On-line shape measurement using micro-optics

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ON-LINE SHAPE MEASUREMENT USING MICRO-OPTICS

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SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING

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On-Line Shape Measurement

Using Micro-optics

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School of Mechanical & Aerospace Engineering

A thesis submitted to the Nanyang Technological University
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ABSTRACT

Physical objects have three dimensional structures(3D). So that a profilometer that produce a 3D profile is invaluable. With the increasing demand for micro-products and bioengineering research, resolutions of 3D profiles with micrometer scale are becoming commonplace. In addition development of large scale production and the real time life science microstructure profile inspection need high-speed display and real-time inspection. The configuration of sensor array detection makes the detection speed much faster than single sensor detection because of sensor array inspects area without lateral scanning. This thesis introduces a multi-channel 3D profile inspection system to realize fast speed inspection with resolution of better than $1\mu\text{m}$. Fiber coupler is introduced in the system as to study and resolve the cross-talk problem.

The principle of the confocal technique, components, configuration and performance are analyzed for the purpose of constructing and experimenting in the first instance a one-channel fiber confocal system. Based on the outcomes of the above research studies, four different configurations of the multi-channel confocal system were developed to meet different application requirements. A basic three-channel fiber confocal 3D profilometer was built and successfully used for inspection of V-grooves used in MOEMS devices.

Experimental and theoretical analyses indicated that the fluctuation of light source is critical problem that will affect system resolution and stability. A mathematical compensation model and a double detector configuration successfully solved the problem. A fast scan algorithm was developed based on three-point interpolation technique in order to speed up confocal signal processing. These two techniques for improving the confocal

system performance are applicable to both single channel confocal and multi-channel confocal systems.

For a multi-channel confocal system, crosstalk was investigated both experimentally and theoretically using time and frequency domain analysis. The results indicated that crosstalk was a critical problem in multi-channel confocal system. The number of crosstalk channels indicated the size of affected area. The crosstalk problem degraded system resolution and stability. The schemes to eliminate crosstalk by modulation and signal processing or modulation-demodulation circuits have been highlighted and presented. In order to complete multi-channel 3D profilometer, two scenarios are discussed. One is to develop a system capable of total eliminating the crosstalk problem while the other is to develop a system, which exploits the crosstalk property.

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LIST OF ABBREVIATION

3D	—three-dimensional
AFM	—atomic force microscopy
APD	—avalanche photodiode
BS	—beam splitter
DFTs	- discrete Fourier transforms
DMI	- displacement measuring interferometer
DS	-- displacement sensor
DSO	--digital storage oscilloscope
DTFS	-discrete-time Fourier series
DTFT	-discrete-time Fourier transform
EP	—expander
EPD	- enhanced photodiode
FFT	—fast Fourier transform
FS	—Fourier series
FT	-Fourier transform
LS	—laser source
LSCM	—laser scanning confocal microscopy
M	—mirror
MEMS	— Micro-electro-mechanical systems
MOEMS	—micro-opto-electro-mechanical system
NEP	- Noise equivalent power
QE	—Quantum efficiency

PD — photodetector

PBS—polarized beam splitter

PM—Power meter

PMC —partially metal-coated

PMT-Photomultiplier tube

PSD — position-sensitive detector

RMS —root mean square

RT—rise time

SEM —scanning electron microscope

Spl—sample

SWLI-scanning white light interferometry

SNF — signal-to-noise ratio

Chapter 1: Introduction

1.1 Background

Three-dimensional (3D) profile inspection is required for many objects in our living environment, such as optical discs, electronic packages, and tissues such as cells and neuro-structures. 3D profilometry is widely applied in many technical fields including optics, electronics, information science and life science research and inspection. With the development of information science, production and the life sciences towards more precision products, research in 3D micro-structure of objects is becoming more important. Study and inspection of object topography and deformation are developing towards micrometer and even nanometer scale.

Electronic products such as electronic packages and wafers are widely used in many kinds of electronic equipment. Standard custom wafer^[1] is a high precision product with the thickness tolerance within $\pm 15\mu\text{m}$. In order for a wafer to stay within these tolerance values, the surface 3D profile should be less than $15\mu\text{m}$, resulting in profile resolution within $1\mu\text{m}$.

Integrated optical elements are widely used in communication system^[2], the structure of some integrated optical elements can be fabricated to several nanometers. Optical and magnetic recording products such as optical disks are some of the most important parts of electronic products used for storage and communication. With the development of large integrated circuits, micro-processing machines and numerical encoding technology, digital video products, such as VCD and DVD, have become main stream of consumer products

and these require ultra-precision manufacturing. The grooves on VCDs and DVDs before recording data are $0.5\mu\text{m}$ wide and $0.1\mu\text{m}$ deep^[3]. With such fine dimension, the inspection equipment should have a resolution of at least $0.05\mu\text{m}$. VCDs and DVDs also require geometrical profile measurement for the mask test, coating test and signal grooves test, which requires even higher resolution during profilometry.

