, r can be obtained from

$$r \approx \sqrt{(m + 1/2)\lambda\mathcal{R}} = \sqrt{2\mathcal{R}d} \quad \text{Equation 3.26}$$

The condition for a dark fringe at r from the axis is

$$\text{Path difference} = 2d = m\lambda \quad \text{Equation 3.27}$$

where the value of d in terms of $\mathcal{R}$ and r is

$$d = \frac{r^2}{2\mathcal{R}} \quad \text{Equation 3.28}$$

Therefore, the radius of the dark ring, r can be obtained from

$$r \approx \sqrt{m\lambda\mathcal{R}} = \sqrt{2\mathcal{R}d} \quad \text{Equation 3.29}$$

In **transmission**, fringes are complementary: dark where those reflected are bright, and vice versa.

3.7 MULTIPLE BEAM INTERFERENCE

3.7.1 Multiple Beam Fringes by Transmission

Figure 3.6: Multiple-beam interference in a plane-parallel plate. [76]

Consider a ray of light incident, as shown in Figure 3.6, on a thin film (thickness d , refractive index n) at an angle θ_1 . Multiple reflections within the film produce a series of transmitted and reflected waves whose amplitudes fall off progressively. The phase difference between successive transmitted or reflected waves is

$$\delta = (4\pi / \lambda) n d \cos \theta_2 \quad \text{Equation 3.30}$$

The complex amplitude of the resultant transmitted wave is the sum of the complex amplitudes of all the transmitted components.

$$\begin{aligned} A_T(\delta) &= t^2 [1 + r^2 \exp(-i) + r^4 \exp(-i2\delta) + \dots] \\ &= t^2 / [1 + r^2 \exp(-i\delta)] \end{aligned} \quad \text{Equation 3.31}$$

where r and t are the coefficients of reflection and transmission (for amplitude) of the surfaces. The intensity in the interference pattern formed in transmission is therefore,

$$\begin{aligned} I_T(\delta) &= |A_T(\delta)|^2 \\ &= T^2 / (1 + R^2 - 2R \cos \delta) \end{aligned} \quad \text{Equation 3.32}$$

where $R = r^2$ and $T = t^2$ are respectively, the coefficients of reflection and transmission for intensity. The curves in Figure 3.7 show that as the coefficient of reflection R increases, the intensity at the minima decreases and the bright fringes become sharper.

Figure 3.7: Intensity distribution in multiple-beam fringes formed by transmitted light for different values of the reflectance, R of the surfaces. [76]

The separation of the fringes corresponds to a change in δ of 2π . The width of the fringes (Full Width at Half Maximum or FWHM) is defined as the separation of two points on either side of a maximum at which the intensity is equal to half its maximum value. At these points

$$\sin(\delta/2) = (1-R)/2R^{1/2} \quad \text{Equation 3.33}$$

When R is close to unity, $\sin(\delta/2) \approx (\delta/2)$ and the change in δ corresponding to the FWHM of the fringes is

$$\Delta\delta_w = 4(1-R)/2R^{1/2} \quad \text{Equation 3.34}$$

The finesse is defined as the ratio of the separation of adjacent fringes (corresponding to a change in δ of 2π) to their FWHM and is given by the relation

$$F = 2\pi / \Delta\delta_w = \pi R^{1/2} / (1-R) \quad \text{Equation 3.35}$$

Figure 3.8: Transmission fringes at reflectance, $R = 0.04$ and $R = 0.8$. [69]

3.7.2 Multiple Beam Fringes by Reflection

The complex amplitude of the reflected wave is obtained by summing the complex amplitudes of all the reflected beams and is given by the relation

$$\begin{aligned} A_R(\delta) &= r[1 - t^2 \exp(-i\delta) - t^2 r^2 \exp(-i2\delta) + \dots] \\ &= r[1 - \exp(-i\delta)] / [1 - r^2 \exp(-i\delta)] \end{aligned} \quad \text{Equation 3.36}$$

The corresponding intensity is, therefore

$$I_R(\delta) = 2R(1 - \cos \delta) / (1 + R^2 - 2R \cos \delta) \quad \text{Equation 3.37}$$

The interference fringes obtained by reflection are complementary to those formed by transmission; when $R \rightarrow 1$, very narrow, dark fringes on a bright background are obtained [70,76].

Figure 3.9: Reflection fringes at reflectance, $R = 0.04$ and $R = 0.8$. [69]

3.8 THE FABRY-PEROT ETALON

Figure 3.10: The Fabry-Perot Etalon. [69]

Developed in France in 1899 shortly after the Michelson Interferometer by C. Fabry (1867-1945) and A. Perot (1863-1925), the Fabry-Perot etalon makes use of multiple-beam interference [77]. Only a very narrow bandwidth of light is allowed to pass through the etalon, while the remaining light is reflected back.

The Fabry-Perot etalon essentially consists of two extremely flat quartz surfaces. Both surfaces are covered with a uniform reflective coating of very thin silver or aluminium film or alternating layers of high and low index dielectric films, with the reflectance of each surface plane is of equal magnitude [78]. These two surfaces are kept separated by an air gap, a solid quartz gap, or by other means, by a distance t which generally varies from several millimetres to several centimetres depending on the application it is intended for. It is very important that the two surfaces be kept very parallel with a high degree of precision [79]. Multiple-beam interference occurs between the beams of light that are multiply reflected between these two reflective interfaces [80].

There are generally two types of FP etalons: the air-spaced etalons and the solid etalons [81].

i) Air-Spaced Etalons

Air-spaced etalons are pairs of plano-plano plates separated by optically contacted spacer blocks. The inner surfaces are coated with partially transmitting etalon coatings; the outer surfaces, with antireflection coatings. Air-spaced etalons offer the following advantages over solid etalons:

- higher thermal stability
- greater mechanical stability
- wider range of free spectral ranges
- pressure tuning
- improved broadband transmission via simultaneous application of perfectly matched etalon coatings
- higher defect finesse

ii) Solid Etalons

Solid etalons are parallel-sided plano-plano plates with etalon coatings on both sides. The cavity is formed by the plate thickness between coatings. Solid etalons offer the following advantages over air-spaced etalons:

- improved narrowband transmission
- higher quality cavities due to multilayer coatings
- ruggedness and compactness
- lower cost
- distortion-free substrates with harder coatings
- potentially higher laser damage thresholds

If the light source entering the etalon is collimated, then the light is reflected back and forth within the etalon, creating an interference pattern. Referring to Figure 3.11, light which is incident from the left on the first reflection surface is split by reflection into a series of parallel transmitted rays. The ray is partially transmitted at each reflection from the second surface. For simplicity, the figure does not show the change in

direction of propagation of light upon refraction, nor does it show the rays that pass back through the first surface and propagate toward the left.

Figure 3.11: Interference in a Fabry-Perot etalon. [82]

The transmitted light formed by the interference pattern produces concentric circular rings called "fringes". The light contained within these fringes (fringes of equal inclination) is extremely narrow in bandwidth and corresponds to the condition

$$2nd \cos\theta = m\lambda \quad \text{Equation 3.38}$$

where d is the separation of the surfaces, n is the refractive index of the medium between them and θ is the angle of incidence within the etalon.

With a collimated beam at normal incidence, the transmittance of the etalon exhibits sharp peaks at wavelengths defined by the condition

$$2nd = m\lambda \quad \text{Equation 3.39}$$

However, for a collimated beam incident at angle θ , the transmission of the etalon is given by the *Airy Formula* [83]:

$$T = \frac{I_{trans}}{I_{inc}} = \frac{1}{1 + \frac{4R}{(1-R)^2} \sin^2 \left(\frac{2\pi nd}{\lambda} \cos \theta \right)} \quad \text{Equation 3.40}$$

Therefore,

$$I_{trans} = \frac{I_{inc}}{1 + \frac{4R}{(1-R)^2} \sin^2 \left(\frac{2\pi nd}{\lambda} \cos \theta \right)} \quad \text{Equation 3.41}$$

The free spectral range (FSR) is given by

$$\text{Free Spectral Range (FSR)} = \frac{1}{2nd} \quad \text{in wave numbers (cm}^{-1}\text{)} \quad \text{Equation 3.42}$$

$$= \frac{c}{2nd} \quad \text{in frequency (Hz)} \quad \text{Equation 3.43}$$

$$= \frac{\lambda^2}{2nd} \quad \text{in wavelength (cm)} \quad \text{Equation 3.44}$$

where d is the etalon spacing or thickness in cm and n is the index of refraction.

The finesse, F is given by

$$\text{Finesse, } F = \frac{\pi \sqrt{R}}{1-R} \quad \text{Equation 3.45}$$

The fringe width (FWHM) or Minimum Resolvable Bandwidth

$$\text{FWHM} = \frac{\text{FSR}}{F} \quad \text{Equation 3.46}$$

$$\text{Maximum Transmission} = \frac{T^2}{(1-R)^2} \quad \text{Equation 3.47}$$

$$\text{Contrast} = \left(\frac{1+R}{1-R} \right)^2 = \frac{I_{\max}}{I_{\min}} \quad \text{Equation 3.48}$$

where,

I_{trans} = transmitted radiation intensity

I_{inc} = incident radiation intensity

R = mirror reflectance (as a fraction of unity)

θ = angle of incidence (inside the etalon)

n = refractive index of cavity (for air gap etalons, $n = 1$)

d = distance between mirror surfaces or cavity gap

c = speed of light

λ = wavelength (free space)

T = transmittance after losses due to absorption & scatter (as a fraction of unity)

Figure 3.12: The transmission pattern of a Fabry-Perot etalon. The transmission peaks, or fringes, are equally spaced with respect to reciprocal wavelength (usually termed wavenumber) or frequency. [81]

3.8.1 Image of the Interference Fringe Pattern with a Narrow Light Source

Figure 3.13 is an illustration of the basic interferometric arrangement of a Fabry-Perot etalon. The light source is usually set at the focus of a collimating lens. Light from a single point in the source is thus introduced as a parallel beam into the Fabry-Perot etalon. Multiple interference will occur as the beam is multiply reflected between the two reflective interfaces of the etalon to form the interference fringe pattern of which the illumination will have been modulated by the interferometer.

Figure 3.13: An illustration of the basic interferometric arrangement of a Fabry-Perot etalon. Light from the source is collimated at lens L_1 and passed through the etalon where multiple interference occurs due to the successively reflected waves. The interference fringe pattern is then focussed onto the focal plane by the lens L_2 . [84]

For a large-area light source, several bright rings will be observed on the image plane. However, for a narrow, low-divergence source (such as a laser beam), the narrow beam will illuminate only a section of the fringe [84]. This section will pass through the centre of the fringe pattern if the source intersects the optic axis determined by the collimating lens and the normal to the optical surfaces of the interferometer. Therefore, for a small-area source, the illumination in the fringe plane will depend on where the beam falls in relation to the 'fringes' determined by the interferometer. If the source lies on the optic axis as defined above, it will automatically illuminate the central part of the fringe pattern.

3.9 CONCLUDING REMARKS

Interference of light occurs when two or more wavefronts are superposed, producing either an addition or subtraction of amplitude in the resultant wave. This will show up as interference fringe patterns, a series of light and dark bands of illumination. These fringe patterns have exceedingly important applications in the field of interferometry, a variety of techniques for precision measurement in spectroscopy and metrology.

Interference fringe patterns can be obtained through many interferometry arrangements, the more popular being the Michelson Interferometer, the Mach-Zehnder Interferometer, the Twyman-Green Interferometer and the Newton's Ring Interferometer.

These fringe patterns can be modified to become finer and sharper by multiple interference. A classic example of a multiple beam interferometer is the Fabry-Perot etalon, two extremely flat quartz surfaces coated with a thin reflective film and separated by an air gap or a solid quartz gap. By increasing the value of the reflectance, R of the reflective coating, the fringe pattern can be made finer and sharper.

CHAPTER 4

THE FEMTOSECOND LASER SYSTEM AND EXPERIMENTAL EQUIPMENT

4.1 INTRODUCTION

In this chapter, the various equipment which constitutes the experimental setup will be introduced and their respective functions explained in detail. The make of the equipment, their specifications, their advantages and their limitations, and their respective roles in the experimental setup will also be reported.

4.2 FEMTOSECOND PULSE LASER SYSTEM

For this experimental research, a commercial femtosecond chirped pulse amplification (CPA) [85,86,87] based Ti:sapphire pulse laser system (BMI Alpha-1000S) is used. The laser system comprises of a Ti:sapphire oscillator, a pulse stretcher, a regenerative amplifier pumped by a Nd:YLF laser, and a pulse compressor (Figure 4.1).

Figure 4.1: Layout and components in the BMI Alpha-1000S femtosecond pulse laser system.

The system operates in the TEM_{00} mode and provides p-polarised laser pulses at 800nm (bandwidth 10nm) with variable output of up to 800mW power or 800μJ pulse energy, and a minimum pulse width of 150fs at the pulse repetition rate of 1kHz.

A central computer control system is integrated into the laser system to enable the control of the movements of the stages for translating the work under the focused laser spot and for maintaining the proper vertical location to maintain the focus. The control system also commands the laser pulse control system to adjust the pulse rate or to change the laser pulse repetition rate to maintain a constant pulse spacing as the speed of the work movement change. The power monitor is used to adjust optical attenuation to reduce or increase the power in the conditioned optical beam.

A video microscope system is also sometimes necessary for proper part location, beam focusing and to monitor the machining operation.

4.2.1 Chirped Pulse Amplification (CPA)

The CPA technique (Figure 4.2) takes advantage of the fact that ultrashort laser pulses have a large associated bandwidth (e.g. a 30fs pulse has a bandwidth of 30nm). Direct amplification of these pulses would lead to catastrophic damage in the amplifying medium through nonlinear effects. Therefore, in order to avoid this damage, the pulse peak intensity must be reduced in the laser. The CPA laser system disperses a laser pulse according to its frequency components, and reorders it into a time-stretched lower-peak-intensity pulse of the same energy. This benign pulse can then be amplified safely to high energy, and then only afterwards reconstituted as a very short pulse of enormous peak power, a pulse which could never itself have passed safely through the laser system [85,86,87].

Figure 4.2: Schematic of the technique of chirped pulse amplification.

4.2.2 TEM₀₀ Mode

The femtosecond pulse laser system is operated in the TEM₀₀ transverse mode. Therefore, the pulse laser beam adopts a Gaussian intensity profile corresponding to the theoretical TEM₀₀ mode. The Gaussian is a radially symmetrical bell-shaped distribution whose electric field variation is given by:

$$E_s = E_0 \exp\left(-\frac{r^2}{w_0^2}\right) \quad \text{Equation 4.1}$$

The intensity distribution is also Gaussian and is given by the term:

$$I = I_0 \exp\left(-\frac{2r^2}{w_0^2}\right) \quad \text{Equation 4.2}$$

where,

E_0 = electric field of the incident beam (volts/m)

I_0 = intensity of the incident beam (watts/m²)

r = radius of the incident beam

w_0 = Gaussian beam radius (the radius at which the intensity has decreased to $1/e^2$ or 0.135 of its peak value)

Figure 4.3: Intensity profile of a Gaussian TEM₀₀ mode beam. [81]

The Gaussian profile has no obvious boundaries to give it a characteristic dimension. Therefore, its diameter has to be defined. The commonly adopted definition is the diameter at which the beam intensity (irradiance) has fallen to $1/e^2$ or 13.5% of its peak value. This diameter contains 86.5% of the total power in the beam. Another term commonly used is the diameter at full width of half maximum (FWHM), or 50%

of peak intensity which is $0.59w_0$. The power contained in this diameter will be half the total power in the beam.

The power contained within a radius r , P_r is obtained by integrating the intensity distribution from 0 to r :

$$P_r = P_\infty \left[1 - \exp\left(-\frac{2r^2}{w_0^2}\right) \right] \quad \text{Equation 4.3}$$

When normalised to the total power of the beam, P_∞ in watts, the curve is the same as that for intensity but with the ordinate inverted. Nearly 100% of the power is contained in a radius $r = 2w_0$. The total power, P_∞ is related to the on-axis intensity, I_0 (watts/m²) by:

$$P_\infty = \left(\frac{\pi w_0^2}{2} \right) I_0 \quad \text{Equation 4.4}$$

$$I_0 = P_\infty \left(\frac{2}{\pi w_0^2} \right) \quad \text{Equation 4.5}$$

Therefore, it can be seen that the on-axis intensity can be very high due to the small area of the beam.

Equation 4.2 can then be rewritten as:

$$I = \frac{2P_\infty}{\pi w_0^2} \exp\left(-\frac{2r^2}{w_0^2}\right) \quad \text{Equation 4.6}$$

4.2.3 Focussing of the Gaussian Beam

Figure 4.4: The $1/e^2$ radius, $w(x)$ and the wavefront curvature, $R(x)$ changes with x through a beam waist at $x = 0$. [88]

Because of the unique self-Fourier Transform characteristic of the Gaussian beam, the transverse distribution intensity remains Gaussian at every point in the system. Only the radius of the Gaussian, $w(x)$ and the radius of curvature of the wavefront, $R(x)$ changes with x through a beam waist at $x = 0$ as shown in Figure 4.4. The governing equations are:

$$w^2(x) = w_0^2 \left[1 + \left(\frac{\lambda x}{\pi w_0^2} \right)^2 \right] \quad \text{Equation 4.7}$$

$$R(x) = x \left[1 + \left(\frac{\pi w_0^2}{\lambda x} \right)^2 \right] \quad \text{Equation 4.8}$$

where w_0 is the beam radius of the Gaussian beam at the $1/e^2$ intensity point and λ is the wavelength of the laser.

At large distances from the beam waist, the beam appears to diverge as a spherical wave from a point source located at the centre of the waist (Figure 4.4). The diverging beam has a full angular width, θ .

$$\theta = \frac{4\lambda}{2\pi w_0} \quad \text{Equation 4.9}$$

Since the origin can be approximated by a point source, θ is given by geometrical optics as the diameter illuminated on the lens, D , divided by the focal length, f of the lens.

$$\theta = \frac{D}{f} = (f\#)^{-1} \quad \text{Equation 4.10}$$

where $f\#$ is the f-number of the lens defined as the lens focal length divided by the beam diameter.

Equating these two expressions, the beam waist diameter in terms of the input beam parameters can be calculated by:

$$2w_0 = \left(\frac{4\lambda}{\pi}\right)(f\#) = \left(\frac{4\lambda}{\pi}\right)\left(\frac{f}{D}\right) \quad \text{Equation 4.11}$$

4.2.3.1 Factors Affecting the Focal Spot Size

There are a number of factors that affect the focal spot size, the most important of these being:

- diffraction
- spherical aberration

4.2.3.1.1 Diffraction

Diffraction is a natural and inescapable result of the wave nature of light. It is present in all optical systems and places the ultimate theoretical limit on their performance. Diffraction causes light beams to spread transversely as they propagate. If a "perfect" lens is used to focus a collimated laser beam, the spot size is limited only by diffraction. The diffraction limited spot size is given by the formula in Equation 4.11.

The most important thing to note about diffraction is that it increases linearly with focal length, but is inversely proportional to beam diameter. Thus, as the input laser beam diameter increases for a given lens, focal spot size decreases due to lower diffraction. Also, as focal length decreases for a given laser beam diameter, the focal spot size again decreases.

4.2.3.1.2 Spherical Aberration

Figure 4.5: Spherical aberration of a plano-convex lens. [81]

When a collimated, on-axis laser beam is focused by an ideal lens, all light rays cross the optical axis at a single point forming a focal spot with a diameter determined by the diffraction limited formula given in Equation 4.11. However, many lenses exhibit a phenomenon called spherical aberration caused by the light rays impinging near the

edge of the lens crossing the optical axis closer to the lens than those going through the center of the lens as shown in Figure 4.5. Spherical aberration has the effect of increasing the focal spot size as well as causing the focal point to occur at a different location than the calculated effective focal length.

The formula for determining an estimate of the focal spot size due to spherical aberration is:

$$\text{Spot size due to spherical aberration} = \frac{kD^3}{f^2} = \frac{kf}{f\#^2} \quad \text{Equation 4.12}$$

where,
 k = function of the index of refraction
 f = focal length of the lens
 D = input beam diameter at the lens (at the $1/e^2$ point)
 $f\#$ = defined as the lens focal length divided by the beam diameter

From Equation 4.12, it can be noted that the focal spot size is proportional to the cube of the beam diameter and inversely proportional to the square of the focal length. Thus, as laser beam diameter decreases for a given lens, spot size rapidly decreases due to spherical aberration. Similarly as focal length increases for a given laser beam diameter, the focal spot size is again reduced.

4.2.3.1.3 Determining the Focal Spot Size

As discussed in the previous sections, the focal spot size due to spherical aberration decreases with increasing $f\#$, whereas the focal spot size due to diffraction and beam divergence increases with increasing $f\#$. Thus, the minimum focal spot size for a given lens can be obtained by balancing these effects:

$$\begin{aligned} \text{Spot size}_{\text{total}} &= 1/2 * \text{spot size}_{\text{diffraction}} + 1/2 * \text{spot size}_{\text{aberration}} \\ &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \end{aligned} \quad \text{Equation 4.13}$$

4.3 HARMONIC GENERATION

The beam wavelength from the laser system falls between 795nm and 805nm and is frequency centred at 800nm in the red light spectrum region. However, most important manufacturing materials such as metals, ceramics and silicon are poor absorbers of red wavelength light as compared to the ultraviolet (UV) wavelength range. That is why excimer lasers which have wavelengths of between 190nm and 350nm play such pivotal roles in laser micromachining.

Also, how small a laser machined feature can go is dependent upon the wavelength of the laser beam used [3,89]. Referring to Equation 4.13, where the f number of the lens, $f\# = f/D$, it is impractical for a lens to have an $f\#$ less than unity, so in general the smallest achievable spot size on target is approximately equivalent to the wavelength of the light used. Hence, it is desirable that the lower ranges of the wavelength of the laser beam are used for micromachining.

Therefore, for the optimisation of machining efficiency, the fundamental beam from the laser system ($\lambda = 800\text{nm}$) is transmitted through a 0.5mm thick non-linear BBO crystal (Second Harmonic Generator) to frequency double and generate pulses of wavelength 400nm in the visible UV.

Harmonic generators are materials which exhibits a nonlinear optical effect when irradiated with high energy laser emissions. More specifically, the electric dipoles established by the electrons and nuclei in these materials oscillate in response to incident radiation such that two separate wavelength emission exit the material. The output of these emissions include the original frequency and a component half the wavelength of the incident beam [90]. A filter or a selective reflective mirror can then be used to filter out the fundamental frequency component to yield the frequency doubled/halved wavelength component.

4.4 BEAM SCANNING SYSTEM

With the ablation of features in the sub-micron proportions, the beam scanning system is very important as the resolution and accuracy of the machined features will depend very much on the precision of the system used.

There are two methods for the scanning of the laser beam onto the workpiece. Either the machine tool, the laser beam in this case, is manipulated while the workpiece remains stationary, or the workpiece is manipulated to move around and across a stationary laser beam.

4.4.1 Machining by Manipulation of the Workpiece

A simple method to raster the laser beam across a workpiece surface is to use a mechanically driven, motorised precision translation stage. The workpiece is mounted onto the stage which can then be manipulated by a PC based motion controller/driver to move around a stationary laser beam.

4.4.1.1 Motorised 3-Axis Translation Stage

The translation stage used in the experimental set-up is procured from Newport Corporation. The Newport high precision multi-axis translation stage Model 562 (refer to Appendix A) was chosen and fitted with motorised actuators (Model 850F-LS), also from Newport (refer to Appendix B).

Among the features of the system are,

- 0.5 inch (12.7mm) travel in each axis
- minimum incremental motion of $0.5\mu\text{m}$
- speed range of $6\mu\text{m}$ to $400\mu\text{m}/\text{sec}$
- $\leq 1.0\mu\text{m}$ bi-directional repeatability
- accuracy of $<0.1\%$ travel
- maximum backlash of $20\mu\text{m}$

The translation stage is controlled by a PC based motion controller/driver (Model ESP6000), also from Newport (refer to Appendix C).

4.4.2 Machining by Manipulation of the Laser Beam

Another method for the scanning of the laser beam onto the workpiece is to raster the laser beam across a stationary workpiece by manipulating the laser beam to scan across the surface of the workpiece. Beam steering can be achieved by using motor-driven scanning mirrors or acousto-optic deflector (AOD).

4.4.2.1 Acousto-Optic Deflector (AOD)

An acousto-optic deflector (AOD) is a non-mechanical beam deflection technique used for high accuracy positioning and high-speed laser beam scanning. Because the AOD is solid state and non-mechanical, it is very stable, accurate, reliable and fast. The AOD can be used to scan a laser beam over a range of angles, or to control the output angle of a laser beam with great accuracy [91].

An AOD consists of a transparent crystal inside which an optical diffraction grating is generated by the density changes associated with an acoustic traveling wave of ultrasound. The crystal essentially acts as an adjustable diffraction grating when variable acoustic frequency is applied [131,132].

Figure 4.6: Schematic of the acousto-optic deflector

The AOD (Figure 4.6) consists of a transparent crystal to which is bonded a transducer, consisting of a layer of piezoelectric material across which an RF voltage is applied. Acoustic/sound waves are generated by the piezoelectric transducer which propagates across the crystal resulting in an acousto-optic effect. The spatially periodic density variations in the crystal induced by the travelling acoustic wave are accompanied by corresponding changes in the index of refraction in the medium. The variable change of the index of refraction of the crystal will diffract the incident light at different angles. By varying the frequency of the RF control signal, the angle of the output laser beam can be adjusted [92,93].

A laser beam incident at the Bragg angle, $\emptyset$ is efficiently diffracted by the grating formed by the acoustic waves. The first order diffracted spot contains about 80% to 90% of the incident light and is deflected by an angle, θ . Some of the light remains undiffracted and some is found in higher diffracted orders [133,134].

The grating period is given by the wavelength of the acoustic wave in the crystal, and the first-order diffracted light is deflected through an angle that depends on the acoustic frequency through

$$\text{Angle of deflection, } \Delta\theta = \lambda f / v$$

Equation 4.14

where λ is the optical wavelength, and v and f are the velocity and frequency of the acoustic wave, respectively (v/f is the ultrasound wavelength) [133,134]. As the angle of deflection is linearly proportional to the acoustic frequency, the higher the frequency, the larger the diffracted angle will be.

AODs generate diffraction patterns of light consisting of a zero-order band (corresponding to the undiffracted beam) as well as higher-order diffraction bands. The position of the zero-order band is fixed, and only the energy that is diffracted into the first-order band is used. Under optimal conditions, the AOD can diffract nearly 80 to 90% of the incident light into the first order diffracted beam. The switching of the incident light beam to the first order diffracted beam can occur in a very short period of time ($<5\mu\text{s}$) depending on how rapidly the acoustic wave field can be turned on and off in the volume of the crystal traversed by the laser beam [92,94].

An AOD deflects a beam along the optical axis (acoustic wave direction), therefore providing only a one-axis scan. However, two AODs in series and at right angles can be used to provide full two-dimensional (X,Y) scanning [95]. Figure 4.7 shows a schematic diagram of the set-up of the two-axis AOD configuration.

Figure 4.7: Two-axis acousto-optic deflector setup. [96]

The specifications of the acousto-optic deflector (AOD) system used in this experiment is listed in Table 4.1 below:

Table 4.1: Specifications of the acousto-optic deflector (AOD) used.

Acousto crystal material	TeO ₂
Aperture (diameter)	20mm
Acoustic velocity (m/s)	650
Optical wavelength (nm)	442
Optical transmission (%)	>95
Diffraction efficiency (%)	≥30
Maximum deflection angle (mrad)	31
Centre frequency (MHz)	105
AO bandwidth (MHz)	50
Random access time (μs)	21

4.5 TELECENTRIC SCAN LENS

Figure 4.8: Schematic illustration and the principles of a telecentric scan lens system (adapted from U.S. Patent 5,404,247)

Because the laser beam exiting the AOD system will be deflected at an angle, the scanned beam will strike the workpiece at varying angles during the successive scans. As the apparent feature/hole diameter is a function of the angle at which the scanned laser beam hits the workpiece, the varying incident angle of the beam would result in a non-uniform, elongated circular feature.

Therefore, in order to obtain precise, uniform circular laser machined features, the laser beam must be made to focus at a perpendicular angle to the workpiece surface at all points along the scan.

Scan lenses are commonly used as a focusing lens to focus laser beams onto a focal plane in optical scanning systems. A telecentric scan lens (Figure 4.8) is a scan lens which has telecentric characteristics, in which the central ray of the focusing bundle of rays exiting the lens will always be parallel to the lens axis and, accordingly, is perpendicular to the focal plane at all points along the scan [136]. Therefore, all the scanned beams regardless of their angle of deflection from the AOD system will be

focused to be incident at an angle normal to the workpiece surface by the telecentric scan lens. The design of a telecentric scan lens is such that the system 'stop'/pupil is located at the front focal point of the lens system [137]. The 'stop' is located at the position where the beam is being deflected from the axis, this location being at the exit plane of the AOD crystal. The telecentricity of the lens also helps to minimize the magnification shift with respect to shifts in the focal plane [135].

Telecentric scan lens are diffraction limited when the lens aperture is at least 1.8 times larger than the $1/e^2$ beam diameter [150]. In such instances, less than 0.1% of the beam intensity is truncated by the lens aperture. The diffraction limited spot size is given by:

$$2w_0 = \frac{4\lambda f}{\pi D} = 1.27 \frac{\lambda f}{D} \quad \text{Equation 4.15}$$

The telecentric scan lens used in this setup has a lens aperture of 34mm and is therefore a diffraction limited lens when used with the 16mm diameter beam in the experiments.

As the chief rays from the telecentric scan lens are parallel to the optical axis in the focal plane, therefore it enables the AOD beam scanning system to raster each of the successive scanning beams parallel to the workpiece (Figure 4.8). This is important as the incident angle of the laser beam has a great effect on the shape and the quality of the machined features.

Telecentric scan lens is commonly used with laser beam scanning systems such as galvanometer scanners, polygon mirrors and AOD systems to obtain a scanning laser beam with a small focused spot size for laser micromachining processes [138-141]

Because of its special advantages in minimizing spot distortion and drill angle, telecentric scan lens are also widely used in critical laser marking applications [143] and laser through-hole drilling in materials. A typical application is in electronics microvia drilling [142].

The telecentric scan lens used in this experimental work is purchased from Special Optics, a manufacturer and designer of precision optical components in America. The lens is designed to be telecentric in the image space with a telecentricity of less than 0.1° within the field depth. Manufacturer's specifications include an effective focal length f of 100mm, lens aperture of 34mm, function of the index of refraction k of 0.043 at λ 400nm, distortion of less than 0.1% at the field corners and an MTF (modulation transfer function value) of above 50% at 130 lp/mm. However at very low frequencies, all lenses exhibit an MTF of nearly 100%.

The telecentric scan lens integrated into this experimental setup functions not only to align the angled beams from the AOD system to be perpendicular to the workpiece, but it also focuses the laser beams to a diameter of its diffraction limited spot size. Therefore, the functions of the telecentric scan lens in this system can be summarized as below:

- i) to focus the laser beam into a diffraction limited spot
- ii) to correct for the beam deflection angle introduced by the AOD scanning by aligning the angled beams to be perpendicular to the workpiece surface
- iii) to obtain a precise, circular laser machined feature

4.5.1 Modulation Transfer Function (MTF)

To properly determine the image quality obtained from a lens or imaging system, the spatial-frequency response of the system must be determined. Spatial-frequency is the scientific term used to describe the spacing of elements in a pattern. This measurement, known as the modulation transfer function (MTF), determines how well the contrast of an image of the pattern is preserved in percentage terms after it passes through a lens [99,100]. Typically, MTF charts plot the percentage contrast loss against resolution measured in line pairs per millimeter (lp/mm).

Performance at the maximum theoretical MTF (MTF=100%) is called "diffraction limited" performance, since diffraction is the reason why MTF falls with increasing

spatial frequency, even for a "perfect" lens. Thus, diffraction ultimately limits the lens's performance.

At very low frequencies, all lenses exhibit an MTF of nearly 100%. The closer the curves are to 100% on the graph, the higher the contrast and resolving power. However, as spatial frequency increases, even for a "perfect" lens, the MTF value becomes lower due to diffraction [99,100]. Of course the degree of blurring can be worse in the presence of lens aberrations.

However, the MTF value is usually only defined at a single point in the image. The MTF "map" will usually be symmetrical with the MTF value at the centre being normally higher than the value at the edge. The MTF value to a lens given by most lens manufacturers is usually weighted as an average across the whole image [97].

4.5.2 Telecentric Lens Verification

As given in Equation 4.15, the diffraction limited spot size of the telecentric scan lens is:

$$2w_0 = \frac{4\lambda f}{\pi D} = 1.27 \frac{\lambda f}{D}$$

Taking into account the effect of spherical aberration of the elements in the lens, the theoretical spot size of the lens ($f=100\text{mm}$) at the input beam diameter of 16mm and laser wavelength, $\lambda = 400\text{nm}$ is calculated as: (from Equation 4.13)

$$\begin{aligned} 2w_0 &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \\ &= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 16} + \frac{0.043 \times 16^3}{2 \times 100^2} = 10\mu\text{m} \end{aligned} \quad \text{Equation 4.16}$$

with k (function of the index of refraction) = 0.043 as given by the lens manufacturer at $\lambda = 400\text{nm}$

For verification of the telecentric lens, the diameter of the output is compared with the theoretical value calculated from Equation 4.16. To do this, the focused beam from the lens was made to machine on a 100nm gold thin film specimen and the diameters of the ablated features were then measured. The number of pulses to hit the target was set at 100 pulses per point. Machining was started from low lasing energy and steadily increased until the diameter of the ablated features no longer increases with the laser energy. The diameter of the features ablated here was then measured with a WYKO surface profiler and found to be approximately 10 μ m (Figure 4.9). This demonstrated that the lens is performing close to it's theoretically calculated "diffraction limit" in Equation 4.16.

Figure 4.9: 10 μ m feature ablated with the telecentric lens of $f=100$ mm at the input beam diameter of 16mm and laser wavelength, $\lambda = 400$ nm.

4.6 SPATIAL FILTERING SYSTEM

The laser beam emitted from a laser system has passed through various optical components such as lenses, prisms, and beam splitters. Imperfections and debris on and within these components can cause degradation of the beam profile. Also, the air through which the beam passes contains particulates that lead to further beam degradation. (In fact, the scattering of laser light by particulates is an established technique for measuring air cleanliness). The spatial noise in the beam can be viewed by expanding a laser beam onto a viewing surface: the whorls, holes and rings superimposed on the ideal pattern of uniform speckles is the spatial noise. Spatial noise can cause random variation and fluctuations in the intensity profile of the laser beam and is therefore, undesirable.

In applications such as interferometry, holography and optical data processing, it is very critical that the nominal beam form be as uniform or at least as smoothly varying as possible. In order to assure this, it is possible to 'clean up' the 'noisy' laser beam by passing it through a spatial filter. This greatly improves the resolution of the beam.

A spatial filter basically, is made up of a well-corrected positive lens, usually a microscope objective, and a pinhole placed at the focus of that lens (Figure 4.10) [101]. This arrangement means that all collimated light is focused precisely at the pinhole. Other lights which has originated at points of contamination such as a scratch on a mirror, within the test setup, is focused before or after the pinhole and consequently does not pass through it. That energy is filtered out of the system by the pinhole.

Figure 4.10: The principles and component configuration of a spatial filter. [88]

4.7 SPECIMEN

Two metallic materials were chosen for the investigation of this research work. These materials were selected based on their wide application and importance in the industry.

Gold is commonly used in the electronic packaging industry as contacts and connectors, and in data storage application as the reflective layer in CDs. Platinum is used in the manufacturing of microscale life science and bio-fluidic devices such as micro-pumps and heart stents because of its non-corrosive and inert properties, and in the fabrication of semiconductors.

The material specimens were prepared as followed:

- 100nm thick pure platinum film sputtered on a 2" × 2" × 3mm fused silica substrate
- 100nm thick pure gold film sputtered on a 2" × 2" × 3mm fused silica substrate

4.8 CONCLUDING REMARKS

In this chapter, the femtosecond pulse laser system, the beam scanning system and the various equipment which constitutes the experimental setup of this research work were introduced and their respective functions explained in detail. A brief explanation on the chirped pulse amplification (CPA) technique was included to shed some light on how the ultrafast pulse lasers systems can give such high peak power. The Gaussian intensity profile of the laser beam corresponding to the TEM₀₀ mode of the laser, the focussing of the Gaussian beam and the factors affecting the focal spot size were also discussed.

Lastly, the specimens and materials used for the investigation of this research work were presented. Platinum and gold were chosen based on their wide application and importance in the industries.

CHAPTER 5

CONCEPT, ANALYSIS AND CHALLENGES

5.1 INTRODUCTION

This chapter aims to guide the reader through the concept of this research work, its advantages and also its limitations. The problems and limitations with regard to this research concept were identified and the methodical steps taken to tackle and solve these challenges are explained. The reader will also be guided through the various improvements and modifications made to the experimental setup.

In the beginning of this chapter, the concept and basic principle of the research is explained: How an interfered beam can enable the ablation of finer, better features compared to the direct laser beam, the advantages of this concept and its limitations. The intensity profile of the interfered beam will then be ascertained if it retains a Gaussian-like profile. This will determine whether it will be possible to control so that only the central fringe will machine which is the concept of this research work.

The challenge in obtaining clear, sharp and stable circular fringes on the femtosecond laser system will then be highlighted.

Next, the analysis on the evolution of the circular interference fringe beam profile as it changes from one stage to another is discussed. The optimal interference beam profile for machining will then be determined.

Later, the problems with regards to the various equipment which incorporates the experimental setup will be detailed and the countermeasures taken in order to solve these problems explained. The effect of pulse energy and the laser fluence fluctuation will also be examined.

Lastly, the interaction between the femtosecond pulsed laser with the materials ablated and its effect on the ablated feature size and quality will be discussed.

5.2 MECHANISM OF SUBMICRON ABLATION WITH INTERFERENCE FRINGES

As explained in Section 2.4, sub spot size microablation by ultrafast lasers has been previously demonstrated [2,3], overcoming previous notions that the minimum achievable machining spot size is limited by the wavelength of the laser light used. It is now possible to obtain a feature as small as 1/10th of the focus spot size itself by the precise controlling of the laser fluence so that only a small portion of the central part of the laser beam is above the breakdown threshold [2,3].

However, there is a limit to how small the features can go down to. Up to now, the smallest feature size obtained with ultrafast laser micromachining is 200nm, or approximately 8% of the original laser spot size of 2.5 μ m [2,4]. To break through this limit and achieve significant reduction in the ablation feature size is the current main challenge faced by researchers in this field.

The minimum focal spot size of a laser beam is limited by the diffraction of the beam and is governed by the wavelength of the laser light and the beam diameter as shown in Equation 4.11. A shorter wavelength laser light used will result in a smaller focal spot size. The wavelength of the femtosecond laser system falls between 795nm and 805nm and is frequency centred at 800nm in the red light spectrum region. However, most important manufacturing materials such as metals, ceramics and silicon are poor absorbers of red wavelength light and have higher optical absorption in the ultraviolet (UV) wavelength range. Therefore, in order to obtain a smaller focal spot size and for the optimisation of machining efficiency, the fundamental beam from the laser system

($\lambda = 800\text{nm}$) is frequency doubled using a BBO second harmonic generator crystal to generate pulses of wavelength 400nm in the visible UV.

With the demand for smaller ablation features, there is an urgent need for a technology that can enable laser micromachining beyond what is achievable thus far. Therefore, a novel concept of first, interfering the laser light, and then using the central bright fringe of the interfered beam to machine is proposed. The significantly sharper profile of the central bright fringe of the interference beam will effectively reduce the machining spot size and subsequently, the size of the ablation features.

The principle of this technique is illustrated in Figure 5.1 and 5.2. Interference is generated on the femtosecond laser to obtain circular interference fringes. The central bright fringe of the interference beam which has a significantly sharper profile (Figure 5.2) is then isolated for use as the new effective machining beam. By carefully controlling the threshold fluence of the laser, it is possible to manipulate such that only a portion of the central bright fringe of the interference beam will machine. Therefore, the effective ablation spot size is dependent on the beam profile of the central bright fringe of the interference beam, which is subsequently affected by the form of the interference fringes (e.g. whether the fringes are close together or far apart) and how sharply defined are the fringes.

To begin, the beam intensity profile of the interfered laser beam is analysed. The interference beam has to be ascertained if it retains a Gaussian envelope after interference as then, it will be easier to isolate the central bright fringe for machining. Furthermore, the profile of the central bright fringe will be sharpest when the interference beam retains a Gaussian envelope compared to, e.g. a flat-top profile.

Figure 5.1: 2D profile of the Gaussian direct laser beam.

Figure 5.2: 2D profile of the interference laser beam. The central bright fringe of the interference beam which has a significantly sharper profile is the new effective machining beam.

5.3 ANALYSIS OF THE LASER INTERFERENCE BEAM

To ascertain the beam intensity profile of the interfered laser beam and to enable the comparison between the interfered beam and the direct non-interfered beam, beam profiling and analysis on a Michelson interferometer setup on a HeNe laser with the BeamScope™ beam analyser (from DataRay Inc) was performed. The HeNe laser was utilised to give a general illustrative representation of the interference beam fringe analysis as the beam analyser is not rated for use with the high peak power of the femtosecond laser.

From the results obtained, it was ascertained that the interfered laser beam falls under a Gaussian-like envelope. Therefore, the interfered beam can be manipulated as explained earlier in Section 5.2 for sub spot micromachining.

5.4 CHALLENGES IN PRODUCING SHARP CIRCULAR FRINGES ON THE FEMTOSECOND PULSE LASER

The first challenge in this research work is to obtain clear, sharp and stable circular fringes on the femtosecond laser system. Recall that for laser light interference to occur, three conditions must be met:

- i) the laser light sources must have appropriate coherence that is, they must maintain a constant phase with respect to each other
- ii) the interfering sources must have identical wavelengths (monochromatic) and polarisation
- iii) the Superposition Principle (Section 3.3) must apply

Obtaining interference on continuous wave (CW) lasers is therefore simple as they maintain coherence over a long distance. A good example is the HeNe CW laser that has a typical coherence length of 20 to 30 cm with some frequency-stabilized versions exhibiting coherence length of up to several kilometers [81]. However, this is not the case with the femtosecond pulse laser which has a very short coherence length. In order to generate interference on the femtosecond pulse laser, the optical path

difference (OPD) between the 2 overlapping laser beams must be maintained within the coherence length. This becomes arduous when the distance discussed is only tens of microns.

For the femtosecond pulse laser system used in this research work (refer to Section 4.2), the coherence length [65,102] of the laser source is calculated to be $45\mu\text{m}$ as shown below.

$$\begin{aligned}
 \text{Coherence length, } l_c &= c \times \tau \\
 &= 3 \times 10^8 \text{ m/s} \times 150\text{fs} \\
 &= 45\mu\text{m}
 \end{aligned}
 \tag{Equation 5.1}$$

where,

c = speed of light = $299\,792\,458 \text{ m/s} \approx 3 \times 10^8 \text{ m/s}$

τ = pulse width of the femtosecond laser system = 150fs

At distances larger than the coherence length of the laser source, the pulses of the split beam 1 and beam 2 will be separated in time and will not be able to superimpose and interfere. Therefore, the optical path difference (OPD) between the 2 overlapping laser beams must be maintained within the coherence length.

To date, interference on ultrafast pulse lasers has only been successfully generated using the Michelson interferometry concept [103,104] and by diffraction [105,106]. The Michelson interferometer (Figure 5.3) [70,72,107] produces circular interference patterns by splitting a beam of the laser light so that one beam strikes a fixed mirror and the other a movable mirror. By adjusting the length of both the arms to differ by a small distance, an optical path difference (OPD) is produced. When the reflected beams are brought back together to overlap, interference will occur.

Figure 5.3: The experimental setup of a Michelson interferometer.

However, an inevitable problem with using the Michelson interferometry setup on an ultrafast pulse laser is that the interference pattern produced is very unstable and fluctuates erratically. This is because the Michelson interferometer is not a common path interferometric setup and comprises of many optical elements, therefore making it difficult to obtain and maintain the micron range OPD required. Also, because of the minute ranges, it is very tedious and time consuming to align the setup. The setup is very sensitive and susceptible to external disturbances such as vibrations, the fluctuation of air temperature and/or pressure at different parts of the setup and even a slight misalignment of the optical elements can upset the equilibrium of the interference setup.

Therefore, in order to fulfil the criteria of this experimental work for achieving clear sharp interference fringes on the femtosecond laser, a better interferometry setup has to be proposed. The setup must be simplified with minimal optical elements in order to effectively control the OPD of the system to be within the coherence length of the laser of $45\mu\text{m}$.

5.5 ANALYSIS OF THE CIRCULAR INTERFERENCE BEAM FRINGE PROFILE EVOLUTION

Another important factor to look at is to analyse and ascertain at which stage of the interference beam fringe profile evolution is best for use in micromachining. The purpose of this section of the research is to ascertain the profile of the circular interference beam at the different stages of the interference evolution and to determine at which stage will the interference fringe profile be optimal for micromachining.

The investigations of the evolution of the interference beam fringe profile were carried out using a Spiricon laser beam analyser (Model LBA-PC) with a Michelson interferometry setup and a HeNe laser. The experiments were carried out with the HeNe laser to give a general illustrative representation of the interference beam profile analysis as the beam analyser is not rated for use with the high peak power of the femtosecond pulse laser.