To meet the demand from high precision topography manufacturing, high precision profile measurement should match the precision of the products and should have higher resolution than products resolution themselves.

The development of large-scale integrated manufacturing has enabled the manufacturing process to speed up. With the short fabrication time in large-scale manufacturing, fast measurement should satisfy the manufacturing process, whether it is for on-line inspection, or for single sampled item measurement. As such, the speed of measurement will become increasingly important.

In life science research and inspection application, more powerful visualized inspection of micro-structures and variation in shape is on its way in fields such as genetics, immunology, molecular biology, neuro variation and in vivo check^[4-6]. Studying these living structures, to observe the change and variation of the living tissues with the outer stimulation, high-speed display and realtime observation of the structure's shape and performance are necessary.

In micro-opto-electro-mechanical system (MOEMS) application, V-grooves for optical fibers are fabricated on single wafer to realize miniaturized high-speed data communication devices. For the fiber to fiber alignment, a $1\mu\text{m}$ axial misalignment can cause the loss of power larger than 3dB ^[7], which degrades the information of communication data. For passive alignment of fibers, the precision tolerance should be

better than $1\mu\text{m}$. With today's technology, the etched V-grooves are typically not perfect due to misalignment and lithography issues. The V-groove fabrication should be repeated so as to find a proper scheme. Therefore, the shape of V-groove needs to be inspected often at different cross sections which require fast profile measurement.

Researchers have made significant effort in the area of 3D profile measurement study using either mechanical, optical or electronic methods. But the outcome is still not satisfactory. From problems of non-linear response with electronic sensor and the problems of deformation and damage induced by contact sensor, mechanical and electronic methods are not suitable for fast and realtime deformation 3D profile inspection. Many researchers have been concentrating on 3D optical metrology to improve measuring resolution and measuring speed for its properties of noncontact, highly linear response, fast response, adequate focusing, high accuracy, high resolution, high sensitivity and high reliability.

Optical 3D shape measurement^[8] has been widely applied in many kinds of technologies, which can generally be put into the following categories:

- time of flight,
- phase measuring,
- triangulation,
- moiré method,
- focus analysis,
- interferometry,
- tunnel microscopy methods and
- atomic force microscopy (AFM).

Comparing these optical methods, time-of flight and phase measurement techniques are well established and commonly applied to long-range measurement. For close-range and topography measurements, the principle of triangulation and moiré methods are often employed^[8]. In addition, the moiré method (projected moiré and moiré interferometer) is a useful tool for surface shape, deformation, or vibration and for the analysis of microstructure. Of the last few methods, image plane locating systems such as confocal analysis and interferometry have now reached a very high technical standard. They can be used to study biological objects as well as to measure the topography of industrial products ^[9,10].

For micro-optic profile measurement, many methods and principles have been applied in numerous commercial products, including interferometers, confocal microscopes, AFM and triangulation. In terms of resolution, AFM can achieve the highest resolution for topography measurements, followed by interferometry and the confocal method, and then triangulation.

AFM is used to capture high resolution, three-dimensional images of the surface structure of any solid. In addition, it is also used to solve processing and materials problems by recording the microscopic shape of the sample surface, and sensing material properties such as stiffness, adhesion, and friction as well as magnetic and electric fields. This gives the information to improve process quality, speed product development and enhance research in a wide range of technologies affecting the electronics, telecommunications, biomedical, chemical, automotive, aerospace, and energy industries. Recently, Advanced Surface Microscopy, Inc. of USA, measured the groove edge on a recordable compact disc (CD-R). An edge roughness of 6.7nm was measured using AFM and ASM's DiscTrack Plus software^[11]. However, the drawback of AFM is that it is a contact mode measurement,

resulting in a slow measuring speed. As such, it can not apply to on-line measurement, and is not appropriate for soft living biomedical profile inspection.

Interferometry^[8] is an old but very powerful technique to measure the deviation between two wavefields with a sensitivity of a fraction of the wavelength of the illumination source. In both research and industrial use, automatic fringe analysis is increasingly important. Solid-state detector arrays and image memory boards together with microprocessors and computers are used to extract information from the interferograms. In this way much more information can be extracted from the interferograms, leading to higher resolution and accuracy. ZMI 2000 System is Displacement Measuring Interferometer Systems produced by Zygo. The highest position resolution is 0.15nm ^[12]. But because interferometer techniques have many technical restrictions, many interferometer systems can not achieve such a high resolution.

Optical triangulation is a powerful technique for non-contact measurements. Triangulation based 3D sensors are appropriate tools for inspection and production line measurement of height, width, thickness, position, vibration and oscillation. In particular, synchronized single-spot scanners fulfill the high requirements of flexibility, range extension, resolution, and robustness. The LC-2400 Series from Keyence Corporation of America, is a laser Displacement Meter based on the triangulation measurement principle. And it is the most accurate and versatile laser measurement system ever developed based on this principle. It provides $0.01\mu\text{m}$ resolution and a sampling rate of 50 kHz. Though this principle could realize high frequency measurement and high resolution, it only produces single-spot detection with spot size of 10 to $20\mu\text{m}$, and the accuracy and precision is not as good as with interferometry and confocal measurement.

Confocal microscopy is a new science, mainly applied to the field of biological and materials specimens' inspection. In recent years, laser scanning confocal microscopy (LSCM) has probed the nanometer realm using near-field method—and in the process, it becomes even more invaluable as a tool for inspection and research. Equally important is the recent development in laser confocal microscopy that generates 3D images of microscopic objects. Applications benefitting from these results include research into current flow in semiconductors and into the movement of biological microorganisms. NanoSurf scanning confocal microscope is a product of UBM Corporation, which is designed for R&D and quality control 3D topographical analysis system. It is based on a white light-confocal technology. Applications can be found in semiconductors, microstructures, mechanics, medical and cosmetics, and optical fibers. From the applications point of view, this principle has a great potential for future development.

Literature reviews of Chapter 2 show significant progress has been achieved during recent years in the development of 3D shape measurement system. Some commercial instruments with high resolution could meet the demand of shape measurement and inspection. However on line micro-optical profile measurement to meet the further demand of industrial inspection and science research with high speed will lead to further interest.

To meet the demand for large-scale integrated manufacturing industries 3D microstructure on-line inspection and real time profile deformation inspection, a fast speed 3D shape measurement system with micro-size resolution is urgently needed.

1.2 project objective and scope

As introduced above, the objective of this project is to develop a micro-optical system-- a

multi-channel fiber confocal for 3D profile measurement system to meet industrial inspection and research requirement of fast speed and resolution better than $1\mu\text{m}$ for real time or on-line inspection.

The main issues studied in this project are:

1. **3D measurement technical review and evaluation of confocal techniques.** This project reviews and compares 3D profile measuring techniques in the fields of mechanical, optical and electronic metrology. In optical metrology, the speed and resolution of several 3D shape measuring techniques are compared for the purpose of this study, confocal measurements are chosen as most suitable technique.
2. **Confocal technique analysis and fiber confocal system construction.** This thesis analyzes the confocal principle, basic configuration, basic components performance and system parameters such as spot size and resolution. Based on the basic principle and configuration, a fiber confocal system is developed and system experimental performance is evaluated by quantitative and qualitative methods. In addition, fiber and fiber coupler properties are studied.
3. **Compensation of light source fluctuation.** A new configuration with a double detector and compensation algorithm is built and tested experimentally to improve system resolution, increase system stability and reduce system noise.
4. **Fast scan algorithm.** In order to realize fast measurement, scanning speed and data processing speed should be improved. This algorithm is developed to reduce the number of sampling points per cycle so that sampling time, signal processing speed and number of data points per cycle will be reduced and overall speed will be increased.

5. **Multi-channel confocal system.** A novel system structure— a multi-channel confocal 3D profile measurement system is designed to realize fast speed measurement. System configuration and analysis are discussed.
6. **Cross-talk study.** In multi-channel confocal system, one channel signal may enter into other channels then cross-talk problem occurs. Cross-talk will decrease system resolution and accuracy, increase measurement error and uncertainty. In order to address and limit crosstalk, a significant number of experiments are presented to show the crosstalk problem. This thesis discusses technical methods to eliminate crosstalk problem with theoretical and experimental analysis.
7. **MOEMS research application.** Based on the multi-channel confocal system analysis, a three-channel confocal system is built and applied in MOEMS for V-groove depth inspection. The characteristics of MOEMS using confocal measurements are investigated.
8. **Future work.** To realize practical instrumentation for a multi-channel confocal system, the circuit is designed to eliminate crosstalk problem. This includes the design of demodulators, filters and amplifier systems. Based on the multi-channel system crosstalk analysis, a new idea is proposed: exploiting crosstalk to develop a multi-channel profilometer.

1.3 Organization

This thesis consists of eight chapters. Following this introduction, Chapter 2 reviews 3D profile optical metrology development, analyses the state of the art and problems and proposes a new idea to develop multi-channel confocal system to solve present problems. Chapter 3 analyses the basic confocal principle and components performance, presents

some basic experiments based on basic configuration.

In Chapter 4, fiber and fiber coupler properties are studied and used to develop a new structure for fiber confocal measurement. The system performance is evaluated from quantitative and qualitative aspects. Subsequently, two techniques are presented to improve system performance, one is for light source fluctuation compensation to reduce system noise and increase system resolution, the other is for a fast scan algorithm to speed up signal process.