By changing the OPD of the interferometer system through the manipulation of the distance of one arm by means of the movable mirror, the interference beam fringe profile was made to morph from one stage to another. The interference fringes/bands were observed to originate from the periphery and disappear at the centre at different stages or vice versa with the OPD change.

Using the Spiricon laser beam analyser, the beam profiles of the circular interference beam at the different stages were captured. The analyser enables the capture of the beam both in 2-dimensional (plan view and front view) and in 3-dimensional profiles complete with essential information such as the peak location, beam width and height, Gaussian fit and peak energy. Figures 5.4 to 5.11 are the images captured of the interference beam fringe profile as it progressively changes from one stage to another.

Plan View and Front View

3-Dimension View

Figure 5.4: Circular interference fringe beam profile - Stage 1

Figure 5.5: Circular interference fringe beam profile - Stage 2

Figure 5.6: Circular interference fringe beam profile - Stage 3

3-Dimension View

Plan View and Front View

Figure 5.7: Circular interference fringe beam profile - Stage 4

Plan View and Front View

3-Dimension View

Figure 5.8: Circular interference fringe beam profile - Stage 5

Plan View and Front View

3-Dimension View

Figure 5.9: Circular interference fringe beam profile - Stage 6

Plan View and Front View

3-Dimension View

Figure 5.10: Circular interference fringe beam profile - Stage 7

Figure 5.1.1: Circular interference fringe beam profile - Stage 8

From the images, it was ascertained that the best interference beam profile for machining is the profile depicted in Figure 5.8 (Stage 5). The reason is because the central bright fringe of the interference beam is at its sharpest and most defined here. In order to obtain a small machining spot size, a beam with a sharp and steep profile should be used (Figure 5.12). At Stage 5, the beam reaches its highest peak with the central bright fringe at its sharpest and most pronounced. Therefore, it can be concluded that the interference beam profile at this stage is the optimum for use in micromachining.

Figure 5.12: The optimal interference fringe beam profile.

5.6 BEAM EXPANSION

Another concern to look at is the laser beam diameter used for machining. The diameter of the laser beam from the femtosecond pulse laser system is 4mm which is too small for use in this experimental setup as the clear aperture diameter of the lenses and optical components used in the setup is 25.4mm with exception of the telecentric scan lens which has a clear aperture of 34mm.

Also, in order to obtain a finer focal spot, a beam of larger diameter should be used. It is shown in Equation 4.11 that the diameter of the diffraction limited focal spot size, d is given by

$$d = \frac{4 \lambda f}{\pi D} \quad \text{Equation 5.2}$$

where D is the beam diameter at the final focusing lens.

From the equation, it can be seen that the focussed spot size, d is inversely proportional to the input beam diameter at the final lens, D . Therefore, to obtain a finer focal spot as is the objective of this research work, a larger diameter beam right before the final focusing should be used, thus the requirement of a beam expander in the experimental setup.

In addition, it is also known that the ray divergence (the deviation/spread of the beam rays from the ideal parallel form) is inversely proportional to the expansion factor. Thus, beam expansion also acts to reduce beam divergence in the system. Therefore, due to the reduced diffraction and less beam divergence of the beam expansion, a smaller spot size diameter of better image quality can be achieved in the focal plane.

There are basically two methods to expand a laser beam using optic elements and at least two lenses are necessary to accomplish this.

Figure 5.13: Two main types of beam expanders. [81]

The first method is known as the Keplerian beam expander (Figure 5.13a). The system consists of two positive lenses positioned with their focal points nominally coincident. The first positive lens (focal length, f_1) will initially focus, and then expands the incoming collimated laser beam, after which the second positive lens (focal length, f_2) then recollimates it. The total distance separating the two lenses is the sum of the two focal lengths $f_1 + f_2$.

The second method is known as the Galilean beam expander (Figure 5.13b). The system consists of a negative diverging lens, followed by a positive collimating lens, positioned with their focal points nominally coincident. The original incoming collimated laser beam is first expanded by the negative lens with focal length, $-f_1$, and then collimated with the positive lens with focal length, f_2 , with a distance separating the two lenses of the sum of the two focal lengths $-f_1 + f_2$.

In both cases, the overall length of the optical system is given by,

$$\text{Overall length} = f_1 + f_2 \quad \text{Equation 5.3}$$

and the magnification is given by,

$$\text{Magnification} = \frac{f_2}{f_1} \quad \text{Equation 5.4}$$

However, as the focal length, f of the negative lens in the Galilean system carries a negative value, the overall length of the system is significantly shorter than the Keplerian system.

A Keplerian beam expander with two lenses of focal length, $f_1 = 50\text{mm}$ and $f_2 = 200\text{mm}$ is integrated into the experimental setup. The reason for using a Keplerian setup although the Galilean setup has an advantage of a shorter overall length is so that a spatial filter can be integrated into the beam expander setup as shown in Figure 5.14. Magnification of the system is therefore, 4X. As the diameter of the laser beam from the femtosecond pulse laser system is 4mm, the diameter of the beam after expansion will therefore be 16mm.

Figure 5.14: The experimental setup integrated with a Keplerian beam expander (4X) and a spatial filter expands the beam diameter from 4mm to 16mm

5.7 PROBLEMS AND ERRORS WITH THE MOTORISED 3-AXIS TRANSLATION STAGE

In the preliminary experimental setup, a mechanically driven, motorised precision translation stage was used to manipulate the workpiece to move around and across the laser beam during machining (refer to Section 4.4.1.1 for the make, specifications, features and further literature on the stage used). The workpiece is mounted onto the stage which is manipulated by a PC based motion controller/driver to move around the stationary laser beam. With the femtosecond pulse laser repetition rate of 1 KHz, the translation stage linear speed is set at 200 μ m/sec to ensure that there are enough pulses striking the machining surface at each point for uniform material removal.

However, as with all motorised, mechanically driven equipment and machinery, there arise various problems and errors such as backlash (motion loss after reversing due to free-play in threaded fittings, gearheads and bearings, etc), stick/slip effect (caused by the fact that the coefficient of static friction being greater than the coefficient of dynamic friction) and hysteresis (position error due to the relaxation of elastic forces in drive components). These errors can be greatly detrimental to the quality of the machining features produced. Although the manufacturers must have surely put in very careful considerations during the designing process, such errors can only be reduced or controlled, but can never be completely eradicated.

Especially since the machining features are in the submicron ranges, such errors no matter how well controlled and minimised, have a detrimental effect on the machining quality, resolution, repeatability and accuracy. From the specifications provided by Newport Corporation, the manufacturer of the stage, the bi-directional repeatability of the stage is approximately 1.0 μ m, the accuracy at about 0.1% travel and backlash of maximum 20 μ m (refer to Appendix A and B for the manufacturer's specification sheet). When machining features in micron range and below, such magnitude of errors although seemingly minute in normal precision machining applications, is unacceptable. This is especially evident during the machining of ultra-fine lines as can be seen in Figure 5.15 through to Figure 5.18.

Figure 5.15: SEM image of a 5 μ m line ablated on 100nm platinum thin film. Note the intermittent machining and non-machining of the line caused by the stick/slip effect of the motorised stage.

(Pulse energy=100nJ, stage linear speed=200 μ m/sec)

Figure 5.16: SEM image of a 5 μ m line ablated on 100nm platinum thin film. Note the inconsistent machining of the line caused by the vibration of the spring-loaded slides of the motorised stage.

(Pulse energy=100nJ, stage linear speed=200 μ m/sec)

Figure 5.17: SEM image of a 5 μ m line ablated on 100nm gold thin film. Note the intermittent machining and non-machining of the line caused by the stick/slip effect of the motorised stage.

(Pulse energy=100nJ, stage linear speed=200 μ m/sec)

Figure 5.18: SEM image of a 5 μ m line ablated on 100nm gold thin film. Note the intermittent machining and non-machining of the line caused by the stick/slip effect of the motorised stage.

(Pulse energy=100nJ, stage linear speed=200 μ m/sec)

The stick and slip effect of the motorised stage causes the machining of incomplete lines and jagged lines of fluctuating thickness as evident in Figure 5.15 through to Figure 5.18 by the intermittent machined and non-machined lines and lines of inconsistent thickness. The lines are also wider/thicker in some places because of the vibration of the stage. This is due to the jerky halted movement of the spring-loaded XYZ slides which are driven by actuators.

5.7.1 Integration of an Acousto-Optic Deflector (AOD) into the Experimental Setup

To counter the problems and errors introduced by the motorised translation stage, it was decided that instead of relying on the stage to manipulate the workpiece to move around the laser beam, the laser shall be manipulated to move across the workpiece. This, was accomplished by integrating a pair of acousto-optic deflectors (AODs) into the setup (refer to Section 4.4.2.1 for further write-ups on the AODs used). The AOD used in this experiment consists of a TeO_2 crystal with a circular aperture of 20mm diameter and up to 31mrad deflection angle.

AOD beam steering is a non-mechanical beam deflection technique used for high accuracy positioning and high-speed laser beam scanning. The AOD can be used to scan a laser beam over a range of angles, or to control the output angle of a laser beam with great accuracy. Because the AOD is solid state and non-mechanical, it is very stable, accurate, reliable and fast. Therefore, by integrating the AOD system into the experimental setup, the accuracy and resolution problems due to the backlash and stick and slip effect encountered with the motorised mechanical stage can be eliminated.

An AOD however, deflects a beam along the optical axis (acoustic wave direction), therefore providing only a single axis scan. However, by integrating two AODs in series and at right angles to each other, full two-dimensional (X,Y) scanning can be achieved as shown in Figure 4.6.

The AOD TeO_2 crystal has the highest efficiency in s-state polarisation light. The second harmonic beam from the SHG BBO crystal however is p-state polarised. Therefore, to convert the p-polarised beam from the laser to s-state polarisation to increase the efficiency of the AOD, a half-wave plate is mounted at the entrance of the Y-axis AOD. However, the Y-axis AOD will transform the s-polarised beam back to p-polarisation in the crystal. The polarisation of the beam therefore has to be reverted back again to the s-state polarisation by yet another half-wave plate at the entrance of the X-axis AOD. The integrated XY-axis scanning AOD system is shown in Figure 5.19. A quarter-wave plate is placed at the output of the X-axis AOD to rotate the polarisation from s-state polarisation to circular polarisation. This is because circularly polarised beam gives better and more uniform machining quality [108,109].

Figure 5.19: The integrated XY-axis scanning AOD system.

Figure 5.20 shows the experimental setup used for the integrated XY-axis scanning AOD system. The motorised stage has been retained in the setup but its role is no longer to manipulate the workpiece during the machining process but merely to ease the focusing of the laser beam onto the workpiece surface before machining, and to

position the workpiece in between machining. During the machining process, the stage is kept immobile.

Figure 5.21 through Figure 5.24 shows the improvement in the line features machined using the new modified setup. The lines machined are finer, less jagged and more consistent, and the edges are much smoother and even.

Figure 5.20: The experimental setup integrated with a 2-axis AOD system for effective beam steering

Figure 5.21: A 10 μ m line machined on a 100nm platinum thin film using the AOD scanning system. Note the vast improvement in the edge quality.

(Pulse energy=300nJ)

Figure 5.22: A 3 μ m line machined on a 100nm platinum thin film using the AOD scanning system. Note the improvement in line thickness. The line machined is finer with good edge quality.

(Pulse energy=100nJ)

Figure 5.23: A 10 μ m line machined on a 100nm gold thin film using the AOD scanning system. Note the improved edge quality.

(Pulse energy=300nJ)

Figure 5.24: A 3 μ m line machined on a 100nm gold thin film using the AOD scanning system. Note the improvement in line thickness. The line machined is finer with good edge quality.

(Pulse energy=100nJ)

However, when the machining of micro holes was tested using the setup (Figure 5.25 through Figure 5.31), the features obtained were not circular in shape as it should be, but are elliptical at a diagonal angle.

Initially, the problem was thought to lie in the laser beam not having been focused perfectly onto the surface of the workpiece during machining. However, after ensuring that the laser beam is indeed perfectly focused, the quality of the ablated holes is still not improved. Finally, after analysing the system, the problem was pinpointed to have resulted from laser beam dispersion as described in Section 5.8.

Figure 5.25: SEM image of the diagonally elliptical ablated holes on a 100nm thick platinum film. The non-circular features are a consequence of beam dispersion.

Figure 5.26: SEM image of the dispersion affected ablation of 5µm holes on a 100nm platinum thin film.

Figure 5.27: Enlarged SEM image of the dispersion affected ablation of 5µm holes on a 100nm platinum thin film.

Figure 5.28: SEM image of the diagonally elliptical ablated 4µm holes on a 100nm gold thin film.

Figure 5.29: Enlarged SEM image of the diagonally elliptical ablated 4µm holes on a 100nm gold thin film.

Figure 5.30: Close up SEM image of the elliptical ablated holes on a 100nm platinum thin film caused by beam dispersion.

Figure 5.31: Close up SEM image of the elliptical ablated holes on a 100nm gold thin film caused by beam dispersion.

5.8 BEAM DISPERSION COMPENSATION

When a single wavelength, monochromatic laser is used with the AOD, the problem of beam dispersion does not arise. However, the beam from the femtosecond laser system is a spectrum-centred beam consisting of a spectral bandwidth of approximately 10nm. This causes a large beam dispersion problem which greatly affects the shape of the beam, and subsequently, resulting in the spatial deformation of the machining feature.

Referring to the Bragg's angle formula, the lower wavelength portion of the spectrum bandwidth is deflected at an angle less than that of the higher wavelengths, resulting in the dispersion effect of the beam [4,110]. The dispersion angle can be obtained from the separation angle θ :

$$\Delta\theta = \lambda_1 f_a / v_a - \lambda_2 f_a / v_a = \Delta\lambda f_a / v_a \quad \text{Equation 5.5}$$

where λ_1 and λ_2 represent the highest and the lowest parts of the spectrum bandwidth respectively, and $\Delta\lambda$ stands for the bandwidth of the spectrum.

The spatial profile of the output laser beam is stretched in the direction of the acoustic wave, resulting in an elliptical beam.

As a two AODs arrangement (Figure 5.21) is used for XY-axis scanning, therefore dispersion will occur in both the X- and the Y-axis. The spatial profile of the laser beam will be stretched in both axes, resulting in an elliptical spot dispersed in a diagonal manner, as depicted in Figure 5.34. The final dispersion angle, $\Delta\theta$ can be obtained from the dispersion angles in the X-axis and the Y-axis, $\Delta\theta_x$ and $\Delta\theta_y$.

$$\Delta\theta = \sqrt{\Delta\theta_x^2 + \Delta\theta_y^2} \quad \text{Equation 5.6}$$

Dispersion also affects the energy concentration of the beam. The energy of a laser beam that is not affected by dispersion is concentrated at the central portion. However, the wavelength dispersion of the laser beam disturbs the Gaussian distribution. This will greatly affect the quality and resolution of the machining features as it should be kept in mind, that only the tip of the beam profile will be used to machine as explained in Section

2.5. With a well-defined Gaussian profile, it is theoretically possible to produce features of down to 1/10th of the laser focused spot size.

5.8.1 Integration of an Acousto-Optic Modulator (AOM) for the Compensation of Beam Dispersion

To compensate for the dispersion effect, a dispersible element must be used in a reverse way to recombine the dispersed spectrum. An acousto-optic modulator (AOM) oriented in a way that the acoustic wave travels in the opposite direction of that of the AOD can be used for this purpose [4,110].

Figure 5.32: Dispersion compensation setup using one AOM.

One AOM will correct the dispersion in only one direction. Therefore, two AOMs will be needed to compensate for the two-axis dispersion of the AOD arrangement used. However, it has been demonstrated [4] that a single AOM can be employed to correct the two-axis dispersion. The AOM is tilted in an angle such that the output beam will disperse with a vector quantity that is equal and opposite to the vector addition direction of the two-axis scanning AODs (Figure 5.32). The degree of tilt which is approximately 45 degrees, is dependent on the resultant vector direction of the 2-axis scanning AODs. With this AOM/AOD configuration, the dispersion of the beam can be effectively recombined to form a corrected collimated beam with minimal optical elements involved

The AOD/AOM setup has an additional advantage of providing precise control of the number of pulses to hit each scan point, even when used on high repetition rate pulse lasers due to its short rise time.

5.9 SCANNED BEAM FOCUSING WITH A TELECENTRIC SCAN LENS

Figure 5.33: Schematic illustration and the principles of a telecentric scan lens system (adapted from U.S. Patent 5,404,247)

Because the laser beam exiting the AOD system will be deflected at an angle, the scanned beam will strike the workpiece at varying angles during the successive scans. As the apparent feature/hole diameter is a function of the angle at which the scanned laser beam hits the workpiece, the varying incident angle of the beam would result in a non-uniform, elongated circular feature.

Therefore, in order to obtain precise, uniform circular laser machined features, the laser beam must be made to focus at a perpendicular angle to the workpiece surface at all points along the scan.

Scan lenses are commonly used as a focusing lens to focus laser beams onto a focal plane in optical scanning systems. A telecentric scan lens (Figure 5.33) is a scan lens which has telecentric characteristics, in which the central ray of the focusing bundle of rays exiting the lens will always be parallel to the lens axis and, accordingly, is perpendicular to the focal plane at all points along the scan [136]. Therefore, all the scanned beams irregardless of their angle of deflection from the AOD system will be focused to be incident at an angle normal to the workpiece surface by the telecentric scan lens. The design of a telecentric scan lens is such that the system 'stop'/pupil is located at the front focal point of the lens system [137]. The 'stop' is located at the position where the beam is being deflected from the axis, this location being at the exit plane of the AOD crystal. The telecentricity of the lens also helps to minimize the magnification shift with respect to shifts in the focal plane [135].

As the chief rays from the telecentric scan lens are parallel to the optical axis in the focal plane, therefore it enables the AOD beam scanning system to raster each of the successive scanning beams parallel to the workpiece (Figure 5.33). This is important as the incident angle of the laser beam has a great effect on the shape and the quality of the machined features.

The telecentric scan lens used in this experimental work is purchased from Special Optics, a manufacturer and designer of precision optical components in America. The lens is designed to be telecentric in the image space with a telecentricity of less than 0.1° within the field depth. Manufacturer's specifications include an effective focal

length f of 100mm, lens aperture of 34mm, function of the index of refraction k of 0.043 at λ 400nm, distortion of less than 0.1% at the field corners and an MTF (modulation transfer function value) of above 50% at 130 lp/mm. However at very low frequencies, all lenses exhibit an MTF of nearly 100%.

The telecentric scan lens integrated into this experimental setup functions not only to align the angled beams from the AOD system to be perpendicular to the workpiece, but it also focuses the laser beams to a diameter of its diffraction limited spot size. As specified by Special Optics [150], the telecentric scan lens is a diffraction limited lens when the lens aperture is at least 1.8 times larger than the $1/e^2$ beam diameter. In such instances, less than 0.1% of the beam intensity is truncated by the lens aperture. The telecentric scan lens used in this setup has a lens aperture of 34mm and is therefore a diffraction limited lens when used with the 16mm diameter beam in the experiments.

Therefore, the function of the telecentric scan lens in this system can be summarized as below:

- i) to focus the laser beam into a diffraction limited spot
- ii) to correct for the beam deflection angle introduced by the AOD scanning by aligning the angled beams to be perpendicular to the workpiece surface
- iii) to obtain a precise, circular laser machined feature

5.10 EFFECT OF PULSE ENERGY ON FEATURE SIZE

As described in Section 2.4, with ultrashort pulse lasers, ablation only occurs when the laser beam's energy density, or fluence passes the threshold value of the material machined. Whenever the fluence exceeds the ablation threshold value for the material, chemical bonds are broken, fracturing the material into energetic fragments resulting in the removal of the material. Hence ablation happens. At fluences below the threshold, only miniscule etching (<0.005 μm per laser pulse) is observed, if at all. But when laser fluence is above the threshold, the etch depth per pulse increases rapidly with increasing laser fluence.

At low laser energy density (fluence), there is no material removal, therefore ablation does not happen. As the energy density is increased, it will eventually reach the ablation threshold point, where material removal will begin. At the point when the laser fluence passes the threshold point and ablation begins, the ablated feature will be the smallest feature obtainable for the material with the particular laser system.

If the laser fluence is increased beyond the threshold fluence, there is more material removal and subsequently, the size of the ablated features will increase correspondingly. The increase in the ablated feature size will sustain until at a certain level where the amount of removed material is not further increased with increasing fluence and there will be no further increase in the ablation features. If the laser fluence is still increased beyond this level, the energy of the additional photons which will not be used to break the bonds and eject the material, will then transform into heat and cause thermal damage [3,18,24].

Figure 5.34: Features from bottom to top, ablated on a 100nm gold film with the direct laser beam at pulse energy of 55nJ, 60nJ and 65nJ, respectively.

Figure 5.34 is the SEM image of the features (from bottom to top) ablated on a 100nm gold film with the direct laser beam at pulse energy of 55nJ, 60nJ and 65nJ, respectively, maintaining all other machining parameters as a constant. It is observed that at 55nJ, there is no significant ablation although there appears miniscule etching, probably indicating the onset of ablation [151]. However, with an increase of 5nJ to 60nJ, ablation was abruptly initiated and a 1000nm feature was obtained. A subsequent energy increase of 5nJ yielded a 1250nm feature, an increase of 250nm in feature size. Therefore, it can be concluded that ablation is initiated once the laser fluence exceeds the threshold fluence of the material machined and that the feature size increases rapidly with increasing laser energy.

In micromachining, the smaller the feature obtained the better. Therefore, the laser fluence used during machining has to be carefully controlled to just slightly above the threshold fluence of the material in order to obtain the smallest ablation feature.

5.10.1 How the Threshold Point is determined during Experimental Work

To determine the point where material removal initiates and ablation begins, the laser is initially set to a low lasing energy. The average laser energy (averaged over 1000 consecutive pulses) is measured using a pyroelectric detector (Ophir PD10) connected to an energy meter placed right after the telecentric lens and before the beam is focussed to hit upon the specimen located at the focal point of the beam.

Laser energy is increased gradually by intensifying the energy by small incremental steps (5 μ W step at a time in the case of Figure 5.36) until the breakdown threshold is traversed and ablation commences. Breakdown is determined when the laser light penetrates through the metallic thin film coated fused silica glass specimen (a CCD camera is placed behind the specimen to observe this phenomenon) indicating that ablation has been initiated and material has been removed. In addition, when breakdown occurs, plasma emission will take place and a spark will be observed in the darkened room. This is identified as the material breakdown threshold point and the laser energy measured at this point is the breakdown threshold energy.