Based on the above chapters' analysis, in Chapter 5, a multi-channel confocal system is developed. Different configurations are proposed to resolve different problems. The configuration of the system components is described and spatial resolution is studied. The cross-talk problem in multi-channel systems is studied experimentally and theoretically. The signal analysis is presented to eliminate crosstalk.

As an application, Chapter 6 precepts an initial study for MOEMS component V-grooves depth inspection. The result is compared with that using a commercial instrument.

In Chapter 7, there are summaries to describe the contribution for this project study.

Finally, in Chapter 8, the future work is discussed. It is the explanation how to complete a one-channel system, how to eliminate the crosstalk to develop a multi-channel system, and how to exploit the crosstalk to develop a novel spectrum profilometer.

Chapter 2 Review of 3D profile optical measurement systems

This chapter reviews 3D profile measuring techniques in the fields of mechanics, optics and electronics. Optical metrology is utilized in this project. Various optical methods employed in profile measuring systems found in the commercial and research field are discussed. The analyses elaborate the current problems and their solutions. From these optical 3D shape measuring techniques, the confocal technique is concentrated on. The reasons for further development of the confocal system and the general objective and orientation of this project are stated.

2.1 Introduction

The profile measurement techniques can be categorized into mechanical, optical and electronic techniques.

Mechanical technique uses contact methods for profile measurement. A force feedback principle is often used. This induced force may cause minor deformation of the surface of the object being measured. In addition, scanning profile may also damage the surface of the sample being measured. Hence, this method is not suitable for high precision, rapid and real time range measurement due to its reliability and contact problems^[13].

Capacitance and inductance based electronic sensors are compact and portable but have relatively small linear measurement ranges^[13]. Furthermore, electronic waves can not be

focused to small size^[14].

Optical metrologies are preferred if a high resolution is needed. Optical sensors have shown their powerful merits as:

- Non-contact
- High resolution
- High sensitivity
- High accuracy
- High reliability

The basic principle of optical profile metrology is to project an optical signal onto an object. The reflected or scattered optical signal is then processed to determine the profile.

Optical profile metrology is broadly categorized into active and passive^[8, 14].

Passive method was first applied in photogrammetry to obtain the topography or complete shape. The desire to capture shape by optical means dates back to the beginning of photography^[15,16]. In the 1860s, Francois VILLEME invented a process known as photosculpture, which used 24 cameras^[15]. Profiles of the subject to be reproduced were taken on photographic plates, projected onto a screen using the magic lantern, and transferred to a piece of clay using a pantograph. As photosculpture was a very expensive and complex process, it was not popular in the commercial market.

The active method saw rapid development since it was first proposed. Many methods exist for optical 3D shape measurement, comprising time of flight and phase measuring^[8, 15, 17], triangulation and projected fringe^[18~22], image plane locating system and focus analysis^[23~26], interferometry^[27~40], and tunnel microscopy^[8, 41]. The commonly used high resolution methods are triangulation, projected fringe, confocal and interferometry. The relevant details are discussed in subsequent sections.

2.1.1 Optical triangulation for 3D profile measurement

Optical triangulation is widely used in non-contact 3D shape measurements and can be broadly categorized into either active or passive type.

Passive triangulation was first used in photogrammetry. But the photosculpture process used in photogrammetry is more expensive than the traditional ways of doing sculpture. The process requires a lot of human intervention in which a large amount of manual work is required to finish the sculpture. Also, a professional sculptor is needed and the photosculpture process requires investment in terms of cameras, projection and reproduction systems, including skilled labour to operate them. It is only with the advent of computers that the process has regained substantial interest, more than 100 years later.

In active triangulation, a laser spot is first projected onto the object. Its image position is subsequently recorded on a position-sensitive detector (PSD) or on a CCD-chip (line or array camera). The lateral displacement of the spot image is directly related to the depth in the object, which is illustrated in fig. 2.1. In this figure, a laser source (*LS*) emits light onto a sample (*Spl*). Because of the roughness on the surface of the specimen, there is a distance, *AZ*, between the illuminated points *P1* and *P2* along the optical axis of the laser source. Reflected light, from two points, *P1* and *P2*, transmits through a lens (*L*) and then forms image on a CCD. For the distance *AZ*, the images of two points *P1* and *P2* are at different positions on the image plane of the CCD. The resolution of the triangulation techniques is given by

$$\Delta z = \frac{\Delta \omega \cdot z_0^2}{B} \quad (2.1)$$

Where, z_0 is the working distance, B is the base, and $\Delta \omega$ is the angular resolution of the

detecting system. The surface profile of objects can be obtained by this method. 3D profile sensors based on triangulation techniques are appropriate tools for inspection and measurement in an industrial environment. In particular, synchronized single-spot scanners fulfil the high requirements of flexibility, range extension, resolution, and robustness.