5.11 EFFECT OF LASER FLUENCE FLUCTUATION ON THE FEATURE SIZE

The femtosecond pulse laser system used in this research work has an inherent 5% beam energy fluctuation. This is due to the low pulse repetition rate of the laser; more pulse build-up time is required in the OPA (optical parameter amplification) amplification system to obtain a high pulse energy resulting in the energy fluctuation. This energy fluctuation will inevitably result in the variation of feature size obtained.

The energy fluctuation of the laser system and its effect on the feature size obtained has been studied by research colleagues [111]. The plot between the machined feature size obtained against the fluence fluctuation in Figure 5.35 taken from their published journal paper shows that a 5% fluctuation in the laser fluence corresponds to a feature size variation of as much as 77%.

Figure 5.35: Feature size variation as a function of fluence fluctuation. [111]

Therefore, the energy fluctuation of the laser system will have a detrimental effect on the machined feature size, especially in micromachining where precision and repeatability is critical. This can be improved by using a laser with a higher pulse repetition rate as it is more stable and efficient. However, the high repetition rate of the laser will consequently induce lower pulse energies. This will not present a problem for most micromachining works as the energy needed are usually very small in the nJ to μ J ranges.

5.12 EFFECT OF FEMTOSECOND PULSED LASER-MATERIAL INTERACTION

In order to understand how material ablation occurs during femtosecond pulse laser micromachining, the interaction between the laser and the substrate material being machined should be investigated. The laser-material interaction will govern the mechanism of the material removal (ablation) and the quality of the feature obtained such as the dimension stability, reproducibility, material collateral damage, cracks and machining residue.

The femtosecond laser and material interaction is defined by the strength of the electron-phonon coupling, pulse width and the laser fluence.

5.12.1 Effect of electron-phonon coupling

In metals, laser light is absorbed by the conduction band electrons. The deposited energy quickly, within femtoseconds, is equilibrated among the electrons and, more slowly, is transferred to the atomic vibrations in the lattice (Figure 5.36). The latter process is governed by the strength of the electron-phonon coupling and can take from a fraction of a picosecond to several tens of picoseconds. Finally, a thermal equilibrium is established between the electrons and phonons, and the heat flow from the surface region into the bulk of the irradiated target driven by the temperature gradient. This describes the event of thermal diffusion through the material. The

length of time it takes for the sub-systems to reach equilibrium is governed by the strength of the electron-phonon coupling [144, 145].

Electron-phonon coupling is important for the studies of femtosecond laser ablation and the establishment of the material breakdown ablation threshold. Noble metals exhibit weak electron-phonon coupling and this explains the high value obtained for the electron heat diffusion length of gold and platinum. Consequently, noble metals exhibit higher ablation thresholds than transition metals due to the energy loss from the target surface as a result of the ballistic transport of non-thermalised electrons and the longer electron heat diffusion length [145]. The lattice temperature rise at the front surface is much slower since most of the absorbed energy is transported into the interior of the metal [146]. On the other hand, transition materials which has stronger electron-phonon coupling exhibits lower ablation thresholds because they retain the absorbed energy density near the surface and prevent much diffusive losses to the interior [146].

The substrate materials used in this work are gold and platinum. They are both noble metals which explain for their relatively high breakdown threshold fluence. The breakdown threshold for platinum and gold has been determined to be 132 mJ/cm^2 and 158 mJ/cm^2 respectively (from Section 2.5.1).

For future work, other metal substrates especially transition materials such as stainless steel and titanium can be investigated. Because of their stronger electron-phonon coupling, these materials will exhibit lower breakdown thresholds. Additionally, weaker laser radiation absorbing materials such as transparent, dielectrics and wide bandgap materials can also be investigated.

5.12.2 Effect of laser fluence

There are two separate ablation phases, namely the “gentle” ablation phase and the “strong” ablation phase, therefore there are two different ablation rates [147]. Whilst operating in the “gentle” ablation phase in a low fluence regime ($F_0 < 1 \text{ J/cm}^2$), the energy of the laser pulses is mainly absorbed by free electrons, due to the inverse

Bremsstrahlung (Figure 5.36) [147]. The ablation rate is low and dependant on the optical penetration depth, α^{-1} , where α is the absorption coefficient of the material at the laser wavelength [145].

Figure 5.36: Schematic of a short-pulse laser ablation in low fluence regime [147].

For low laser fluences ($F_0 < 1 \text{ J/cm}^2$), the ablation depth per pulse is given by:

$$d = \frac{1}{\alpha_{eff}} \ln \left(\frac{F_0}{F_{th}} \right) \quad \text{Equation 5.7}$$

For femtosecond “gentle” ablation in the low fluence regime, the thermal penetration depth during the ablation process is smaller than the absorption length. Therefore, the heat conduction can be neglected, minimizing the effect of a heat-affected zone (HAZ) around the ablated feature. Also, since the thermal losses are absent, the hole can be drilled with much lower laser fluences [147].

When operating in the stronger ablation phase at higher laser fluences ($F_0 > 1 \text{ J/cm}^2$), the ablation rate is greater and is characterized by the “electron heat diffusion length”, γ . This parameter measures the distance through which the heat energy has been transported via the electrons. [145]

For higher laser fluences ($F_0 > 1 \text{ J/cm}^2$), the second logarithmic dependence appears and can be described by:

$$d = \gamma \ln\left(\frac{F_0}{F_{th}}\right) \quad \text{Equation 5.8}$$

The femtosecond ablation work described in this thesis has been carried out in the in low fluence regime, at laser fluence very close to the material breakdown threshold fluence. Therefore, the “gentle” ablation phase applies and the ablation depth is governed by Equation 5.7 (also described in Section 2.5.1). Heat conduction through the material is negligible and therefore, there will be minimal heat-affected zone (HAZ) around the ablated feature.

5.12.3 Effect of pulse width

Pulse width, or the duration of the pulse, greatly affects the peak power of a laser because it defines the amount of time the material being machined interacts with the light. Pulse widths of longer duration are generally associated with lower intensity lasers and longer periods of light exposure, while pulse widths of shorter duration are associated with higher intensity lasers and shorter light exposure, characteristics essential for high-precision laser machining.

In the case of a femtosecond pulse laser (pulse width from 10 to 1000 femtoseconds), ablation occurs mainly in the plasma phase. The absorbed laser energy is first deposited into the thermal energy of the electrons. A considerable part of the thermal electron energy is transferred to the lattice (Figure 5.38). The energy transfer is very fast and occurs on a picosecond time scale. The extremely fast energy transfer results in the creation of plasma and vapor phases. The formation of plasma plumes occurs after the termination of the laser pulse and this prevents the problem of plasma shielding effect faced in longer pulse ablation such as in pico- and nanosecond pulse machining [148].

Also, as the pulse duration of the femtosecond laser is so short, there is not sufficient time for the pulse energy to be distributed to the substrate in the form of heat or shock. Therefore, thermal diffusion into the substrate is negligible resulting in a minimum heat-affected zone (HAZ) [16,20,23,149]. And as the energy does not have time to diffuse away, the efficiency of the machining process is high and there are negligible thermal losses due to heat diffusion. Subsequently, the threshold fluence for ultrafast pulse lasers is lower than for longer pulse lasers.

Therefore, the advantages of an ultrafast femtosecond pulsed laser over a longer pulsed laser such as a pico- or nanosecond pulsed laser are: very rapid creation of vapor and plasma phases, negligible heat conduction (minimal HAZ) and the absence of a liquid phase, allowing for better control and higher reproducibility of the ablation process [147].

5.13 CONCLUDING REMARKS

The mechanism of submicron ablation with interference fringes has been described in detail and the limitations highlighted. The smallest feature size achieved with the current laser micromachining technology using direct laser beam is 200nm. The aim of this proposed research concept is to break through this 200nm limit to achieve smaller, finer ablation features.

The intensity profile of the interfered beam has been ascertained to retain a Gaussian-like profile making it easier to isolate the central bright fringe for machining. Furthermore, the profile of the central bright fringe will be sharpest when the interference beam retains a Gaussian envelope compared to, e.g. a flat-top profile. The best interference beam profile for the use in this laser micromachining concept has also been identified at Stage 5 when the beam reaches its highest peak with the central bright fringe at its sharpest and most pronounced.

Next the short coherence length limitation and the challenges in obtaining clear, sharp and stable circular fringes on the femtosecond laser system had been identified.

Problems related to the experimental setup and the various equipment which incorporates the experimental setup were identified and the countermeasures taken in order to solve these problems were also explained.

Further, the effect of laser pulse energy and the laser fluence fluctuation on the machined feature size were discussed.

Lastly, the interaction between the femtosecond pulsed laser with the material ablated and its effect on the ablated feature size and quality was discussed.

CHAPTER 6

MACH-ZEHNDER INTERFEROMETRY SETUP

6.1 INTRODUCTION

In order to generate circular interference fringes with the femtosecond laser, a Mach-Zehnder interferometer setup is introduced into the experimental setup. The equipment and optical components used and the concept of the interferometer setup will be explained. The methodology of the experimental work and the results obtained will then be presented, compared and a conclusion made based on the observations.

6.2 THE MACH-ZEHNDER INTERFEROMETER

The Mach-Zehnder interferometer is an amplitude-splitting interferometer consisting of two beamsplitters and two totally reflecting mirrors. The typical setup of this interferometer is shown in Figure 6.1. The incoming beam from the laser is split at the first beamsplitter into two separate beams and made to travel at perpendicular paths. The two beams are reflected at the mirrors and recombined at the second beamsplitter. Interference occurs when there's a difference between the optical paths. This can be introduced by a slight tilt of one of the beam splitters.

Figure 6.1: The Mach-Zehnder interferometer setup. [65]

6.3 EXPERIMENTAL SETUP AND RESULTS

A Mach-Zehnder interferometer setup was integrated into the laser setup as shown in Figure 6.2 in order to generate interference on the femtosecond pulse laser.

The laser beam emitted from the femtosecond pulse laser system at the compressor module is 4mm in diameter. A Keplerian beam expander with two lenses of focal length, $f_1 = 50\text{mm}$ and $f_2 = 200\text{mm}$ and a clear aperture diameter of 25.4mm with their focal points positioned nominally coincident is integrated into the experimental setup in order to expand the laser beam. The 4X effective magnification yields a collimated beam of 16mm.

Figure 6.2: The experimental setup integrated with the Mach-Zehnder interferometer.

The purpose of expanding the laser beam is to reduce the effects of beam diffraction to obtain a smaller focussing spot (the focal spot size is inversely proportional to the diameter of the laser beam as shown in the diffraction limited spot size formula in Equation 4.11). However, the expansion of the beam is limited by the size of the lenses used. As the clear aperture of the lenses used in this experimental setup is 25.4mm (exception of the telecentric scan lens with a clear aperture of 34mm), a beam diameter of 16mm is determined to prevent beam clipping/truncation and to ensure that diffraction effects are negligible. A spatial filter is also included to filter out spatial noises and to improve beam quality and concentricity.

The collimated beam is split into two equal intensity beams using a non-polarizing 50/50 beamsplitter, BS₁. After reflection at mirrors M₁ and M₂, the two beams are then recombined at beamsplitter, BS₂ to obtain circular interference fringes. A rotatable compensation plate, CP is inserted into the second arm after mirror M₂ for the optical path difference correction between the two arms of the interferometer.

A diaphragm is used to isolate the central bright fringe of the circular interference beam for machining. The diaphragm acts as a field stop to limit the field of view to only the full diameter of the central bright fringe, which is the subject of interest. As the whole diameter of the beam of interest (the central bright fringe) is passed through the diaphragm, it is assumed that no part of the intended beam is vignetted and diffraction effects are assumed to be negligible. The isolated central bright fringe of the interference beam is then scanned across the stationary workpiece using the acousto-optic deflector (AOD) and telecentric lens setup.

The number of pulses to hit the target is set at 100 pulses per scan point. Machining is started from low lasing energy before ablation is initiated. The average laser energy (averaged over 1000 consecutive pulses) is measured using a pyroelectric detector (Ophir PD10) connected to an energy meter placed right after the telecentric lens and before the beam is focused to hit upon the specimen located at the focal point of the beam.

Laser energy is increased gradually by increasing the energy in small increments of 1nJ at a time until the breakdown threshold is traversed and ablation commences. For

every increase in the pulse energy from the laser source, the pulse energy right after the telecentric lens is recorded using the energy meter. Breakdown is determined when the laser light penetrates through the metallic thin film coated fused silica glass specimen (a CCD camera is placed behind the specimen to observe this phenomenon) indicating that ablation has been initiated and material has been removed. In addition, when breakdown occurs, plasma emission will take place and a spark will be observed in the darkened room. This is identified as the material breakdown threshold point and the laser energy measured at this point is the breakdown threshold energy of the material.

The experiment above is repeated by removing the Mach-Zehnder interferometer setup and the diaphragm from the experimental setup. The direct laser beam is scanned across the workpiece using the acousto-optic deflector (AOD) and telecentric scan lens setup. The ablated features obtained from both setup configurations are then compared.

Figure 6.3: The smallest feature of 600nm ablated on a 100nm gold thin film with the interfered laser beam (Pulse energy: 32nJ).

Figure 6.4: The 1.1µm feature ablated on 100nm thick gold film with the direct laser beam (Pulse energy: 61nJ).

The 600nm feature in Figure 6.3 is the smallest feature obtained using the interfered laser beam (hereupon, referring to the central bright fringe of the interference beam) compared to the 1.1 μ m feature obtained with the direct laser beam in Figure 6.4. As both features are the smallest features obtained for the respective beams, it is concluded that they are ablated at the laser fluence of 158mJ/cm² (the threshold fluence of gold). The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.55. The reduction in size of the feature ablated with the interference beam is because of the sharper beam profile of the central bright fringe of the interference beam compared to the Gaussian beam profile of the direct laser beam.

It was also observed that periodic ripple structures are evident around the area of ablation. These ripple structures has a periodicity of approximately 300nm to 400nm, close to the wavelength of the laser light used ($\lambda = 400\text{nm}$). These near laser wavelength periodic ripple structures obtained are attributed to normal vaporization along the lines of constructive interference which arises when the incident beam interferes with a scattered tangential wave [145,153,154]. Incident laser light is partially scattered by surface defects into a tangential wave which travels across the material surface. The scattered tangential wave then interferes with the incident laser light resulting in interference and the formation of the rippled periodic surface structure in the order of the laser wavelength around the ablated area.

Features ablated with the direct laser beam were found to be quite uniform with slight size variation of less than 10% due to the laser beam intensity fluctuation. However, the size of the features obtained with the interfered beam was found to be inconsistent although machining was carried out while maintaining all other parameters constant. The features varied from 600nm to up to 3 μ m as shown in Figure 6.5. From the results obtained, it can be seen that the repeatability is very poor. Even when the laser machining parameters and pulse energy were kept at a constant, the size of the machining features can differ by up to 400%.

Figure 6.5: The large variation in feature size ablated with the Mach-Zehnder interference beam due to the instability of the interference beam.

The large variation in the feature size obtained with the interfered beam is attributed to the interference beam pattern instability. When the interference beam is inspected visually using a screen before it was focussed, it was observed that the interference beam was unstable and fluctuates erratically. Not only were there obvious fluctuations in the interference beam intensity but the beam profile of the interference beam was very unstable. The rings of the interference fringes kept appearing and disappearing, originating from the periphery and disappearing at the centre of the beam, and vice versa.

The interference beam instability is attributed to the unstable optical path length, OPL in the interferometer setup system. Because of the sensitivity of the optical setup and the very short coherence length of the laser, even minor errors such as a slight misalignment of the optical elements and external environmental disturbances such as vibrations, fluctuation of air temperature and/or pressure at different parts of the setup

can upset the equilibrium of the interference setup causing instability to the OPL and resulting in phase change and fluctuation to the interference beam profile.

In Section 5.5, it has been ascertained that the best interference beam profile for machining is when the peak of the central bright fringe of the interference beam is at its highest and most pronounce. Therefore, the stability of the interference beam is crucial in order to maintain the interference fringe profile at this optimum stage for machining.

Moreover, because of the short coherence length of the femtosecond pulse laser, it is very tedious and time consuming to align the setup. As explained in Section 5.4, the optical path difference, OPD between the 2 overlapping laser beams must be maintained within the coherence length of the laser in order for the beams to interfere. The coherence length of the femtosecond pulse laser system used in this research work is calculated to be $45\mu\text{m}$ as shown in Equation 5.1. This means that the alignment of the optical elements which comprises the setup must be very precise to maintain the OPD to within this minute range. External environmental disturbances such as vibrations, air temperature and pressure fluctuation which can upset the equilibrium of the interference setup have to be tightly controlled or eliminated.

The Mach-Zehnder interferometer's generally complex and large setup comprising of many optical elements and the fact that it is not a common path setup makes it difficult to obtain and maintain the $45\mu\text{m}$ OPD required. Alignment of the length and angle of every single optical component is therefore very critical and had to be very precise.

6.4 CONCLUDING REMARKS

A Mach-Zehnder interferometry setup is integrated into the experimental setup to successfully generate circular interference fringes. The central bright fringe of the interference beam was used to machine and the features obtained were compared with the features ablated with the direct laser beam.

A 600nm feature was obtained using the interfered laser beam compared to a 1.1 μ m feature obtained with the direct laser beam at the same laser fluence. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.55.

Repeatability is found to be very poor and the ablated features obtained with the interfered beam were inconsistent, varying from 600nm to up to 3 μ m although machining was undertaken whilst maintaining all other laser machining parameters constant. This is attributed to the interference beam instability due to the sensitivity of the Mach-Zehnder setup to external environmental disturbances such as vibrations, air temperature and pressure fluctuation, subsequently resulting in the fluctuation of the OPL.

A 45.5% reduction in feature size was achieved using the interfered beam compared to the features machined using the direct laser beam. The reduction in the feature size ablated with the interference beam is because of the sharper beam profile of the central bright fringe of the interference beam compared to the Gaussian beam profile of the direct laser beam. However, the smallest ablated feature obtained of 600nm falls short of the objective of this research work which is to obtain machining features of below 200nm.

CHAPTER 7

NEWTON'S RING INTERFEROMETRY SETUP

7.1 INTRODUCTION

To address the problem of the Mach-Zehnder interferometer setup as highlighted in Chapter 6, a common path interferometer setup is proposed. A simple and effective method for obtaining sharp circular fringes on the femtosecond pulse laser is achieved by using a Newton's ring interferometer setup (refer to Section 3.6 for detailed literature on the interferometer). It is a common path setup and it consists of minimal optical components therefore making it stable and easy to set up.

7.2 MODIFICATION OF THE NEWTON'S RING SETUP FOR USE ON OUR EXPERIMENTAL SETUP

Generally, a Newton's ring setup consists of a long focal length convex lens of shallow spherical curve placed in contact with an optical flat or glass plate (Figure 3.5(a)). However, with this setup, the fringes obtained will not be clear and well defined as most of the light will transmit through the optics with only a small percentage of light reflecting back from the optical flat and the curved surface of the lens to interfere.

Therefore, a modified Newton's ring setup is proposed. However, the principle of the original concept remains. A silvered curved mirror surface with a 2000mm radius of curvature is placed in contact with an optical flat with a beam splitter coating of 50/50 reflectance/transmission ratio at angle 45° for wavelength 400nm. Incoming laser light will partially transmit and partially reflect at the beam splitter coated surface of the optical flat. The transmitted light will then proceed on to reflect off the surface of the silvered curved mirror surface and then interfere with the reflected light from the beam splitter coated surface of the optical flat to interfere. This is illustrated in Figure 7.1 below.

Figure 7.1: The modified Newton's Ring setup.

The experimental optical setup for obtaining interference fringes with the Newton's Ring arrangement is schematically shown in Figure 7.2.

Figure 7.2: The experimental setup with the integrated Newton's Ring interferometer setup.

7.3 MATLAB[®] VISUALISATION AND ANALYSIS

The ultrafast pulse laser beam has a Gaussian intensity profile corresponding to the theoretical TEM₀₀ mode. The intensity distribution of the Gaussian TEM₀₀ beam is given by the term:

$$I = I_0 \exp\left(-\frac{2r^2}{w_0^2}\right) \quad \text{Equation 7.1}$$

where,

I_0 = intensity of the incident beam

r = radius of the incident beam

w_0 = Gaussian beam radius (the radius at which the intensity has decreased to $1/e^2$ or 0.135 of its peak value)

For common optical path interferometers such as the Newton's Ring interferometer, the amplitudes of both waves are equal at the point of interference (i.e., $\vec{E}_{01} = \vec{E}_{02}$), and hence, the intensity contributions from both sources are also equal. Therefore, $I_1 = I_2 = I_0$. The interference intensity term represented by Equation 3.21 can then be rewritten as:

$$I = 2I_0(1 + \cos \delta) = 4I_0 \cos^2 \frac{\delta}{2} \quad \text{Equation 7.2}$$

where,

I_0 = intensity of the incident beam

δ = phase difference

However, for the Newton's Ring interferometer, the beams are actually the split beam from the original incident laser beam, I_0 , split at the 50/50 R/T ratio beam splitter coated surface. Therefore, the interference intensity term for the Newton's Ring interferometer can now be written as:

$$I = 2 \cdot \frac{1}{2} I_0 (1 + \cos \delta) = 2 I_0 \cos^2 \frac{\delta}{2} \quad \text{Equation 7.3}$$

It is known that,

$$\text{Phase difference, } \delta = \frac{2\pi}{\lambda} \cdot \text{OPD} \quad \text{Equation 7.4}$$

and the optical path difference (OPD) in the case of the Newton's Ring interferometer is $2d$ (refer to Section 3.6).

From Equation 3.25,

$$2d = \frac{r^2}{\mathfrak{R}} \quad \text{Equation 7.5}$$

Therefore, Equation 7.3 can be rewritten as:

$$I = 2 I_0 \cos^2 \frac{\pi r^2}{\lambda \mathfrak{R}} \quad \text{Equation 7.6}$$

However, the above term applies only in ideal cases. Due to losses incurred by the laser light reflecting out from the optical flat and through absorption by the beam splitter coating and silver coating of the mirror curved surface, the beam will assume a gradually dissipating distribution. By using a beam analyser (BeamScope™ from DataRay Inc), it was ascertained that the interfered beam takes on a Gaussian profile. Therefore, the interference intensity function in Equation 7.6 can be rewritten by merging with the Gaussian distribution function to obtain the interference intensity distribution term in Equation 7.7.

$$I = 2I_0 \cos^2 \frac{\pi r^2}{\lambda \mathfrak{R}} \bullet \exp \left(- \frac{2r^2}{w_0^2} \right)$$

Equation 7.7

Using MATLAB®, the Gaussian beam function (Equation 7.1) is plotted against the Newton’s Ring interference beam function (Equation 7.7) for an incident laser beam diameter of 16mm. From the 2D intensity profile plot (Figure 7.3), it is evident that the profile of the central bright fringe of the interference beam is significantly sharper compared to the Gaussian direct laser beam. This reinstates that the effective ablation spot of the laser can be significantly reduced if the laser beam is first interfered, and then the central bright fringe used for machining as compared with just using the direct laser beam.

Figure 7.3: The intensity profile plot of the Newton’s Ring interference beam profile against the direct laser beam profile.

As can be seen from Figure 7.3, the peak intensity of the Newton's Ring interference beam is twice of the direct laser beam. This is a further advantage as it means that only half of the laser energy from the source is required by the interfered beam to attain a certain level of peak intensity/power as compared to the direct laser beam.

Also, by comparing the profile of the central bright fringe of the interfered beam with the profile of the direct laser beam from the graph plotted, it can be seen that the profile of the central bright fringe of the interfered beam is much sharper than the profile of the Gaussian direct laser beam. By using the sharper profiled central bright fringe of the interfered laser beam over the direct laser beam to machine, it is expected that the ablation spot size will be reduced significantly.

7.4 MODELLING AND CURVE FITTING OF THE CENTRAL BRIGHT FRINGE

The central bright fringe of the interfered beam is not a Gaussian profile beam. Therefore, the new intensity profile and the associated distribution function of the central bright fringe have to be determined. In order to do that, graph data modelling and curve fitting were applied.

Firstly, the central bright fringe of the interfered beam was calculated and then plotted. Using the TableCurve 2D software by Systat Software Inc, the data obtained from the calculations were modelled, and the graph obtained was then curve-fitted (Figure 7.4).

Figure 7.4: Curve-fitting of the Newton's Ring central bright fringe using TableCurve 2D.

The central bright fringe of the interfered beam was found to follow a Beta distribution with a function of:

$$y = \frac{a \left[\frac{x-b + \frac{c(d-1)}{d+e-2}}{c} \right]^{d-1} \left[1 - \frac{x-b + \frac{c(d-1)}{d+e-2}}{c} \right]^{e-1}}{\left[\frac{d-1}{d+e-2} \right]^{d-1} \left[\frac{e-1}{d+e-2} \right]^{e-1}} \quad \text{Equation 7.8}$$

From the curve-fitting data, the variables were ascertained to be:

$$\begin{aligned} a &= 0.98945 & d &= 4.05 \\ b &= -4.49e-13 & e &= 4.05 \\ c &= 13.59 \end{aligned}$$

Therefore, Equation 7.8 can be rewritten as:

$$y = \frac{0.98945 \left[\frac{x + 4.49e - 13 + \frac{13.59(4.05-1)}{4.05+4.05-2}}{13.59} \right]^{4.05-1} \left[1 - \frac{x + 4.49e - 13 + \frac{13.59(4.05-1)}{4.05+4.05-2}}{13.59} \right]^{4.05-1}}{\left[\frac{4.05-1}{4.05+4.05-2} \right]^{2(4.05-1)}}$$

$$= \frac{0.98945 \left[\frac{x + 6.795}{13.59} \right]^{3.05} \left[1 - \frac{x + 6.795}{13.59} \right]^{3.05}}{0.0146} \quad \text{Equation 7.9}$$

For the verification of the curve-fitted distribution function, MATLAB was used to plot the Equation 7.9 (Figure 7.5).

Figure 7.5: The intensity profile plot of the central bright fringe of the Newton's Ring interference beam from Equation 7.9.

From the MATLAB data, the central bright fringe diameter was determined to be 1.8mm at $1/e^2$.

7.5 EXPERIMENTAL SETUP AND RESULTS

The Newton's Ring interferometer setup (Figure 7.6), consisting of a silvered curved mirror surface with a 2000mm radius of curvature placed in contact with an optical flat with a beam splitter coating of 50/50 reflectance/transmission ratio, is integrated into the laser setup as shown in Figure 7.2 to generate interference on the femtosecond pulse laser.

The laser beam emitted from the femtosecond pulse laser system at the compressor module is 4mm in diameter. A Keplerian beam expander with two lenses of focal length, $f_1 = 50\text{mm}$ and $f_2 = 200\text{mm}$ with diameter of 25.4mm and positioned with their focal points nominally coincident is integrated into the experimental setup in order to expand the laser beam. The 4X effective magnification yields a collimated beam of 16mm. The purpose of expanding the laser beam is to reduce the effects of beam diffraction to obtain a smaller focussing spot (the focal spot size is inversely proportional to the diameter of the laser beam as shown in the diffraction limited spot size formula in Equation 4.11). However, the expansion of the beam is limited by the size of the lenses used. As the clear aperture of the lenses used in this experimental setup is 25.4mm (exception of the clear aperture of the telecentric scan lens of 34mm), a beam diameter of 16mm is determined to prevent beam clipping/truncation and to ensure that diffraction effects are negligible. A spatial filter is also included to filter out spatial noises and to improve beam quality and concentricity.

The collimated beam is interfered at the Newton's Ring setup (Figure 7.7) consisting of a silvered curved mirror surface with a radius of curvature, $\mathcal{R}$ of 2000mm placed in contact with an optical flat with a 50/50 reflectance/transmission ratio beamsplitter coating, to obtain circular interference fringes. A diaphragm is used to isolate the central bright fringe of the interference beam for machining. The diaphragm acts as a field stop to limit the field of view to only the full diameter of the central bright fringe, which is the subject of interest. As the whole diameter of the beam of interest (the central bright fringe) is passed through the diaphragm, it is assumed that no part of the intended beam is vignetted and diffraction effects are assumed to be negligible.

The isolated central bright fringe of the interference beam is then scanned across the stationary workpiece using the acousto-optic deflector (AOD) and telecentric lens setup.

Figure 7.6: The Newton's Ring interferometer setup used in the experiments.

The number of pulses to hit the target is set at 100 pulses per scan point. Machining is started from low lasing energy before ablation is initiated. The average laser energy (averaged over 1000 consecutive pulses) is measured using a pyroelectric detector (Ophir PD10) connected to an energy meter placed right after the telecentric lens and before the beam is focused to hit upon the substrate located at the focal point of the beam.

Laser energy is increased gradually by increasing the energy in small incremental steps of $1nJ$ at a time until the breakdown threshold is traversed and ablation commences. For every increase in the pulse energy from the laser source, the pulse

energy right after the telecentric lens is recorded using the energy meter. Breakdown is determined when the laser light penetrates through the metallic thin film coated fused silica glass specimen (a CCD camera is placed behind the specimen to observe this phenomenon) indicating that ablation has been initiated and material has been removed. In addition, when breakdown occurs, plasma emission will take place and a spark will be observed in the darkened room. This is identified as the material breakdown threshold point and the laser energy measured at this point is the breakdown threshold energy of the material.

The experiment above is repeated by removing the Newton's Ring setup from the experimental setup and using the direct laser beam to machine. The features obtained from both setup configurations are then compared. The thin film substrate is removed and the experiment is repeated with a thin film substrate of another material.

Figure 7.7: A 350nm hole ablated on a 100nm thick gold film with the interfered laser beam.

Pulse energy: 33nJ

Figure 7.8: A 1µm hole ablated on a 100nm thick gold film with the direct laser beam.

Pulse energy: 58nJ

Figure 7.9: A 350nm hole ablated on a 100nm thick platinum film with the interfered laser beam.

Pulse energy: 31nJ

Figure 7.10: A 1µm hole ablated on 100nm thick platinum with the direct laser beam.

Pulse energy: 54nJ

Figure 7.7 is the SEM image of the smallest ablated feature achieved on a 100nm thick gold film using the interfered laser beam (hereupon, referring to the central bright fringe of the interference beam) while Figure 7.8 is the smallest feature obtained using the direct laser beam. The pulse energy recorded is 33nJ for the feature obtained with the interfered beam and 58nJ for the feature obtained with the direct laser beam.

Figure 7.9 is the SEM image of the smallest ablated feature achieved on a 100nm thick platinum film using the interfered laser beam while Figure 7.10 is the smallest feature obtained using the direct laser beam. The pulse energy recorded is 31nJ for the feature obtained with the interfered beam and 54nJ for the feature obtained with the direct laser beam.

On the gold specimen, a 350nm (0.35 μ m) feature was obtained using the interfered laser beam compared to a 1 μ m feature using the direct laser beam. As both features are the smallest features obtained for the respective beams, it is concluded that they are ablated at the laser fluence of 158 mJ/cm² (the breakdown threshold fluence of gold). The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is calculated to be 0.35.

On the platinum specimen, a 350nm (0.35 μ m) feature was also obtained using the interfered laser beam compared to a 1 μ m feature using the direct laser beam. As both features are the smallest features obtained for the respective beams, it is concluded that they are ablated at the laser fluence of 132 mJ/cm² (the breakdown threshold fluence of platinum). The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is calculated to be 0.35.

The reduction in size of the features ablated with the interference beam is because of the sharper beam profile of the central bright fringe of the interference beam compared to the Gaussian beam profile of the direct laser beam. From the MATLAB intensity profile plot in Figure 7.3, it is evident that the profile of the central bright fringe of the interference beam is significantly sharper compared to the Gaussian

direct laser beam. From curve fitting, the central bright fringe of the interference beam was found to follow a Beta distribution.

It was also observed that for the platinum substrate, periodic ripple structures are evident around the area of ablation. These ripple structures has a periodicity of approximately 300nm to 400nm, close to the wavelength of the laser light used ($\lambda = 400\text{nm}$). These near laser wavelength periodic ripple structures obtained are attributed to normal vaporization along the lines of constructive interference which arises when the incident beam interferes with a scattered tangential wave [145,153,154]. Incident laser light is partially scattered by surface defects into a tangential wave which travels across the material surface. The scattered tangential wave then interferes with the incident laser light resulting in interference and the formation of the rippled periodic surface structure in the order of the laser wavelength around the ablated area.

However, no apparent periodic ripple structures are evident on the gold substrate. Instead, a ring is observed around the ablated features. This is attributed to the redeposition of the ablated particles (debris) removed during the ablation process. The absence of the ripple structures on the gold substrate compared to those observed on the platinum substrate could be due to the different laser-material interaction between the two metals and the laser parameters (laser energy, laser fluence, etc).

Gold, which is a noble metal (where all the d-bands of the electronic structure are filled and do not cross the Fermi level) is less reactive compared to platinum where two of the d-bands cross the Fermi level. Therefore, platinum which has a lower surface energy compared to gold, will interact more readily with laser irradiation resulting in the surface modification of the material.

In order to gain a deeper understanding of the material modification and removal mechanism and to understand better the mechanism of the ripple formation, the interaction between the different materials and the femtosecond laser parameters (e.g., laser energy, laser fluence) should be investigated for future works.

7.6 VERIFICATION OF THE THRESHOLD ENERGY

In order to verify that the smallest ablation feature obtained is indeed machined at threshold, the threshold energy recorded during machining using the energy meter is compared to the theoretical threshold energy.

For the gold specimen, the threshold energy recorded for the 350nm feature ablated with the central bright fringe of the interfered beam is 33nJ while the threshold energy recorded for the 1000nm feature ablated with the direct laser beam is 58nJ.

From theoretical calculations, with the central bright fringe of the interfered beam, the diffraction limited focused spot size diameter at $1/e^2$, d (Equation 4.13) is calculated to be:

$$d = \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2}$$

$$= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 1.8} + \frac{0.043 \times 1.8^3}{2 \times 100^2} = 14.1 \mu m \quad \text{Equation 7.10}$$

with the diameter of the central bright fringe, $D = 1.8\text{mm}$ and k (function of the index of refraction) = 0.043 as given by the lens manufacturer at $\lambda = 400\text{nm}$

For femtosecond lasers, the threshold fluence can be precisely determined (Section 2.5). Therefore, it is possible to control that only a small portion of the focused spot size exceeds the ablation threshold thus enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the interfered beam of 350nm (Figure 7.7) is concluded to be ablated at the laser fluence of 158 mJ/cm² (the breakdown threshold fluence of gold). Therefore,

Spot size diameter at threshold, $d_{th} = 350\text{nm} = 3.5 \times 10^{-5}\text{cm}$

$$\begin{aligned}\text{Spot area at threshold, } a &= \pi r_{th}^2 = 3.142 \times 1.75^2 \times 10^{-10} \text{ cm}^2 \\ &= 9.62 \times 10^{-10} \text{ cm}^2\end{aligned}\quad \text{Equation 7.11}$$

$$\begin{aligned}\text{Energy at threshold, } E(r) &= 158 \text{ mJ/cm}^2 \times 9.62 \times 10^{-10} \text{ cm}^2 \\ &= 1.52 \times 10^{-7} \text{ mJ} = 0.152 \text{ nJ}\end{aligned}\quad \text{Equation 7.12}$$

Assuming the intensity profile distribution of the central bright fringe in Equation 7.9, the total pulse energy, $E(\infty)$ can be calculated as:

$$\begin{aligned}E(\infty) &= \frac{E(r)}{\left[1 - \frac{0.98945 \left[\frac{r_{th} + 6.795}{13.59} \right]^{3.05} \left[1 - \frac{r_{th} + 6.795}{13.59} \right]^{3.05}}{0.0146} \right]} \\ &= \frac{0.152 \text{ nJ}}{\left[1 - \frac{0.98945 \left[\frac{0.175 + 6.795}{13.59} \right]^{3.05} \left[1 - \frac{0.175 + 6.795}{13.59} \right]^{3.05}}{0.0146} \right]} = 12.16 \text{ nJ}\end{aligned}\quad \text{Equation 7.13}$$

Total pulse energy, $E(\infty) = 12.16 \text{ nJ}$ at $1/e^2$

For the feature ablated with the direct laser beam, the diffraction limited focused spot size diameter at $1/e^2$, d can be calculated as:

$$\begin{aligned}d &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \\ &= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 16} + \frac{0.043 \times 16^3}{2 \times 100^2} = 10 \mu\text{m}\end{aligned}\quad \text{Equation 7.14}$$

Because the threshold fluence of femtosecond laser can be precisely determined, it is possible to control that only a small portion of the focused spot size exceeds the ablation threshold therefore enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the direct beam of $1\mu\text{m}$ (Figure 7.8) is concluded to be ablated at the laser fluence of 158 mJ/cm^2 (the breakdown threshold fluence of gold). Therefore,

$$\text{Spot size diameter at threshold, } d_{th} = 1000\text{nm} = 1 \times 10^{-4}\text{ cm}$$

$$\begin{aligned} \text{Spot area at threshold, } a &= \pi r_{th}^2 = 3.142 \times 0.5^2 \times 10^{-8}\text{ cm}^2 \\ &= 7.854 \times 10^{-9}\text{ cm}^2 \end{aligned} \quad \text{Equation 7.15}$$

$$\begin{aligned} \text{Energy at threshold, } E(r) &= 158\text{mJ/cm}^2 \times 7.854 \times 10^{-9}\text{ cm}^2 \\ &= 1.241 \times 10^{-6}\text{ mJ} = 1.241\text{ nJ} \end{aligned} \quad \text{Equation 7.16}$$

Assuming a Gaussian intensity profile, the total pulse energy, $E(\infty)$ can be calculated as:

$$\begin{aligned} E(r) &= E(\infty) \left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right] \\ E(\infty) &= \frac{E(r)}{\left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right]} = \frac{1.241\text{ nJ}}{\left[1 - \exp\left(-\frac{2 \times 0.5^2 \mu\text{m}^2}{5^2 \mu\text{m}^2}\right) \right]} \\ &= 62.67\text{ nJ} \end{aligned} \quad \text{Equation 7.17}$$

Total pulse energy, $E(\infty) = 62.67\text{ nJ}$ at $1/e^2$

For the platinum specimen, the threshold energy recorded for the 350nm feature ablated with the interfered beam is 31nJ while the threshold energy recorded for the 1000nm feature ablated with the direct laser beam is 54nJ.

From theoretical calculations, for the feature ablated with the interfered beam, the diffraction limited focused spot size diameter at $1/e^2$, d can be calculated as:

$$d = \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2}$$

$$= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 1.8} + \frac{0.043 \times 1.8^3}{2 \times 100^2} = 14.1 \mu m \quad \text{Equation 7.18}$$

For femtosecond lasers, the threshold fluence can be precisely determined. Therefore, it is possible to control that only a small portion of the focused spot size exceeds the ablation threshold thus enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the interfered beam of 350nm (Figure 7.9) is concluded to be ablated at the laser fluence of 132 mJ/cm² (the breakdown threshold fluence of platinum). Therefore,

$$\text{Spot size diameter at threshold, } d_{th} = 350nm = 3.5 \times 10^{-5} cm$$

$$\text{Spot area at threshold, } a = \pi r_{th}^2 = 3.142 \times 1.75^2 \times 10^{-10} cm^2$$

$$= 9.62 \times 10^{-10} cm^2 \quad \text{Equation 7.19}$$

$$\text{Energy at threshold, } E(r) = 132mJ/cm^2 \times 9.62 \times 10^{-10} cm^2$$

$$= 1.27 \times 10^{-7} mJ = 0.127nJ \quad \text{Equation 7.20}$$

Total pulse energy, $E(\infty)$

$$\begin{aligned}
 E(\infty) &= \frac{E(r)}{1 - \frac{0.98945 \left[\frac{r_{th} + 6.795}{13.59} \right]^{3.05} \left[1 - \frac{r_{th} + 6.795}{13.59} \right]^{3.05}}{0.0146}} \quad \text{Equation 7.21} \\
 &= \frac{0.127 \text{ nJ}}{1 - \frac{0.98945 \left[\frac{0.175 + 6.795}{13.59} \right]^{3.05} \left[1 - \frac{0.175 + 6.795}{13.59} \right]^{3.05}}{0.0146}} = 10.16 \text{ nJ}
 \end{aligned}$$

Total pulse energy, $E(\infty) = 10.16 \text{ nJ}$ at $1/e^2$

For the feature ablated with the direct laser beam, the diffraction limited focused spot size diameter at $1/e^2$, d can be calculated as:

$$\begin{aligned}
 d &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \\
 &= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 16} + \frac{0.043 \times 16^3}{2 \times 100^2} = 10 \mu\text{m} \quad \text{Equation 7.22}
 \end{aligned}$$

Because the threshold fluence of femtosecond laser can be precisely determined, it is possible to control that only a small portion of the focused spot size exceeds the ablation threshold therefore enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the direct beam of $1 \mu\text{m}$ (Figure 7.8) is concluded to be ablated at the laser fluence of 132 mJ/cm^2 (the breakdown threshold fluence of platinum). Therefore,

Spot size diameter at threshold, $d_{th} = 1000nm = 1 \times 10^{-4} cm$

Spot area at threshold, $a = 7.854 \times 10^{-9} cm^2$

$$\begin{aligned} \text{Energy at threshold, } E(r) &= 132mJ/cm^2 \times 7.854 \times 10^{-9} cm^2 \\ &= 1.037 \times 10^{-6} mJ = 1.037nJ \end{aligned} \quad \text{Equation 7.23}$$

Total pulse energy, $E(\infty)$

$$\begin{aligned} E(r) &= E(\infty) \left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right] \quad \text{Equation 7.24} \\ E(\infty) &= \frac{E(r)}{\left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right]} = \frac{1.037nJ}{\left[1 - \exp\left(-\frac{2 \times 0.5^2 \mu m^2}{5^2 \mu m^2}\right) \right]} \\ &= 52.37nJ \end{aligned}$$

Total pulse energy, $E(\infty) = 52.37nJ$ at $1/e^2$

For the gold specimen, the threshold energy computed from theoretical calculations for the 350nm feature ablated with the interfered beam is 12.16nJ while the threshold energy computed for the 1000nm feature ablated with the direct laser is 62.67nJ. These numbers are compared to the 33nJ threshold energy recorded during the experiment for the 350nm feature ablated with the interfered beam and 58nJ threshold energy recorded during the experiment for the 1000nm feature ablated with the direct laser beam.

For the platinum specimen, the threshold energy computed theoretically for the 350nm feature ablated with the interfered beam is 10.16nJ while the threshold energy computed for the 1000nm feature ablated with the direct laser is 52.37nJ. These numbers are compared to the 31nJ threshold energy recorded during the experiment for the 350nm feature ablated with the interfered beam and 54nJ threshold energy

recorded during the experiment for the 1000nm feature ablated with the direct laser beam.

It was found that the threshold energy recorded during the experimental work correlates well with the calculated threshold energy. The difference in results of 2 to 20nJ could be due to energy losses at the telecentric lens because of absorption and reflection and the scattering of the laser light at the highly reflective surface of the metallic substrate.

7.7 COMPARISON BETWEEN THE NEWTON'S RING SETUP AND THE MACH-ZEHNDER INTERFEROMETER SETUP

With the Mach-Zehnder interferometer setup described in Chapter 6, a 600nm feature was obtained on a gold specimen using the interfered laser beam compared to a 1.1µm feature obtained with the direct laser beam. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.55, or an almost 45.5% reduction in feature size.

Meanwhile, with the Newton's Ring interferometer setup, 350nm features were obtained on a gold specimen by using the interfered laser beam compared to the 1µm features using the direct laser beam. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.35, or a 65% reduction in feature size.

It was found that a further reduction in feature size was achieved with the Newton's Ring interferometer setup compared to the initial Mach-Zehnder interferometer setup. With the Newton's Ring setup, a 350nm feature was obtained compared to the 600nm feature ablated with the Mach-Zehnder setup. This is equivalent to a further reduction in feature size of at least 40% with the Newton's Ring interferometer setup.

In addition, the problem of the interference beam pattern instability inherent in the Mach-Zehnder interferometer setup has been solved with the Newton's Ring setup. With its common path configuration and simple setup, fluctuation in the OPD due to

misalignment and environmental disturbances were eliminated. Clear, sharp interference fringes were successfully generated with the Newton's Ring setup subsequently, yielding smaller, finer machining features.

7.8 CONCLUDING REMARKS

A Newton's Ring interferometer setup was integrated into the experimental setup to successfully generate sharp, stable circular interference fringes. Machining was undertaken on both gold and platinum substrates with the central bright fringe of the interfered laser beam and the ablation features obtained using the interference beam were compared with the features ablated with the direct laser beam.

For both the gold and platinum specimen, a 350nm (0.35 μ m) feature was obtained by using the interfered laser beam compared to a 1 μ m feature using the direct laser beam at the same laser fluence. The ratio of the feature size ablated with the interfered beam compared to the feature size ablated with the direct beam is 0.35 or a 65% reduction in feature size.

The diffraction limited focused spot size diameter for the interfered beam (central bright fringe) is found to be slightly larger compared with the direct beam. For both the gold and platinum substrates, a focal spot size of 14.1 μ m is calculated for the interfered beam against a focal spot size of 10 μ m for the direct beam.

However, a smaller ablation feature was obtained with the interfered beam compared to the direct beam. For both the gold and platinum specimen, a 350nm (0.35 μ m) feature was obtained by using the interfered laser beam compared to a 1 μ m feature using the direct laser beam at the same laser fluence. These features are concluded to be ablated at the breakdown threshold fluence of the material machined as they are the smallest ablated features obtained.