Present commercial products based on the scanning triangulation principle have been developed and reached maturity. The KL series Displacement Meter, from Anritsu Corporation, uses this triangulation method for displacement measurements. Within this series, KL130B offers the best specifications of 16KHz sampling frequency, 0.3ms response time, 10 to 20 μ m laser spot size, 10 nm resolution, and 7mm working distance.

Proscan series profilometer – the product of Scantron Industrial Products Ltd, is used for fast and accurate 3D surface profiling and topography inspection,, displacement and thickness measurement .It employs measurement technology of triangulation with speeds of measurement up to 2,000 points per second coupled with a resolution of 10nm.

LV series, LT series, LK series and LC series Lzser Displacement Measurement System Keyence Corporation are based on the principle of triangulation. Regular-reflective type (Models LC-242012430) and diffuse-reflective type (2440/2350) sensor heads are available to reduce scatter effect, assuring precision measurement on various surfaces. These have been developed for research and development as well as for inspection and production line in measurement of height, width, thickness, length, position, runout, vibration and oscillation for different resolution. LC series provides 10nm resolution with a maximum sampling rate of 50 kHz.

2.1.2 Projected fringe technical analysis

Projecting fringes is an extension of triangulation for out-of-plane and topography measurements.

Projected fringe patterns can be formed by different methods, such as projecting either a grating-like structure^[8] or an interference pattern[42] or diffraction pattern[43] onto the object^[15, 18, 19, 44–51]. The height variation or object deformation leads to a modification of the projected fringes, which in turn are compared with the original or synthetically generated patterns. Typical contour-line separations can vary from micrometers to millimeters.

For a grating with sinusoidal intensity distribution projected onto an object and the intensity on the image plane of the detector array, can be written as

$$I(x, y, \psi) = a(x, y) + b(x, y) \cdot \cos[\phi(x, y) + \psi] \quad (2.2)$$

where, $a(x, y)$ is the amplitude of stray light while $b(x, y)$ is the amplitude of local changing reflectivity. $\phi(x, y)$ is the phase function, which is related the object shape. ψ is the phase shift typically between 0 to 2π ^[18, 19]. This equation is equivalent to a two-beam interference pattern. As a result, the same algorithms such as Fourier transform and phase shifting methods^[47, 49, 52–54] for fringe analysis can be used.

Figure 2.2 shows a configuration schematic diagram for 3D profile measurement. The object height, $h(x, y)$, is measured relative to the reference plane (X-Y plane) in the figure. A sinusoidal grating pattern is projected onto a 3D diffuse object from the point $G(X_0, 0, Z_0)$, and the exit pupil of a CCC camera is from the point $P(0, 0, Z_0)$. The grating pattern and the exit pupil of the CCD are on the same height level. The grating phase on the point B of the object is the same as on the point A of the reference plane, that is

$$\varphi_A = \varphi_B$$

reference plane. Thus, the distance of two points AC is obtained from

$$AC = \frac{\varphi(x, y)_{BC}}{2\pi f} \quad (2.3)$$

where $f = \frac{1}{p}$ is spatial frequency of the projected grating and p is the grating period perpendicular to the illumination axis. Then, the object height, $h(x, y)$, at point B relative to the reference plane is expressed as

$$h(x, y) = \frac{Z_0 \cdot AC}{X_0 \left[1 + \left(\frac{AC}{X_0} \right) \right]} \quad (2.4)$$

The grating projection microscopes extends the applications for qualitative and quantitative 3D vision. The highest lateral and vertical resolution is $0.05\mu\text{m}$, depending on the grating structure, lens aperture and the field size^[13,16].

For the principle restriction, fringe projection is not suitable for high resolution profile measurement. When the surface roughness is large ($r_a > 0.1\mu\text{m}$), fringe projection is the ideal choice. This technique has been applied in the objects with rough surfaces like sheet-metal, ground and turned metal surfaces, plastics and ceramics, even biological surfaces like the human cornea^[19].

2.1.3 Interferometry for high precision topography measurement

Interferometry is an old but very powerful distance measurement technique first developed by Albert Michelson in the second half of the last century to measure the velocity at which light travels through space. This method can measure the deviation between two wave fields with a sensitivity of a fraction of the wavelength of the illumination source. The interference pattern of two beams is influenced by frequency, phase and polarization of light. Two beams derived from the same light source have the same frequency and

coherence. The interference pattern is determined by the phase difference between the two beams, while the phase difference is related to the path length difference. The path length difference between the reference beam and measurement beam generates an interferogram, which contours the surface of the object.

Figure 2.3 is a schematic principle of interferometry for shape measurement. A beam emitting from a laser source (LS) is divided into two by a beam splitter (BS1). One is the reference beam, reflected at BS1 towards a beam splitter (BS2), the other is the measuring beam, passing through BS1 and reflected by a mirror (M) towards an inspected sample (Spl). Two beams recombine together at the BS2, and then received by a photodetector (PD).