The reduction in size of the features ablated with the interference beam is because of the sharper beam profile of the central bright fringe of the interference beam

compared to the Gaussian beam profile of the direct laser beam. From curve fitting, the central bright fringe of the interference beam was found to follow a Beta distribution. Using MATLAB to plot the intensity profile (Figure 7.3), it is evident that the profile of the central bright fringe of the interference beam is significantly sharper compared to the Gaussian direct laser beam, resulting in the ablation of smaller, finer features. From the MATLAB data, the central bright fringe diameter was also determined to be 1.8mm at $1/e^2$.

In this research work, the beam diameter investigated for both the direct and interfered beam (full beam) is 16mm. However, for the investigations with the interfered beam, only the central bright fringe is used for ablation. Therefore, the effective beam diameter for the interfered beam is 1.8mm (diameter of the central bright fringe) compared to the effective beam diameter of 16mm for the direct beam. In order to obtain a clearer understanding, it is proposed that a central bright fringe of diameter the same with the diameter of the direct beam is investigated for future works. This will enable a better comparison and correlation of the different beam profile and the resultant ablation feature size.

By comparing the results obtained with the Newton's Ring interferometer setup with the results obtained with the Mach-Zehnder interferometer setup, it was found that a further decrement in feature size of 40% was achieved with the Newton's Ring setup.

In addition, the problem of the interference beam pattern instability inherent in the Mach-Zehnder interferometer setup has been minimised with the Newton's Ring setup. With its simple, common path configuration, fluctuation in the OPD due to misalignment and environmental disturbances were eliminated yielding clear, sharp interference fringes.

However, the results still fall short of the objective of this research work which is to obtain ablation features of 200nm and below. Therefore, further improvement to the experimental setup has to be done.

In order to acquire finer machining features, a machining beam with a sharper intensity profile must be used. Therefore, an interference beam with finer, sharper

interference fringes has to be applied. It is also desirable to obtain interference fringes which are spaced further apart from each other (Figure 7.11b).

This is to facilitate the isolation of the central bright fringe for machining. If the fringes are spaced very close together, it will be difficult to isolate the central peak fringe from the 2nd order and subsequent order fringes.

Also, with finer, sharper fringes, it will be possible to achieve ablation features of higher aspect ratios and smaller tapers as demonstrated in Figure 7.11b.

Figure 7.11: a) Beam profile of presently used interference fringe.
b) Beam profile of desired interference fringe.

Therefore, in order to obtain even smaller ablation features with the femtosecond laser, the next challenge is to achieve an interference beam with finer, sharper and more defined interference fringes.

CHAPTER 8

MULTIPLE INTERFERENCE SETUP

8.1 INTRODUCTION

As mentioned in Section 7.8, in order to obtain finer ablation features, a machining beam with a sharper profile must be used. Therefore, an interference beam with finer, sharper interference fringes must be obtained. To achieve this, multiple interference of the femtosecond laser beam is proposed.

With multiple interference, the intensity at the minima decreases and the bright fringes will subsequently become sharper and narrower. Hence, very narrow and sharp, bright fringes on a dark background can be obtained (Figure 8.2). An account on the principles of multiple interference is detailed in Section 3.7.

The Fabry-Perot interferometer is the most commonly used interferometer for the generation of multiple interference in lasers. The interferometer consists of two planar, parallel and highly reflective surfaces separated by a gap of distance, d . Light entering by way of the partially silvered plate is multiply reflected within the gap, resulting in multiple interference of the light.

Figure 8.1: The 2-beam interference beam profile.

Figure 8.2: The multiple interference beam profile.

8.2 A FABRY-PEROT ETALON FOR THE GENERATION OF MULTIPLE INTERFERENCE ON THE FEMTOSECOND PULSE LASER

A Fabry-Perot etalon (refer to Section 3.8 for further literature on the Fabry-Perot etalon) is used to generate multiple interference on the femtosecond pulse laser. However, commercially available Fabry-Perot etalons are not suited for use on the femtosecond pulse laser used in this research work because of several reasons. The short coherence length of the laser of $45\mu\text{m}$ (from Equation 5.1) requires the gap between the two reflecting surfaces to be kept very small ($\leq 5\mu\text{m}$) to allow for multiple reflections and subsequently, multiple interference of the laser light to occur in the etalon. However, the typical gap thickness of commercially available etalons are from $25\mu\text{m}$ to 10mm for air spaced etalons and $250\mu\text{m}$ to 15mm for solid etalons [64]. Furthermore, special coating techniques must be employed for the metallic/dielectric reflective coating and special grade of optical glass must be used to ensure that they are resistant to the high energy damage typical of femtosecond pulse lasers.

Therefore, an air-spaced Fabry-Perot etalon with an air gap thickness of $5\mu\text{m}$ and a reflectance, R of 80% was custom fabricated by CVI Laser Corporation for use on the femtosecond pulse laser. The specifications of the etalon are as listed in Table 8.1:

Table 8.1: Specifications of the Fabry-Perot etalon from CVI Laser.

Substrate material	BK7 fused silica
Air gap thickness	$5\mu\text{m}$
Reflectance	0.8 (80%)
Centre wavelength	400nm
Clear aperture diameter	20mm
Reflecting coating	ZrO ₂ and SiO ₂ multilayer dielectric

8.3 THEORETICAL CALCULATIONS AND ANALYSIS ON THE FABRY-PEROT ETALON

From Equation 3.41, the intensity of the transmitted interference beam can be rewritten as:

$$\text{Transmitted intensity, } I_t = \frac{I_0}{1 + \Phi \sin^2\left(\frac{\delta}{2}\right)} \quad \text{Equation 8.1}$$

where I_0 = incident light intensity

with the coefficient of finesse, Φ is calculated to be,

$$\begin{aligned} \Phi &= \frac{4R}{(1 - R)^2} \\ &= \frac{4(0.8)}{0.2^2} = 80 \end{aligned} \quad \text{Equation 8.2}$$

where R = reflectivity (as a fraction of unity)

and the phase difference, δ at transmission peak is,

$$\delta = \frac{4\pi}{\lambda} n d \cos\theta = 2\pi m \quad \text{Equation 8.3}$$

where λ = wavelength of laser (free space)
 n = refractive index of cavity (1 in the case of air gap etalon)
 d = gap distance
 θ = angle of incidence of light in the etalon
 m = order number

However, the above intensity term applies only in ideal cases. From the interference beam generated on the femtosecond pulse laser, it can be seen that there is a gradual intensity falloff moving radially away from the centre of the interference pattern. This is attributed to the finite aperture size on the etalon where constructive interference

that would take many reflections inside the etalon was cut off by the edge of the apparatus.

Using a beam analyser (BeamScopeTM from DataRay Inc), it was ascertained that the interfered beam takes on a Gaussian profile. This is supported by Davies et al. [115] where they ascertained that the Fabry-Perot intensity profile takes on a Voigt profile. The Voigt profile is essentially Gaussian from the peak out to about three full widths at half height from the peak. Hence, in this research study, it may be considered a Gaussian profile as only the upper part (>0.8 of peak) of the profile is of particular interest.

Therefore, the interference intensity function in Equation 8.1 can be rewritten by merging with the Gaussian distribution function to obtain the interference intensity distribution term in Equation 8.4.

$$\text{Transmitted intensity, } I_t = \frac{I_0}{1 + \Phi \sin^2\left(\frac{\delta}{2}\right)} \cdot \exp\left(-\frac{2r^2}{w_0^2}\right) \quad \text{Equation 8.4}$$

8.4 MATLAB[®] VISUALISATION AND ANALYSIS

Using MATLAB[®], the multiple interference beam function (Equation 8.4) is plotted against the Gaussian beam function (Equation 7.3) for an incident beam diameter of 16mm. The 2D (Figure 8.3) and 3D (Figure 8.4) plot generated shows that the interference fringes of the multiple interference beam are significantly sharper and finer compared to those obtained with the Newton's Ring interferometer setup in Figure 7.3.

As can be seen from the plots, only the first order and second order fringe is contained in the interference beam envelope of the multiple interference beam generated with the Fabry-Perot etalon in this research work. This is because, for a narrow source (such as a laser source), the narrow beam will illuminate only a section of the fringe

pattern depending on where the beam falls in relation to the ‘fringes’ determined by the interferometer as explained in Section 3.8.1. If the laser source lies on the optic axis as in this case, the beam will automatically illuminate only the central part of the fringe pattern generated [84].

Figure 8.3: The intensity profile plot of the multiple interference beam profile against the direct laser beam profile.

By comparing the profile of the central bright fringe of the interfered beam with the profile of the direct laser beam from the Figure 8.3, it can be seen that the profile of the central bright fringe of the interfered beam is much sharper than the Gaussian profile of the direct laser beam. By using the sharper profiled central bright fringe of the interfered laser beam over the direct laser beam to machine, it is expected that the ablation spot size will be reduced significantly.

Figure 8.4: The MATLAB® 3D intensity profile plot of the Newton's Ring interference beam over the direct laser beam.

8.5 MODELLING AND CURVE FITTING OF THE CENTRAL BRIGHT FRINGE

The central bright fringe of the interfered beam is not a Gaussian profile beam. Therefore, the new intensity profile and the associated distribution function of the central bright fringe have to be determined. In order to do that, graph data modelling and curve fitting were applied.

Firstly, the central bright fringe of the interfered beam is calculated and then plotted. Using the TableCurve 2D software by Systat Software Inc, the data obtained from the calculations were modelled, and the graph obtained was then curve-fitted (Figure 8.5).

Figure 8.5: Curve-fitting of the central bright fringe of the Fabry-Perot multiple interference beam using TableCurve 2D.

The central bright fringe of the multiple interference beam was found to follow a Gaussian-Lorentzian XP distribution with a function of:

$$y = \frac{a}{\left[1 + d\left(\frac{x-b}{c}\right)^2\right] \exp\left[\frac{1-d}{b}\left(\frac{x-b}{c}\right)^2\right]} \quad \text{Equation 8.5}$$

From the curve-fitting data, the variables were ascertained to be:

$$a = 1$$

$$b = -2.4\text{e-}24$$

$$c = 0.224$$

$$d = 1$$

Therefore, Equation 8.5 can be rewritten as:

$$y = \frac{1}{\left[1 + \left(\frac{x + 2.4e - 24}{0.224}\right)^2\right]} \quad \text{Equation 8.6}$$

For the verification of the curve-fitted distribution function, MATLAB was used to plot the Equation 8.6 (Figure 8.6).

Figure 8.6: The intensity profile plot of the central bright fringe of the Fabry-Perot multiple interference beam from Equation 8.6.

From the MATLAB data, the central bright fringe diameter was determined to be 1.5mm at $1/e^2$.

8.6 EXPERIMENTAL SETUP AND RESULTS

In order to generate multiple interference on the femtosecond pulse laser, an air-spaced Fabry-Perot etalon (refer to Table 8.1 for full specifications) is integrated into the laser setup as shown in Figure 8.7.

The laser beam emitted from the femtosecond pulse laser system at the compressor module is 4mm in diameter. A Keplerian beam expander with two lenses of focal length, $f_1 = 50\text{mm}$ and $f_2 = 200\text{mm}$ with diameter of 25.4mm and positioned with their focal points nominally coincident is integrated into the experimental setup in order to expand the laser beam. The 4X effective magnification yields a collimated beam of 16mm. The purpose of expanding the laser beam is to reduce the effects of beam diffraction to obtain a smaller focussing spot (the focal spot size is inversely proportional to the diameter of the laser beam as shown in the diffraction limited spot size formula in Equation 4.11). However, the expansion of the beam is limited by the size of the lenses used. As the clear aperture of the lenses used in this experimental setup is 25.4mm (exception of the clear aperture of the telecentric scan lens of 34mm), a beam diameter of 16mm is determined to prevent beam clipping/truncation and to ensure that diffraction effects are negligible. A spatial filter is also included to filter out spatial noises and to improve beam quality and concentricity.

The collimated beam is passed through the Fabry-Perot etalon to achieve multiple interference of the beam. As only the first order and second order fringe is contained in the interference beam envelope of the multiple interference beam and the two fringes are spaced far apart from each other (Figure 8.3), there is no need for a diaphragm for the isolation of the central bright fringe. This is because at threshold, only a portion of the central bright fringe will exceed the threshold fluence and is utilised for machining. The second order fringe which is spaced far to the low intensity of the beam envelope can be safely assumed to not partake in the machining process as its energy is too low. The central bright fringe of the interference beam is then scanned across the stationary workpiece using the acousto-optic deflector (AOD) and telecentric scan lens setup.

Figure 8.7: The experimental setup integrated with the Fabry-Perot etalon.

The number of pulses to hit the target is set at 100 pulses per scan point. Machining is started from low lasing energy before ablation is initiated. The average laser energy (averaged over 1000 consecutive pulses) is measured using a pyroelectric detector (Ophir PD10) connected to an energy meter placed right after the telecentric lens and before the beam is focused to hit upon the substrate located at the focal point of the beam.

Laser energy is increased gradually by increasing the energy by small increments of 0.1 nJ at a time until the breakdown threshold is traversed and ablation commences. For every increase in the pulse energy from the laser source, the pulse energy right after the telecentric lens is recorded using the energy meter. Breakdown is determined when the laser light penetrates through the metallic thin film coated fused silica glass substrate (a CCD camera is placed behind the specimen to observe this phenomenon) indicating that ablation has been initiated and material has been removed. In addition, when breakdown occurs, plasma emission will take place and a spark will be observed in the darkened room. This is identified as the material breakdown threshold point and the laser energy measured at this point is the breakdown threshold energy of the material.

The experiment above is repeated by removing the Fabry-Perot etalon from the setup and using the direct laser beam to machine. The features obtained from both setup configurations are then compared. The thin film substrate is removed and the experiment is repeated with a thin film substrate of another material.

Figure 8.8 is the AFM analysis of the smallest ablation feature achieved on a 100nm thick gold film using the central bright fringe of the multiple interference beam to machine while Figure 8.9 is the smallest feature obtained using the direct laser beam. The pulse energy recorded is 4nJ for the feature obtained with the interfered beam and 59nJ for the feature obtained with the direct laser beam.

Figure 8.10 is the AFM analysis of the smallest ablation feature achieved on a 100nm thick platinum film using the central bright fringe of the multiple interference beam while Figure 8.11 is the smallest feature obtained using the direct laser beam. The pulse energy recorded is 5nJ for the feature obtained with the interfered beam and 59nJ for the feature obtained with the direct laser beam.

Figure 8.8: AFM analysis of the 105nm feature ablated on a 100nm gold thin film using the central bright fringe of the multiple interference beam (Pulse energy: 4nJ).

Figure 8.9: AFM analysis of the 938nm feature ablated on a 100nm gold thin film using the direct laser beam (Pulse energy: 59nJ).

Figure 8.10: AFM analysis of the 169nm feature ablated on a 100nm platinum thin film using the central bright fringe of the multiple interference beam (Pulse energy: 5nJ).

Figure 8.11: AFM analysis of the 1055nm feature ablated on a 100nm platinum thin film using the direct laser beam (Pulse energy: 59nJ).

On the gold specimen, a 105nm feature was obtained using the multiple interfered laser beam compared to a 938nm feature using the direct laser beam. As both features are the smallest features obtained for the respective beams, it is concluded that they are ablated at the laser fluence of $158\text{mJ}/\text{cm}^2$ (the breakdown threshold fluence of gold). The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.1125, or an almost 89% decrement in feature size.

On the platinum specimen, a 169nm feature was obtained using the multiple interfered laser beam compared to a 1055nm feature using the direct laser beam. As both features are the smallest features obtained for the respective beams, it is concluded that they are ablated at the laser fluence of $132\text{mJ}/\text{cm}^2$ (the breakdown threshold fluence of platinum). The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.1601, or an almost 84% decrement in feature size.

The reduction in size of the features ablated with the interference beam is because of the sharper beam profile of the central bright fringe of the interference beam compared to the Gaussian beam profile of the direct laser beam. From the MATLAB intensity profile plot in Figure 8.3, it is evident that the profile of the central bright fringe of the interference beam is significantly sharper compared to the Gaussian direct laser beam. From curve fitting, the central bright fringe of the interference beam was found to follow a Gaussian-Lorentzian XP distribution.

It was observed that for both the gold and platinum substrates, small periodic features are evident around the area of ablation. These very small features are especially noticeable in the zoomed in pictures of Figure 8.6 and Figure 8.8. These periodic features of approximately 50 to 200nm are smaller than the wavelength of the laser light used ($\lambda = 400\text{nm}$). A possible explanation for this occurrence may be a self-organization structure formation during the relaxation of the highly non-equilibrium surface of the area around the ablation spot as reported by Kautek et al [152]. During machining, the area around the ablation feature is also irradiated by the laser beam. However, because the section of the laser beam at these areas has not reached the

ablation threshold of the material, ablation therefore was not initiated. According to Kautek, without ablation, i.e. without bond-breaking, the energy from the irradiation can cause rapid excitation of the electrons resulting in massive instability in the crystal lattice within a few 10fs due to a perturbation of the interatomic bonds. Therefore, below the threshold fluence but above a modification threshold, this instability then relaxes on a several 100fs time scale by surface reorganization in regular, periodic structures.

These small periodic features were found to depend strongly on the chemical composition of the material ablated. Therefore, laser-material interaction for the different types of material and at different laser fluences should be investigated in detail in order to understand better the mechanism of these ripples formation.

8.7 VERIFICATION OF THE THRESHOLD ENERGY

In order to verify that the smallest ablation feature obtained is indeed machined at the threshold, the threshold energy recorded during machining using the energy meter is compared to the theoretical threshold energy.

For the gold specimen, the threshold energy recorded for the 105nm feature ablated with the multiple interfered beam is 4nJ while the threshold energy recorded for the 938nm feature ablated with the direct laser beam is 59nJ.

From theoretical calculations, with the central bright fringe of the interfered beam, the diffraction limited focused spot size diameter at $1/e^2$, d (Equation 4.13) is calculated to be:

$$\begin{aligned}
 d &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \\
 &= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 1.5} + \frac{0.043 \times 1.5^3}{2 \times 100^2} = 17 \mu m
 \end{aligned}
 \tag{Equation 8.7}$$

with the diameter of the central bright fringe, $D = 1.5\text{mm}$ and k (function of the index of refraction) = 0.043 as given by the lens manufacturer at $\lambda = 400\text{nm}$

Because the threshold fluence of femtosecond laser can be precisely determined (Section 2.5), it is possible to control that only a small portion of the focused spot size exceeds the ablation threshold therefore enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the interfered beam of 105nm (Figure 8.8) is concluded to be ablated at the laser fluence of 158 mJ/cm² (the breakdown threshold fluence of gold). Therefore,

Spot size diameter at threshold, $d_{th} = 105nm = 1.05 \times 10^{-5} cm$

$$\begin{aligned} \text{Spot area at threshold, } a &= \pi r_{th}^2 = 3.142 \times 0.525^2 \times 10^{-10} cm^2 \\ &= 8.66 \times 10^{-11} cm^2 \end{aligned} \quad \text{Equation 8.8}$$

$$\begin{aligned} \text{Energy at threshold, } E(r) &= 158 mJ/cm^2 \times 8.66 \times 10^{-11} cm^2 \\ &= 1.368 \times 10^{-8} mJ = 0.0137 nJ \end{aligned} \quad \text{Equation 8.9}$$

Assuming the interference intensity distribution profile in Equation 8.4, the total pulse energy, $E(\infty)$ can be calculated as:

$$\begin{aligned} E(\infty) &= \frac{E(r)}{\left[1 - \frac{1}{1 + \left(\frac{r_{th} + 2.4e - 24}{0.224} \right)^2} \right]} \\ &= \frac{0.0137 nJ}{\left[1 - \frac{1}{1 + \left(\frac{0.0525 + 2.4e - 24}{0.224} \right)^2} \right]} = 0.263 nJ \end{aligned} \quad \text{Equation 8.10}$$

Total pulse energy, $E(\infty) = 0.263 nJ$ at $1/e^2$

For the feature ablated with the direct laser beam, the focused beam spot size diameter at $1/e^2$, d can be calculated as:

$$\begin{aligned} d &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \\ &= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 16} + \frac{0.043 \times 16^3}{2 \times 100^2} = 10 \mu\text{m} \end{aligned} \quad \text{Equation 8.11}$$

For femtosecond lasers, the threshold fluence can be precisely determined. Therefore, it is possible to control that only a small portion of the focused spot size exceeds the ablation threshold thus enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the direct beam of 938nm (Figure 8.9) is concluded to be ablated at the laser fluence of 158 mJ/cm^2 (the breakdown threshold fluence of gold). Therefore,

Spot size diameter at threshold, $d_{th} = 938 \text{ nm} = 0.938 \times 10^{-4} \text{ cm}$

$$\begin{aligned} \text{Spot area at threshold, } a &= \pi r_{th}^2 = 3.142 \times 0.47^2 \times 10^{-8} \text{ cm}^2 \\ &= 6.91 \times 10^{-9} \text{ cm}^2 \end{aligned} \quad \text{Equation 8.12}$$

$$\begin{aligned} \text{Energy at threshold, } E(r) &= 158 \text{ mJ/cm}^2 \times 6.91 \times 10^{-9} \text{ cm}^2 \\ &= 1.09 \times 10^{-6} \text{ mJ} = 1.09 \text{ nJ} \end{aligned} \quad \text{Equation 8.13}$$

Assuming a Gaussian intensity profile, the total pulse energy, $E(\infty)$ can be calculated as:

$$E(r) = E(\infty) \left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right] \quad \text{Equation 8.14}$$

$$\begin{aligned} E(\infty) &= \frac{E(r)}{\left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right]} = \frac{1.09nJ}{\left[1 - \exp\left(-\frac{2 \times 0.469^2 \mu m^2}{5^2 \mu m^2}\right) \right]} \\ &= 62.49nJ \end{aligned}$$

Total pulse energy, $E(\infty) = 62.49nJ$ at $1/e^2$

For the platinum specimen, the threshold energy recorded for the 169nm feature ablated with the multiple interfered beam is 5nJ while the threshold energy recorded for the 1055nm feature ablated with the direct laser beam is 59nJ.

From theoretical calculations, for the feature ablated with the multiple interfered beam, the focused beam spot size diameter at $1/e^2$, d can be calculated as:

$$\begin{aligned} d &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \\ &= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 1.5} + \frac{0.043 \times 1.5^3}{2 \times 100^2} = 17 \mu m \end{aligned} \quad \text{Equation 8.15}$$

Because the threshold fluence of femtosecond laser can be precisely determined, it is possible to control that only a small portion of the focused spot size exceeds the ablation threshold therefore enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the interfered beam of 169nm (Figure 8.10) is concluded to be ablated at the laser fluence of 132 mJ/cm² (the breakdown threshold fluence of platinum). Therefore,

Spot size diameter at threshold, $d_{th} = 169nm = 1.69 \times 10^{-5} cm$

$$\begin{aligned} \text{Spot area at threshold, } a &= \pi r_{th}^2 = 3.142 \times 0.845^2 \times 10^{-10} \text{ cm}^2 \\ &= 2.24 \times 10^{-10} \text{ cm}^2 \end{aligned} \quad \text{Equation 8.16}$$

$$\begin{aligned} \text{Energy at threshold, } E(r) &= 132 \text{ mJ/cm}^2 \times 2.24 \times 10^{-10} \text{ cm}^2 \\ &= 2.957 \times 10^{-8} \text{ mJ} = 0.0296 \text{ nJ} \end{aligned} \quad \text{Equation 8.17}$$

Total pulse energy, $E(\infty)$

$$\begin{aligned} E(\infty) &= \frac{E(r)}{\left[1 - \frac{1}{1 + \left(\frac{r_{th} + 2.4e - 24}{0.224} \right)^2} \right]} \\ &= \frac{0.0296 \text{ nJ}}{\left[1 - \frac{1}{1 + \left(\frac{0.0845 + 2.4e - 24}{0.224} \right)^2} \right]} = 0.238 \text{ nJ} \end{aligned} \quad \text{Equation 8.18}$$

Total pulse energy, $E(\infty) = 0.238 \text{ nJ}$ at $1/e^2$

For the feature ablated with the direct laser beam, the focused beam spot size diameter at $1/e^2$, d can be calculated as:

$$\begin{aligned} d &= \frac{2\lambda f}{\pi D} + \frac{kD^3}{2f^2} \\ &= \frac{2 \times 400 \times 10^{-6} \times 100}{\pi \times 16} + \frac{0.043 \times 16^3}{2 \times 100^2} = 10 \mu\text{m} \end{aligned} \quad \text{Equation 8.19}$$

For femtosecond lasers, the threshold fluence can be precisely determined. Therefore, it is possible to control that only a small portion of the focused spot size exceeds the

ablation threshold thus enabling the ablation of features substantially smaller than the diffraction limited focused spot size.

The smallest feature ablated with the direct beam of 1055nm (Figure 8.11) is concluded to be ablated at the laser fluence of 132 mJ/cm² (the breakdown threshold fluence of platinum). Therefore,

Spot size diameter at threshold, $d_{th} = 1055nm = 1.055 \times 10^{-4} cm$

$$\begin{aligned} \text{Spot area at threshold, } a &= \pi r_{th}^2 = 3.142 \times 0.5275^2 \times 10^{-8} cm^2 \\ &= 8.74 \times 10^{-9} cm^2 \end{aligned} \quad \text{Equation 8.20}$$

$$\begin{aligned} \text{Energy at threshold, } E(r) &= 132 mJ/cm^2 \times 8.74 \times 10^{-9} cm^2 \\ &= 1.154 \times 10^{-6} mJ = 1.154 nJ \end{aligned} \quad \text{Equation 8.21}$$

Total pulse energy, $E(\infty)$

$$\begin{aligned} E(r) &= E(\infty) \left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right] \\ E(\infty) &= \frac{E(r)}{\left[1 - \exp\left(-\frac{2r_{th}^2}{r^2}\right) \right]} = \frac{1.154 nJ}{\left[1 - \exp\left(-\frac{2 \times 0.5275^2 \mu m^2}{5^2 \mu m^2}\right) \right]} \\ &= 52.42 nJ \end{aligned} \quad \text{Equation 8.22}$$

Total pulse energy, $E(\infty) = 52.42 nJ$ at $1/e^2$

For the gold specimen, from theoretical calculations, the threshold energy computed for the 105nm feature ablated with the interfered beam is 0.263nJ while the threshold energy computed for the 938nm feature ablated with the direct laser is 62.49nJ. These numbers are compared to the 4nJ threshold energy recorded during the experiment for

the 105nm feature ablated with the interfered beam and 59nJ threshold energy recorded during the experiment for the 938nm feature ablated with the direct laser beam.

For the platinum specimen, the threshold energy computed theoretically for the 169nm feature ablated with the interfered beam is 0.238nJ while the threshold energy computed for the 1055nm feature ablated with the direct laser is 52.42nJ. These numbers are compared to the 5nJ threshold energy recorded during the experiment for the 169nm feature ablated with the interfered beam and 59nJ threshold energy recorded during the experiment for the 1055nm feature ablated with the direct laser beam.

It was found that the threshold energy recorded during the experimental work correlates well with the calculated threshold energy. The slight difference in results of 3 to 6nJ could be attributed to energy losses due to reflection at the highly reflective surface of the metallic substrate.

8.8 COMPARISON BETWEEN THE FABRY PEROT ETALON SETUP AND THE NEWTON'S RING SETUP

With the Newton's Ring interferometer setup, 350nm features were obtained on both the gold and platinum specimens by using the central bright fringe of the interfered laser beam to machine compared to the 1µm features using the direct laser beam. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.35.

Meanwhile, with the Fabry-Perot etalon setup, a 105nm feature was obtained on the gold specimen using the central bright fringe of the multiple interference laser beam to machine compared to a 938nm feature using the direct laser beam while for the platinum specimen, a 169nm feature was obtained using the multiple interfered laser beam compared to a 1055nm feature with the direct laser beam. This translates to a ratio of the ablated feature size using the interfered beam to the ablated feature size

using the direct beam diameter of 0.1125 for the gold specimen, and 0.1601 for the platinum specimen.

To summarise the above, by using the central bright fringe of the Fabry-Perot multiple interference beam to machine compared to the Newton's Ring interference beam, a further decrement in feature size of at least 50% can be achieved. This is due to the change of the central bright fringe profile from the Beta distribution profile of the Newton's Ring beam to the sharper Gaussian-Lorentzian XP distribution profile of the multiple interference beam.

This can be seen more clearly in the MATLAB® intensity profile plot of the central bright fringe of the multiple interference beam over the Newton's Ring interference beam in Figure 8.12.

Figure 8.12: The MATLAB® 2D intensity profile plot of the central bright fringe of the Newton's Ring interference beam vs. the multiple interference beam.

From the plot above, it is clearly illustrated that the Gaussian-Lorentzian XP distribution profile of the central bright fringe of the multiple interference beam is much sharper compared to the Beta distribution profile of the central bright fringe of the Newton's Ring interference beam. Subsequently, the sharper beam profile resulted in smaller, finer ablation capabilities.

Therefore, to conclude, with the utilisation of the central bright fringe of the multiple interference laser beam to machine, ablation features down to 100nm or an almost 89% decrement in feature size was successfully demonstrated on the femtosecond pulse laser system.

8.9 CONCLUDING REMARKS

A Fabry-Perot etalon setup is integrated into the experimental setup to generate circular interference fringes with very sharp and fine bright fringes. Machining was performed on both gold and platinum substrates and the ablation features obtained using the central bright fringe of the multiple interference beam were compared with the features ablated with the direct laser beam.

On the gold specimen, a 105nm feature was ablated using the central bright fringe of the multiple interference beam compared to a 938nm feature using the direct laser beam at the same laser fluence. The size ratio of the feature ablated with the interfered beam to the feature ablated with the direct laser beam is 0.11, or an almost 89% decrement in feature size.

On the platinum specimen, a 169nm feature was ablated using the central bright fringe of the multiple interference beam compared to a 1055nm feature using the direct laser beam at same laser fluence. The size ratio of the feature ablated with the interfered beam to the feature ablated using the direct beam diameter is 0.16, or an almost 84% decrement in feature size.

The diffraction limited focused spot size diameter for the interfered beam (central bright fringe) is found to be slightly larger compared with the direct beam. For both

the gold and platinum substrates, a focal spot size of $17\mu\text{m}$ is calculated for the interfered beam against a focal spot size of $10\mu\text{m}$ for the direct beam.

However, a smaller ablation feature was obtained with the interfered beam compared to the direct beam. For the gold specimen, a 105nm feature was obtained by using the interfered laser beam compared to a 938nm feature using the direct laser beam at the same laser fluence. And for the platinum specimen, a 169nm feature was obtained by using the interfered laser beam compared to a 1055nm feature using the direct laser beam at the same laser fluence. These features are concluded to be ablated at the breakdown threshold fluence of the material machined as they are the smallest ablated features obtained.

The reduction in size of the features ablated with the interference beam is because of the sharper beam profile of the central bright fringe of the interference beam compared to the Gaussian beam profile of the direct laser beam. From curve fitting, the central bright fringe of the interference beam was found to follow a Gaussian-Lorentzian XP distribution. Using MATLAB to plot the intensity profile (Figure 8.3), it is evident that the profile of the central bright fringe of the interference beam is significantly sharper compared to the Gaussian direct laser beam. From the MATLAB data, the central bright fringe diameter was also determined to be 1.5mm at $1/e^2$.

In this research work, the beam diameter investigated for both the direct and interfered beam (full beam) is 16mm . However, for the investigations with the interfered beam, only the central bright fringe is used for ablation. Therefore, the effective beam diameter for the interfered beam is 1.5mm (diameter of the central bright fringe) compared to the effective beam diameter of 16mm for the direct beam. In order to obtain a clearer understanding, it is proposed that a central bright fringe of diameter the same with the diameter of the direct beam is investigated for future works. This will enable a better comparison and correlation of the different beam profile and the resultant ablation feature size.

Lastly, when the results obtained with the Fabry-Perot interferometer setup and the results obtained with the Newton's Ring interferometer setup were compared, it was

found that a further decrement in feature size of at least 50% can be achieved with the Fabry-Perot interferometer setup. Therefore, it can be concluded that the multiple interference of the femtosecond laser beam gives the best submicromachining capabilities on the femtosecond pulse laser system, demonstrating that the machining of features down to 100nm or an almost 89% decrement in feature size is achievable.

CHAPTER 9

SIGNIFICANCE OF WORK AND COMPARISON WITH OTHER NANOFABRICATION TECHNOLOGIES

9.1 INTRODUCTION

The continuing trend towards miniaturisation has increased the need for new micromachining technologies capable of machining into the sub-micrometer ranges. Microengineered devices and systems are being applied to an increasing range of applications in the automotive, aerospace, micro-electro-mechanical systems (MEMS), telecommunications, biotechnology and biomedical/pharmaceutical industries. In fact, miniaturisation could truly be one of the strategic innovations fuelling industrial development in the next century. According to the Japanese Micromachine Center Roadmap, the total market size for micromachining technology will be between 40 and 50 US dollar billions by year 2015.

The future of miniaturisation and nanotechnology are intimately tied together. The smallest feature sizes on today's ICs are already falling below 50nm. The International Technology Roadmap for Semiconductors projects that in 15 years the smallest feature size will be <10nm [116].

9.2 CURRENT NANOFABRICATION TECHNOLOGIES

Current nanofabrication technologies that can machine in the sub-micron region include lithography, ultrafast pulse laser ablation, near-field laser machining, focused ion beam (FIB) milling and electron beam machining.

9.2.1 Lithography Method

Lithography can be grouped into two conventional techniques: projection lithography and scanning beam (or maskless) lithography. The most common type of projection lithography is photolithography.

9.2.1.1 Photolithography Method

Currently, the most advanced photolithographic tools used in high volume manufacturing employs deep-ultraviolet (DUV) radiation with a wavelength of 248 nm to print features that have line widths as small as 200 nm. However, by using short wavelengths (down to 157 nm), reduction optics between the mask and substrate, phase shifting corrections to intensity and immersion optics, feature size of approximately 50 nm has been reported [117], although this is still not optimized for high volume manufacturing environment.

Unfortunately, there are limits to the smallest feature size that is possible with photolithography. That's because the light that is used to pass through the mask has a fundamental restriction known as the 'diffraction limit of light'. While it is possible to create lithographic machines that can go smaller (e.g. by employing shorter wavelength light in the extreme UV), prohibitive costs are preventing all but the most powerful chipmakers to pursue the research.

9.2.1.2 Scanning Beam Lithography Method

Scanning beam lithographic techniques, such as electron beam and focused ion beam lithography, offer alternative approaches to patterning small features. These systems do not require a mask. Such methods are known as Direct Write to Wafer methods (DWW). These techniques are, however, slower than the parallel approach of projection lithography. A pattern is carved out line-by-line by scanning a high-energy beam of electrons or ions over a resist material.

The resolution of electron beam lithography is limited by high-energy secondary electrons and by scattering of electrons from the primary beam within the resist and from the substrate. Typical e-beam writing minimum feature size is approximately 20 nm although features down to 10 nm have been reported [118] while a 5 nm feature [119] has been reported with focused ion beam (FIB) lithography method.

Nanolithography has also been performed using scanning near-field optical lithography (SNOL). The fiber optic probe is used as a light source to expose a photoresist, and patterns are generated by scanning the probe over the resist surface. This technique is not diffraction limited and is only limited by the aperture size of the probe. To date, 50nm lines [127] have been patterned using a phase mask and 70nm lines [128] using an amplitude mask.

A number of new, unconventional lithography methods are also being developed for nanofabrication including soft lithography, scanning probe lithography (SPL) and edge lithography.

9.2.2 Focused Ion Beam (FIB) Milling

In the process of FIB milling, material is removed by the physical sputtering action of ion bombardment. The disruption of the crystalline lattice by the bombarding ion beams of high ion energies leads to a crystal-to-amorphous transformation [120], and ultimately to material removal by sputtering.

FIB milling has certain limitations to achieving a high aspect ratio, such as a redeposition effect and ion beam profile [121]. During milling, sputtered material is redeposited on the opposite wall of a trench producing undesirable profiles. A profile of a milled cavity will also depend on the ion beam profile, which is Gaussian with exponential tails. Nevertheless by modeling and controlling the FIB milling process, it is feasible to produce good quality micrometer and sub-micrometer size features. Also, because of its small spot size (10–500 nm) and slow material removal rate, it is a time consuming process and is therefore not recommended for the mass production of large structures.

Features down to 160nm [122,123] and 50nm [124] trenches have been reported with FIB milling.

9.2.3 Electron Beam Machining

In a vacuum chamber, a beam of high-velocity electrons is focused on a workpiece. The kinetic energy of the electrons, upon striking the workpiece, changes to heat, which vaporizes minute amounts of the material. The resolution of electron beam machining is limited by high-energy secondary electrons and by the scattering of electrons of the primary beam from the material machined.

Typical electron beam diameter ranges from 8nm to 1 μ m. A 56nm feature has been reported using direct electron beam writing [125,126].

9.2.4 Near-field Laser Micromachining

A femtosecond laser is used in combination with a scanning near-field optical microscope (SNOM) by coupling the femtosecond pulses into a fiber tip. This approach is not diffraction limited and is not limited by thermal effects. It allows the nanometer spatial resolution of the SNOM to be combined with the femtosecond temporal and is only limited by the aperture size of the probe. This technique also

allows material processing at atmospheric pressure. Features of 100nm were reported with this technique [5,6].

9.3 NEW PROPOSED NANOFABRICATION TECHNOLOGY USING PULSE LASER INTERFERENCE

A new micromachining technique utilizing the central bright fringe of a femtosecond laser interference beam is proposed. As described in Section 5.2, by interfering the laser beam to obtain circular interference fringes, and then employing the sharper profiled central bright fringe of the interference beam to machine, a smaller machining spot size can be achieved.

Currently, the smallest feature size obtained with conventional direct beam micromachining with ultrafast lasers is 200nm, or approximately 8% of the original laser spot size of 2.5μm [2,4]. With this proposed concept, ablation features of down to 100nm in diameter have been reported. With further development of this concept, features of below 100nm is achievable.

9.4 COMPARISON BETWEEN THE CURRENT NANOFABRICATION TECHNOLOGIES WITH PROPOSED LASER INTERFERENCE TECHNIQUE

Table 9.1 shows the respective smallest feature size reported for the various nanofabrication technologies in the market currently. The smallest feature reported is a 5nm feature using focused ion beam lithography method [119]. Other technologies yield feature size capabilities of between 50nm to 200nm.

Table 9.1: Machining capabilities of current nanofabrication technologies.

Nanofabrication Technology	Smallest Feature Size (nm)
Photolithography	50
Electron Beam Lithography	20
FIB Lithography	5
Near-field Lithography	50
Conventional Laser Ablation	200
Near-field Laser Machining	100
Electron Beam Machining	56
Focused Ion Beam (FIB) Milling	50

By comparing the 100nm feature size capability of the proposed femtosecond laser interference micromachining method with the current nanofabrication technologies in the market, the nanofabrication capability of the proposed technique is on level pegging with the other technologies.

Table 9.2 highlights the advantages and disadvantages of the respective nanofabrication technologies in comparison with the proposed femtosecond pulse laser interference micromachining technique in the shaded column.

Table 9.2: Advantages and disadvantages of the various nanofabrication technologies.

ATTRIBUTES	PROCESS					
	FIB	E-beam	Laser interference micro-machining	Near-field laser machining	Lithography	
					Photolithography	Scan beam lithography
Material	Wide range possible except for very hard & brittle material	Almost all materials	Almost all materials	Almost all materials	Generally wide range of metals and semiconductor	Generally wide range of metals and semiconductor
Cost	High set-up cost; expensive machine	High set-up cost, expensive machine	Low to moderate set-up cost; no tool wear	Moderate set-up cost; no tool wear	Low cost	Could be costly depending on beam system used
Resolution Limit	50nm	50nm	100nm	100nm	50nm	5nm
Taper	Insignificant	Insignificant	Yes	Yes	Yes	Yes
High Volume Production	Not economic	Possible but costly	Possible but slow	Possible but slow	Good	Possible but costly
Low Volume Production	Excellent	Excellent	Excellent	Excellent	Not economic	Good

Tooling	Moderate tooling cost	Low to moderate tooling cost	Low to moderate tooling cost	Low to moderate tooling cost	Low tooling cost	Moderate tooling cost
Maintenance	High	High	Low	Low	Low	High
Others	Low material removal rate, necessity of vacuum, use of hazardous gas	High energy consumption, necessity of vacuum, electron scattering	Diffraction limited	No diffraction limit	Diffraction limited, use of hazardous chemical/gas	Limited by high-energy secondary electrons and by scattering of electrons when beam hit resist and substrate

From Table 9.2, it can be seen that the proposed micromachining technique using femtosecond pulsed laser interference performed excellently in many aspects. It can achieve very small machining features of down to 100nm on almost all materials from very hard and brittle materials such as ceramics and even diamond, to delicate materials such as biological tissues. It can also machine both conductive and non-conductive materials, and it is a medium to low cost process with no tool wear and minimal maintenance.

It is a direct, single step process, unlike the lithographic method which requires numerous steps and processes. It is also able to perform selective material removal. By the proper selection of laser fluence, it can be controlled that only one type of material be removed without affecting the underlayers. This will be useful in processes such as wire stripping and skiving.

As the duration of the ultrafast pulse laser pulse is shorter than the heat diffusion time, energy does not have time to diffuse away. Therefore, the efficiency of the process is high and there are no thermal losses due to heat diffusion. As a result, there is minimal or no heat affected zone (HAZ) to the material machined and the process can be highly precise with good repeatability.

Lastly, as the process does not require a vacuum environment, material and machine handling is easy and fuss free. It is a relatively fast process compared with the FIB process and the scan beam lithography method. And as it does not use nor emit any toxic materials such as gases (FIB, electron beam) and chemicals (lithography), there is no requirement for extra handling cost such as toxic gas/chemical disposal issues. Once set up, the system requires minimal maintenance as it does not use consumables and there is no tool wear.

9.5 CONCLUDING REMARKS

Laser machining is fast becoming the preferred micromachining technology of tomorrow. In the emerging market for ultra precision laser technology with ever shrinking feature size requirement, the proposed micromachining technique utilising the central bright fringe of a femtosecond laser interference beam to machine, is one of the solutions for obtaining machining features of 200nm and below.

There are currently only a few micromachining technologies which can deliver machining capabilities of features size ranges of 200nm and below. These include lithography methods, near-field laser micromachining, focused ion beam (FIB) milling and electron beam machining. When compared with these technologies, the proposed femtosecond pulse laser interference micromachining technique is on level pegging feature size wise. However, the proposed technique scores because of its simplicity, versatility and cost effectiveness. With further development, this novel technique could very well become an important technology for tomorrow's nanofabrication industry.

Potential applications include the microdrilling of microvias for the printed circuit boards/ printed wire boards (PCB/PWB) and flex industries, microdrilling for microscale fluidic devices such as ink-jet printer nozzles and catheters for controlled drug delivery. It can also be used for minimally invasive surgery (MIS) based on tiny microdevices which can be inserted into patient blood vessels.

CHAPTER 10

CONCLUSION AND RECOMMENDATIONS

Referring to the objectives of this research work, it can be concluded that this research work is in line and supportive to the aims and goals of this project. A laser optical system and experimental setup has been developed to successfully generate femtosecond pulse laser interference for performing submicromachining. Machining features of down to an unprecedented 100nm have been demonstrated using the novel method of using the central bright fringe of an interfered laser beam to machine over the conventional method of using the direct laser beam to machine. This is within the stated objective of achieving machining features of 200nm and below.

Interference was successfully demonstrated on the femtosecond pulse laser using the Mach-Zehnder interferometry method, the Newton's Ring interferometry method and the Fabry Perot etalon method despite the limitation of the short OPD of 45 μ m. The interference beam generated with the Mach-Zehnder method was found to be unstable due to its relatively complex and large setup and was replaced with the Newton's Ring method. Because of its common path configuration, the fringes generated with the Newton's Ring setup are much sharper and stable. The Newton's Ring method was later replaced with the Fabry-Perot etalon method to generate multiple interference of the laser, producing interference fringes with sharp and well defined peaks.

Machining using 2 beam interference methods (Mach-Zehnder and Newton’s Ring interferometry setup) and multiple beam interference method (Fabry Perot etalon setup) were investigated. Results obtained through the experimental work were compared to the results obtained through theoretical calculations and MATLAB® analysis.

Table 10.1 summarizes the smallest feature size and feature size reduction obtained with the Mach-Zehnder, Newton’s Ring & Fabry-Perot interferometry techniques respectively.

Table 10.1: Smallest feature size obtained and feature size reduction for the respective interference techniques.

Interference technique	Smallest feature size	Reduction in size
Mach-Zehnder (Gold)	600nm	45.5%
Newton’s Ring (Gold)	350nm	65%
Newton’s Ring (Platinum)	350nm	65%
Fabry-Perot (Gold)	105nm	89%
Fabry Perot (Platinum)	169nm	84%

With the Mach-Zehnder setup, a 600nm feature was obtained using the central bright fringe of the interference beam to machine compared to a 1.1µm feature obtained with the direct laser beam at the same laser fluence. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.55, or a 45.5% reduction in feature size.