Suppose, E_1 and E_2 are the amplitude of the optical field of reference beam and measuring beam respectively. The intensity at the photodetector is given by

$$I = E_1^2 + E_2^2 + 2E_1 \cdot E_2 \cdot \cos(\phi_1 - \phi_2) \quad (2.5)$$

where the interference term $2E_1 \cdot E_2 \cdot \cos(\phi_1 - \phi_2)$ is seen as the periodic intensity variation related to the phase difference of the recombined waves. ϕ_1 and ϕ_2 are phases at the photodetector of the reference beam and measuring beam respectively. This difference in phase is due to the difference in their traversed optical path lengths by the two interferometric arms and notes as

$$\Delta\phi = |\phi_1 - \phi_2| = 2nd \left(\frac{2\pi}{\lambda} \right) \quad (2.6)$$

Scanning the sample along X-Y director, the profile of the sample is then obtained.

Interferometry is a powerful tool for measuring the surface topography of the object because it can detect the object surface point by point or by an area of the object surface. Figure 2.4 is the case of area detection. In this configuration, a charge coupled device (CCD) is used instead of the point detector in fig. 2.3 and a beam expander (EP) is set

between the laser source and BS 1. An interferogram which contains profile information of the sample is then obtained through the use of the CCD.

Interferometry has been widely used in two-beam interferometer^[55], two-wavelength interferometer^[56], multiple wavelength interferometer^[57], shearing interferometer^[58, 59], white-light interferometer^[60-63] and heterodyne interferometer^[64, 65], etc.

ZYGO's ZMI series displacement measuring interferometer (DMI) and NewView 5000 scanning white light interferometry (SWLI) are used in a variety of applications with high resolution real time position control systems^[66], such as those used in semiconductor lithography, e-beam and laser reticle writers, CD measurement tools, process equipment, and memory repair tools, etc. The higher resolution product is ZMI 2000, which provides a position resolution of 0.31 nm and system output data rates are up to 10^4 KHz sampling. The highest resolution product is NewView 5000 SWLI, which provides a 0.1nm position resolution. ZYGO's interferometer product has thus realized high-resolution, high-speed measurement^[67].

2.1.4 Confocal analysis

Confocal microscopy is a new science. The first patent for a confocal microscope was obtained by Minsky in 1957^[24, 26]. The first pure analogue mechanical confocal microscope was designed and produced by Eggar and Petráň^[24, 26]. It was not until the late seventies, with the advent of affordable computers, lasers, and the development of digital image processing software, that the first single-beam confocal laser scanning microscope was developed in a number of laboratories and applied to biological and materials specimens.

The confocal principle is illustrated in fig.2.5. In such devices, light source is first focused onto the specimen by a lens through a pinhole aperture. Light from the specimen, either

reflected or fluorescent, then passes through the same focusing lens, which acts as both objective and condenser. A beamsplitter diverts this light to another pinhole aperture. Light passing through the second pinhole (confocal aperture) is then converted to an electrical signal by a detector. For a confocal device, the highest intensity collected by photodetector denotes the measured point in focus.

Laser-based confocal microscope in recent years has probed the nanometer realm using near-field method^[4, 25] and it has become an even more invaluable tool for inspection and research. Equally important is recent developments in laser confocal microscope that generates 3D images of microscopic objects. Applications benefiting from these results include research into current flow in semiconductors and the movement of biological micro-organisms.

In contrast to conventional microscopes, LSCM allows only light from the focal plane to pass through to obtain sharp 3D imaging of objects^[68]

Confocal microscopy as a technique for the biological sciences was established with the introduction of the Bio-Rad MRC500 confocal system in 1986. Since then confocal imaging has provided biologists with a means of achieving the highest quality results in fluorescent imaging both in terms of image quality and resolution.

Such confocal microscopes have found applications in bio-research and medical diagnostics. Living skin can be imaged in three dimensions, allowing fast diagnosis of a variety of ailments. The advanced capabilities also are of interest to the cosmetics industry. Recently, researchers at cosmetics firm L'Oreal (Aulnay-sous-bois, France), working with Nolan Instruments Inc. (Middletown, WI), developed a confocal laser microscope that provides sharp 3D images of living skin^[4, 69] by scanning 30 optical sections per second with 1 μ m resolution. Confocal imaging techniques also can measure the depth and the

shape of drilled holes or check the texture of fabric for imperfection^[4].

The LT Series Laser Confocal Displacement Meter developed by Keyence Corporation, represents a major breakthrough in laser confocal measurement technology. It offers long range measurement scope, small diameter of laser beam and a proprietary electro-optical system. The smallest laser beam diameter offered by LT series is $2\mu\text{m}$. The LT's exceptional measurement accuracy is not affected by surface colour, wetness, texture or any other conditions that can adversely affect the accuracy of other displacement sensors. In addition to its precision measurement capabilities, the sensor heads incorporate a built-in CCD camera which provides a microscopic view of the target surface being measured. Also, precise positioning of the LT's ultra-small, $2\mu\text{m}$ diameter beam spot is facilitated with a "cross-hair" cursor, resulting in a $0.1\mu\text{m}$ measuring resolution^[70].