Meanwhile, with the Newton’s Ring setup, a 350nm feature was obtained by using the central bright fringe of the interference beam to machine compared to a 1µm feature using the direct laser beam at the same laser fluence for both the gold and platinum

specimen. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.35, or a 65% reduction in feature size.

When the results obtained with the Newton's Ring interferometer setup are compared to the Mach-Zehnder interferometer setup, it was found that a further reduction in feature size of at least 40% was achieved. In addition, the problem of the interference beam pattern instability inherent in the Mach-Zehnder interferometer setup has been solved with the Newton's Ring setup. With its common path configuration and simple setup, fluctuation in the OPD due to misalignment and environmental disturbances were eliminated. Clear, sharp interference fringes were successfully generated with the Newton's Ring setup yielding smaller, finer machining features.

With the Fabry-Perot etalon setup, a 105nm feature was achieved using the central bright fringe of the multiple interference beam to machine compared to a 938nm feature using the direct laser beam at the same laser fluence on the gold specimen. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.11, or an almost 89% reduction in feature size.

For the platinum specimen, a 169nm feature was achieved using the multiple interfered laser beam compared to a 1055nm feature using the direct laser beam at same laser fluence. The ratio of the feature size machined using the interfered beam to the feature size machined using the direct beam diameter is 0.16, or an almost 84% reduction in feature size.

When the results obtained with the Fabry-Perot interferometer setup are compared to the Newton's Ring interferometer setup, it was found that a further reduction in feature size of at least 50% could be achieved by adopting the multiple interference concept.

Therefore, it can be concluded that the multiple interfered laser beam gives the best submicromachining capabilities on the femtosecond pulse laser system, demonstrating that machining of features down to 100nm or an almost 89% reduction in feature size

over the features obtain with the conventional laser micromachining method using the direct beam.

10.1 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

As this research concept is just in its infancy, there are still many possibilities of further developing this system.

The core of this research work is to utilise the phenomenon of light interference to refine the beam machining area, and subsequently reduce the feature size. 2 beam interference (Mach-Zehnder and Newton's Ring interferometer) and multiple beam interference (Fabry-Perot etalon) have been introduced in this research work. However, other interferometric methods such as utilising a Bessel beam or a zone plate (multiple light diffraction) could also be viable and should be investigated.

The stability of the laser also plays an important role in determining the quality and size of the features. The option of using a high pulse repetition rate laser should be explored as they provide higher optical efficiency and pulse energy stability. Also, as the energy required in micromachining and sub micromachining are quite low, the option of using the ultrafast laser oscillator without the CPA module should also be examined.

Lastly, the machining and material parameters should be investigated further to determine the best range of parameters to be used to obtain the best results after which a theoretical model can then be conceived for use in the industries.

10.1.1 Bessel Beam

Bessel beams can be produced using phase masks or from cones in reflection or transmission. In the form of a transmitting glass cone, this element is called an axicon. Geometrically, when the laser beam is sent through the flat base of the axicon, it

refracts from the conical surface and interferes to form a high intensity focal zone with a constant diameter, hence a non-diffracting beam (Figure 10.1).

The cross section of the field of such a beam is given by a zero-order Bessel function and is thus called a “Bessel beam”. A Bessel beam has an amplitude profile with a sharply peaked central lobe propagating without spreading over a relatively long distance, $z_{\max}$.

Figure 10.1: Transformation of a Gaussian beam into a Bessel beam by an axicon. The Bessel beam exists in the hatched area.

The generation of Bessel beams with ultrafast lasers has been researched and has been successfully proven possible [112,113,114]. However, it has only been used in such applications as nonlinear spectroscopy and measuring techniques.

The important feature of the Bessel beam and its interest in this research is its sharply peaked central fringe as can be seen from the beam intensity profile (Figure 10.2). By integrating the axicon into the experimental setup to obtain a femtosecond Bessel beam, the sharply defined central fringe holds much promise for the use in the submicromachining of ultrafine features with high aspect ratios and almost no taper.

Figure 10.2: Intensity profile of a Bessel beam.

10.1.2 High Pulse Repetition Rate Lasers

Ultrafast pulse lasers with high pulse repetition rates inherently have higher operating efficiency which essentially gives higher beam stability for precise, fine machining. The femtosecond pulse laser used in this research work, the BMI Alpha-1000S, provides variable pulse output energy of up to of 800mW or 800 μ J at a low pulse repetition rate of 1kHz.

A high pulse repetition rate laser could be adopted to increase the laser operating efficiency and consequently, the energy stability of the beam. An example is the Mira 900 modelocked Titanium:Sapphire (Ti:S) laser system from Coherent Laser Group, Inc which can generate laser pulses of pulse repetition rate of 76MHz, pulse width of 250fs at pulse energy of 15 to 20nJ/pulse. Stability of the laser can be controlled to less than 3% energy fluctuation.

Also, for the femtosecond laser system used in this research work, the output pulse energy of the laser oscillator is only a meagre 2.5nJ, which is too low for use in machining. Therefore, a chirped pulse amplification (CPA) system has to be utilised

to amplify the laser pulse energy. The process which includes many optical elements and the modification of the original laser beam will inevitably cause the degradation and instability of the laser beam, resulting in beam energy fluctuation and noises. As the ablation features are in the submicron ranges, beam energy fluctuation can cause serious distortion to the features machined.

This can be avoided if a laser system capable of supplying higher energy laser pulses from the oscillator is used. As the energy requirement for use in micromachining is quite low (in the ranges of nJ to μ J), the energy from the oscillator is usually adequate for direct use in machining without the need for the amplification of the laser pulses. With the elimination of the CPA system, the new laser system can be more compact, less costly and most importantly, provide high quality beam pulses of high stability.

10.1.3 Investigation on Machining of other Materials and the effect of Linear and Non linear Absorption of the Materials

As this research work was done only on metallic thin films (gold and platinum) and at low fluence near threshold, only linear absorption is taken into consideration. The absorption mechanism is different for opaque and transparent materials. Linear absorption is the main contribution in opaque materials such as metals whereas absorption has to be realized by nonlinear processes in transparent and wide bandgap materials such as glass and dielectrics [33,34,35]. These nonlinear processes include avalanche, tunneling and multiphoton ionization [37,130]. An additional mechanism called Coulomb explosion was reported recently [129,130]. It was demonstrated that dielectrics (in contrast to metals and semiconductors) are strongly charged at the surface on a femtosecond time scale and undergo an impulsive explosion. It has also been observed that the effect of incubation is virtually absent in metals [36].

Micromachining method on transparent and wide bandgap materials with the proposed femtosecond pulse laser interference technique and the effect of linear and non linear absorption should be investigated.

10.1.4 Investigation of the Machining and Material Parameters

The quality of the machining features will depend on the balance between machining parameters such as the laser intensity, laser wavelength, laser pulse energy/fluence, material, pulse width, and the number of pulses (pulse repetition rate) and the material properties such as the material bonding energy, conductivity and material laser absorption coefficient.

Therefore, investigation of the machining and material parameters and their effect on the resulting ablation feature size should be dealt with further to ascertain the best range of parameters for obtaining the best machining features after which a theoretical model can then be conceived for use in the industries.

10.1.5 Investigation on the Formation of Periodic Structures/Ripples

The formation of regular, periodic structures or ripples around the ablation site was observed on different materials at different machining conditions. As the femtosecond laser ablation process is a non-thermal process due to its ultrashort pulse width, these surface modification structures could not have been caused by heat damage as there's minimal heat diffusion.

Two types of periodic structures were observed in this research work. Ripples with a periodicity near to the laser wavelength was observed on the substrates ablated at higher fluences (experiments with the Mach-Zehnder and Newton's Ring interferometer setup) while structures with a periodicity of smaller than laser wavelength was observed on the substrates ablated at low fluences (Fabry-Perot interferometer setup experiments).

The near laser wavelength periodic ripple structures obtained at the higher fluences are attributed to normal vaporization along the lines of constructive interference which arises when the incident beam interferes with a scattered tangential wave [145,153,154]. Incident laser light is partially scattered by surface defects into a tangential wave which travels across the material surface. The scattered tangential

wave then interferes with the incident laser light resulting in interference and the formation of the rippled surface structure with a periodicity in the order of the laser wavelength around the ablated area.

Meanwhile, the smaller than laser wavelength periodic structures obtained at the lower fluences may be induced by a self-organization structure formation during the relaxation of the highly non-equilibrium surface including non-thermal melting processes as reported by Kautek et al [152]. Without ablation, i.e. without bond-breaking, rapid excitation of electrons can cause massive instability in the crystal lattice within a few 10 fs due to a perturbation of the interatomic bonds. Therefore, below threshold fluences but above a modification threshold, this instability relaxes on a several 100 fs time scale by surface reorganization in regular, periodic structures.

These small periodic features were found to depend strongly on the chemical composition of the material ablated. Therefore, laser-material interaction for the different types of material and at different laser fluences should be investigated in detail in order to understand better the mechanism of the ripple formation.

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APPENDIX

THALES LASER

Alpha 1000/S

**Ultrafast kHz
Series**

**High Repetition
Rate
Modular Design
Ti:sapphire**

Alpha 1000/S series is our compact amplifier based on the titanium doped sapphire technology for scientific applications.

Alpha 1000/S Ti:sapphire regenerative amplifier produces femtosecond pulses at the millijoule pulse energy¹ level at 1 kHz repetition rate. The amplifier is pumped with a CW lamp-pumped Nd:YLF laser characterized by its outstanding stability.

Operating at a pulsewidth < 100 fs, pulses are stretched prior amplification and then recompressed into a single dedicated enclosure providing optimum efficiency.

Seeded with any femtosecond oscillator² exhibiting a spectrum in excess of 15 nm FWHM, Alpha 1000/S provides amplified pulses with the pulse characteristics and bandwidths required for the broadest range of applications.

¹Higher pulse energy is available upon specific request.

²Alpha 1000/S accepts a large number of ultrafast oscillators.

Features

- Up to 2 mJ @ 1 kHz, 800 nm
- Operation < 100 fs or 1.5 ps
- Flexible, modular set-up
- Excellent mode quality
- Various femtosecond oscillators compliant
- No satellite pulses in ps time regime

Applications

- Micromachining
- Scientific
- Biology

THALES

Output Specifications

Model	Standard	Picosecond Extension
Repetition rate (kHz)	1	
Wavelength (nm)	800 ± 20 (1)	
Pulse duration	< 100 fs (2)	< 1.5 ps (3)
Energy per pulse	800 μ J up to 2 mJ (4)	> 600 μ J
Pulse-to-pulse stability (% rms)	< 1.3	
Pre-pulse contrast ratio	$> 500 : 1$	
Post-pulse contrast ratio	$> 100 : 1$	
Typical picosecond contrast	$> 1,000 : 1$ @ 1 ps $> 10,000 : 1$ @ 5 ps $> 100,000 : 1$ @ 10 ps	
Typical time-bandwidth product	1.5 x Fourier-transform limit	
Beam profile before compressor	Gaussian	
Typical M^2	< 1.3	
Pump system	YLF 12 W @ 527 nm	

High Contrast Extension upon request.
Dual 10 Hz/kHz option available.

- (1) Tunability of the standard system is possible on demand, requiring a tunable oscillator exhibiting an average power > 500 mW.
(2) Assuming an oscillator exhibiting a spectrum in excess of 15 nm FWHM. Alpha 1000/S accepts a number of femtosecond oscillators.
(3) Assuming an oscillator exhibiting a spectrum in excess of 2 nm FWHM.
(4) Higher energy is available on demand.

Typical Alpha 1000/S @ 800 μ J Layout

Dimensions are given in mm (in).

Due to Thales Laser continuous product improvement policy, specifications are subject to change without notice.

THALES
LASER

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ESP6000

PC-Based High-Performance Motion Controller

Key Features

- 1–6 axes of open or closed-loop DC and stepper motor control
- 8 channel, 16-bit A/D input for high resolution analog data acquisition
- Synchronizes external functions with the executed motion
- Captures position within 0.06 μ s
- PCI card format allows fast data transfer to the user application
- Multi-axis synchronized motion
- Continuous path contouring for complex motion profiling
- High precision motion using PID-FF control algorithms

The ESP6000 is an advanced 32-bit PCI bus based motion controller combining accurate motion trajectory with high performance data-acquisition and external event synchronization. The ESP6000 can drive and control up to six axes of motion using any combination of DC and/or stepper motors. It contains complete on-board motion processing intelligence and a PCI computer interface for fast communication. When used with our UNIDRIV6000 or ESP6000DCIB motor drivers, the ESP6000 provides true "plug-and-play" compatibility with Newport's motorized products.

Technology

The ESP6000 uses a 32-bit floating point, 60 MHz DSP processor for high precision synchronized control. A digital PID-FF (feed-forward) servo loop updates all axes with a cycle time of 400 μ s for precise velocity profile tracking and accurate positioning. A 18-bit DC motor command output delivers the needed resolution and stability for high precision applica-

tions. A wide velocity bandwidth is provided with programmable range from 0.06 to 16,000,000 encoder counts/sec to accommodate a large variety of low- and high-speed applications.

Motion

The ESP6000 provides several modes of positioning including synchronized and non-synchronized point-to-point, jogging, linear or circular interpolation. Continuous path contouring is accomplished easily, without the need to be experts in multi-axis command programming. Trajectories, even complex ones, can be simply broken down into straight and curved segments. The controller does the rest, including precise monitoring of the speed and the acceleration all along the trajectory. This capability is critical for applications like laser-scribing, micro-ablation, or ultra-sonic measurement inspection. In addition, any axis of the ESP6000 can be "slaved" to any other axis or to an external encoder (trackball control), even if they have different motor/gearhead ratios or

lead screw pitches (electronic gearing). This feature is essential when multiple stages are required to move large or over-sized loads such as in gantry systems. Other sophisticated motion features include on-the-fly position, velocity, or trajectory changes for complex motion and alignment routines. Software limits can be set to improve systems safety. A advanced origin search routine includes encoder index pulse consideration for precision homing. Backlash and linear error compensation eliminate repeatable system errors.

Inputs/Outputs

The strength of the ESP6000 is its high performance data acquisition and external control and synchronization capabilities. An 8-channel, 16-bit instrument grade analog-to-digital converter allows data acquisition that is exactly correlated to the axis position without stopping the motion. This powerful feature can greatly improve throughput and accuracy of applications requiring analysis of information based on position. The desired motion can simply be initiated, then analog data, axis position, and time stamp data is streamed to the PC memory and captured by the user program. External data acquisition tools can be synchronized by the ESP6000 as well. The output can be configured either to provide a single trigger at a specified position crossing, or to provide continuous trigger outputs at a specified distance interval. 24 Opto22 compatible, bi-directional digital I/O can be user-configured as either inputs or outputs to perform certain tasks. Valuable

tasks include monitoring the motion status, stopping a motion or executing a command. An additional watchdog timer and remote interlock are supplied for added system safety.

Programming

The ESP6000 makes programming complex motions easy using a powerful programming language with over 100 commands. Free LabVIEW™ software drivers and extensive DLL's for all most popular Windows versions are available and get constantly updated through our website at www.newport.com. A complete range of utility programs is provided to minimize start-up time and to make application development easier. The tools include a user interface program for configuration, a PID servo tuning utility, and our Motion Wizard to configure non-Newport stages. An ASCII interface is also available for simplicity of operation. An extensive on-line help system supplies programming details and examples.

Motor drivers

The ESP6000 can be used with either the ESP6000DCIB or the UNIDRIV6000 drivers to provide full plug-and-play compatibility with Newport's motorized stages. The ESP6000DCIB (see page 1101) can control up to 4 axes of small DC motors up to 10 watts/axis. For larger motors, select the UNIDRIV6000 (see page 1098) that can power up to any combination of six axes of DC and/or stepper motors.

Specifications

Number of Axes	1-6 axes of any combination of stepper and DC motors
Computing Power	400 μ s servo cycle up to 6 axes
	32 Bit, 60 MHz DSP processor
	Digital PID servo loop with velocity and acceleration feed forward
Motion	Trapezoidal and s-curve velocity profile
	Synchronized and non-synchronized point-to-point
	Jogging, Continuous moves
	6D Linear interpolation, 2D Circular Interpolation
	Master-slave, Electronic gearing
	On-the-fly trajectory modification, changes of target position, speed, acceleration, PID
Contouring	2D Contouring with continuous buffer loading
External Event Synchronization	On-the-fly data acquisition of up to 10 position counters and 8 analog channels per servo cycle (approx. 30 μ s latency per analog channel)
	Continuous data streaming up to 170 kB/s
	Trigger output on axis position and distance interval
	Program execution depending on TTL I/O status
	Position capture within 0.06 μ s of the occurrence of an input
Programming	100+ intuitive, 2 letter ASCII commands
	Command set includes: User defined units, software limits, home search (with and w/o top zero), linear error and backlash compensation, etc.
Software Drivers	DLL covering 100+ commands for Windows 95/98/2000/NT/ME
	Drivers for LabView 4.x
	Software development tools compatible with Windows 95/98/2000/NT/ME: Terminal program, ASCII command interface, PID tuning program, Motion Wizard (used to configure non-ESP compatible stages)
Computer Interfaces	Full length PCI bus card for 586/Pentium compatible PC's
I/O	24 Opto22 compatible, user programmable TTL I/O (programmed in groups of 8)
	8 channel 16-bit analog input with programmable ranges: +/-5V, +/-10V, 0-5V or 0-10V
	"Watchdog" timer and remote interlock
Memory	128 kB system configuration flash EPROM
	Data storage buffer for up to 1,000 lines (up to 6 axis position plus 8 analog inputs)
	512 kB Flash non-volatile firmware memory
DC Motor Control	Closed-loop operation only
	18-bit DAC resolution
	16 MHz max. encoder input frequency
Stepper Motor Control	Open- or closed-loop operation
	2.5 MHz maximum pulse rate
Power Requirements	+5V, 1.8A (max); +12 V, 0.2A (max), -12V, 0.2A (max)

The ESP's tuning program allows you to quickly and easily optimize the PID servo parameters.

561/562 Series

ULTRAlign™ Precision Multi-Axis Positioning System

561 and 562 Series ULTRAlign™ Linear Stages feature stainless steel construction for superior long-term stability, with thermally matched, hardened steel crossed-roller bearings for unsurpassed performance. The crossed-roller bearings and precision-manufactured bearing reference surfaces provide exceptionally linear travel, with angular deviation better than 100 μ rad about any axis. We measure each stage on a six-axis interferometer to ensure performance.

561/562 Series Stages are ultra-high performance positioners. They were originally designed for precision fiber optic alignment, one of the most demanding precision positioning applications. Today, they are finding increasing applications in other fields as well. In addition to the three-axis XYZ positioners shown here, optional tilt and rotation stages can be added to the 561 and 562 (see page 188). With up to six degrees of freedom, high-performance ULTRAlign stages offer a superior positioning solution.

The robust design of the 562 Series Stages makes them ideally suited for repetitive, high-use industrial manufacturing and research applications. These

stages have greater thermal immunity due to their higher mass. And larger diameter bearings increase the stiffness of the stage. Oversized loads and complicated platform configurations can easily be accommodated, since all actuators are located below the top surface level. Generous hole patterns, with your choice of English (1/4-20) or metric (M6) threads, provide convenient mounting options.

Each 561/562 stage axis is equipped with a non-influencing locking mechanism to maintain sub-micron positioning when locking or unlocking. Specially designed actuator mounting blocks allow quick and easy actuator changes, on any axis, at any time. Both right- and left-handed stages are available for ergonomic actuator placement. And a choice of manual, motorized, or electrostrictive actuators will meet every positioning need.

The height of ULTRAlign 561D-XYZ and 561D-YZ stages can be matched to the height of the 562-XYZ by using the 561-ADPT Adaptor (see page 191). This will allow you to use both series of stages in one system.

Key Features

- Stainless steel construction for the ultimate long-term stability
- Hardened steel, crossed-roller bearings for high rigidity and precision motion
- Angular deviation better than 100 μ rad about any axis – guaranteed
- Compatible with Newport manual, motorized, and electrostrictive actuators
- Right- and left-handed configurations

Model 562 with SM-13 micrometers. Vertical platform translates to within 0.031 in. (0.79 mm) of work surface. Order micrometers separately.

TRANSLATION STAGES
STAGES
AMPLIFIERS

Specifications

	561 Series	562 Series
Maximum Travel X, Z axis	0.25 in. (6 mm)	0.5 in. (13 mm)
Maximum Travel Y axis	0.5 in. (13 mm)	0.5 in. (13 mm)
Angular Deviation	<100 μ rad	<100 μ rad
Load Capacity	5 lb (22 N)	35 lb (156 N)
Optical Axis Height	3.125 in. (79.4 mm)	3.875 in. (98.4 mm)

Ordering Information

Model	Metric Model	Actuators Required*
561D-XYZ	M-561D-XYZ	3
561D-XYZ-LH	M-561D-XYZ-LH	3
561D-YZ	M-561D-YZ	2
562-XYZ	M-562-XYZ	3
562-XYZ-LH	M-562-XYZ-LH	3

* Actuators must be ordered separately
Left-handed versions contain "-LH" in the Model number
For **Vacuum Compatible** versions (50% price premium at time of order), append "V" to the part no.,
eg., 562-XYZV. Please see page 821 for specifics.

Preloaded cross-roller bearings provide repeatable, zero stick-slip linear motion with negligible side-play. The roller strips hold cylindrical rollers alternately inclined 90° to assure constant linear contact with the hardened and ground ways.

Recommended Actuators

Manual Drives	Description	561	562	Travel* (mm)	Minimum Incremental Motion (µm)
AJS Series	Fine Adjustment Screw	•	•	6–13	0.6–0.9
HPS Series	Fine Adjustment Screw	•	•	13	0.75–0.9
SM-06	Micrometer	•		6	1
SM-13	Micrometer	•	•	13	1
HR-6	High-Resolution Micrometer	•		6	0.5
HR-13	High-Resolution Micrometer	•	•	13	0.5
DM-6L	Differential Micrometer	•		6	0.1
DM-13, DM-13L	Differential Micrometer	•	•	13	0.1
DS-4F	High-Precision Adjuster	•		8	0.02
Motorized Drives					
850G Series	Motorized Actuator	•	•	50	1
CMA Series	Motorized Actuator	•	•	12.5	0.2–0.5
PM500-1A Series	Motorized Actuator	•	•	25	0.05–0.1
AD Series	Electrostrictive Actuator	•	•	13	0.04–0.06

* Travel on 561 X and Z axis is limited to 6 mm.

Model 561D-XYZ

Model 562 configured with Tip/Tilt stage (see page 188 for details).

561-GON Miniature Goniometer. For this and other ULTRAlign™ accessories, see page 188

MODEL	THREAD	DIMENSION
	B	C
ENGLISH INCHES		
561D-XYZ	8-32	1.000
561-XYZ-LH	8-32	1.000
METRIC MILLIMETERS		
M-561D-XYZ	M4	25.0
M-561-XYZ-LH	M4	25.0