Zygo's KMS and AMS Metrology Systems are designed specifically for the inspection and measurement of incoming photomasks, CDs, magnetic heads and wafers by combining dimensional metrology with through-focus 3D confocal imaging. The resolution is about 15nm.

Another company, NanoSurf, developed a scanning confocal microscope for R&D and Quality Control 3D topographical analysis system. based on a white light-confocal technology^[71]. Customer applications could be found in semiconductor, microstructures, mechanics, medical and cosmetics and fibers. The maximum vertical resolution is 5nm.

2.2 Present status of 3D profile measurement metrology

Reviewing the development of 3D profile metrology resulting from various industry innovation products and present research studies, high resolution 3D profile measurement has made a great progress. However, high speed and on line measurement is still

unresolved.

Various methods such as triangulation, interferometry and confocal, can provide nanometer scale resolution measurement. The shortcomings are elaborated as below.

2.2.1 Resolution and accuracy problems

Triangulation method has developed for over a hundred years since its discovery. The technique is very mature for high resolution profiling. 3D profile measurement products based on triangulation method are applicable to a maximum resolution of 10nm. The product of KL13OB Series Displacement Meter, based on triangulation principle, developed in 1992, could offer up to a 10nm resolution. The present products developed based on triangulation principle are still not able to break through that resolution size though their function always has been improved. The resolution of the triangulation method is difficult to increase.

In fringe projection method, the fringes can be projected to a large area on the sample surface. Due to the ambiguity of target discontinuities, coarser steps measurements, and the problem of occlusion, this technique is not suitable for high resolution measurements. For higher surface roughness ($r_a \geq 0.1 \mu\text{m}$) this technique is the best choice to use.

All triangulation methods have zones of occlusion, particularly in the near-field. The near-field blind areas are the regions where the accuracy would be greatest, given that for triangulation, accuracy is inversely proportional to target distance. Occlusion liability can be lowered by decreasing the baseline between transmitter and receiver, thereby lowering the triangulation angle, which results in lower resolution [14,17].

Interferometry was also developed for over a hundred years since the first interferometer

was proposed^[72]. The principle showed its powerful advantages with very high resolution and accuracy. The highest resolution attainable by an interferometer is 0.1nm with existing techniques. Though interferometry method is superior, the realization is also the most difficult due to its high sensitivity influenced by environmental disturbances such as vibrations, air flow, etc. Thus subtle environment noise would greatly affect accuracy of the measurement. Interferometry accuracy is also constrained by light source stability. When laser diode is used as the light source, a compact design of interferometer can be formed, but frequency drift, temperature drift and polarization drift all affect the system stability and accuracy. To keep the accuracy in the level of its resolution, the construction is very complex and the price is very high.

Confocal Microscopy is a very new technology^[26] and has shown great promise. With only half a century's development, resolution of 5nm has been achieved. For the coaxial method, the source of illumination and the receiver are coaxial. From this view, confocal principle is as good as interferometry and the accuracy is higher than the triangulation method under the same resolution condition. This advantage would seemingly overcome the synchronization problem for area scanning. With respect to environmental disturbances such as vibrations and air flow, etc, confocal is less sensitive than interferometry and the environmental noise factor affecting accuracy is not as obvious as interferometry.

2.2.2 Spatial resolution problems

Spatial resolution is also an important question when discussing the measuring resolution. Measuring resolution--axial resolution, is referred to the resolution along optical axis. While, spatial resolution, which is also called lateral resolution or transverse resolution, is

referred to the resolution in the normal plane of optical axis. It is obvious that the larger the spot size, the lower the transverse resolution. In a same measuring system, axial resolution and transverse resolution should match each other. The best match would be to have same resolution for both.

Triangulation methods are the most common form of range finding in use, but their inherent limitations have stunted exploitation. The beam spot diameter is very large as compared to the resolution of measured distance, resulting in a low spatial resolution. Typical spatial resolution of commercial products by triangulation method is above $10\mu\text{m}$.

Depth information can be obtained by interferometry by measuring the degree of coherence between corresponding pixels in the object and reference plane using the entire available illumination^[73] All transverse points are measured in parallel, and both transverse resolution and depth response are comparable with that of a confocal microscope.

Both confocal and interferometer produce high spatial resolution. The confocal spot size can be smaller than $1\mu\text{m}$. Spatial resolution is better than axial resolution.

2.2.3 Measuring speed and real time inspection problems

On-line inspection and fast sampling in large integrated manufacturing is very important. But commercial profile inspection products can not satisfy on-line inspection.

Fringe projection method can realize fast surface area inspection. But the processing, phase shifting, requires human intervention, which does not allow realtime measurement.

Even though triangulation and confocal techniques realize area scan, the sampling frequency is high, single spot measurement one by one is still a time consuming technique. Though LC-2400 series triangulation measurement system could provide $0.01\mu\text{m}$ resolution and 50 kHz sampling frequency with a $100\mu\text{s}$ response time and spot diameter $20 \times 12\mu\text{m}$, to detect an area of $1 \times 1\text{mm}^2$ specimen with point adjacent point measuring, it should have 4167 cycles and lasts for 0.5s neglecting the time required for mechanical motion. Actually, the mechanical motion costs far more time than optic and electronic signal changing. Furthermore, confocal technique requires the scan to be along the optical axis. To have $1\mu\text{m}$ measured range with $0.01\mu\text{m}$ resolution and measuring step, 100 steps require for one spot inspection. To inspect a 5" high resolution profile such as wafer (or CD), it requires 5.275×10^7 cycles' sampling for triangulation method with specifications mentioned above and 6.45×10^{10} steps' sampling for confocal method with $5\mu\text{m}$ spot size and $1\mu\text{m}$ measured range and the same resolution as the triangulation method. Interference microscopy may offer a simpler and perhaps faster solution, in part because lateral scanning is eliminated. But this method is very difficult to realize and very complex.

2.2.4 Other problems

For the triangulation profilometer, it has a restriction that in scanning modes intending to acquire data of a size over an area of view, it is inconvenient to synchronize the movement of structured illumination with the view field of the receiver which indicates that good synchronization and high resolution could not keep together in the mean time^[18].

Interferometry need high reflective surface and cannot usually be applied to measure

optically rough surfaces which are with a mean micro-roughness of a fraction of the wavelength to a few wavelengths of the light used for interferometric measurements. In interferometry, an ambiguity problem occurs when the phase difference of a neighbored pixel is more than 2π . Interferometry measurement requires calibration while confocal methodology does not need calibration.

2.3 Conclusions

The above investigation and analysis indicate that a high resolution 3D profile measurement system supporting real time imaging is an important topic. This project is to realize 3D shape inspection with fast speed and higher resolution as noted confocal method offers distinct advantages: contact free and non-invasive operation; non-destructive and a micron scale resolution.

Confocal method is similar to interferometry as far as a coaxial configuration where readings are collected along the probe beam optic axis. However, calibration is not required as is the case with the interferometry.

Confocal technique can reach higher axial resolution, higher spatial resolution, and better accuracy comparing with triangulation technique and without synchronization problem encountered in triangulation technique. These advantages appeal to researchers to exploit confocal technique to realize fast speed 3D shape measurement. Single point inspection suffers from a low speed when performing 3D shape measurement. A multi-channel confocal system to improve on the slow speed of a single channel is proposed and demonstrated as an initial step to achieve micro sensor-array confocal system.

Figures

Fig. 2.1 Diagram of triangulation principle.

Fig. 2.2 Schematic configuration of projected fringe principle.

Fig. 2.3 Common principle of interferometry.

Fig. 2.4 Area detection diagram of interferometry.

Fig. 2.5 Confocal principle[4].

Chapter 3 Confocal system

In this chapter, the confocal principle, construction of the confocal system and component's performance are anatomized. Based on this principle, some experiments and configuration analysis are conducted.

3.1 Confocal principle

The principle advantage of confocal system is its optical sectioning capability. The basic principle of confocal system is illustrated in figure 3.1. Light from the source (S) first passes through a pinhole aperture (P1) before being focused on to the specimen (Sp1) by a pair of lenses (L1 and L2). Light from the specimen, either reflected or fluorescence, then passes through the same focusing lenses, which act as both objective and condenser. A beam-splitter (BS) diverts this light to another pinhole aperture (P2). The light passing through detection pinhole is then converted to an electrical signal by a photodetector (PD). The first pinhole P1 is known as the illumination pinhole while the second one, P2, as detection pinhole. This topology is in contrast to a conventional microscope that allows out-of-focus images from off-focal-plane (defocused plane) layers to be seen.

For comparison, the simplest configuration of conventional microscope is illustrated in figure 3.2. Light passing through a condenser (L1) illuminates an object surface uniformly. A point, P_o , of the object on the object plane of an objective (L2), forms an image on an image plane (I) at P_i . The object plane is not in the focal plane of the objective, but a little longer than the focal length to get higher magnification of image. Because no detection pinhole is set before the detector, all information of the object, in-focus and defocused, is

collected simultaneously by the detector. The defocused information appears blurred and superimposed on a focused image of a section of the object. At best the blur detracts from the visual appearance of the image and at worst the noise of the blur totally obscures any description of the object of interest in the in-focus region^[71].

In confocal microscope, only when the object is in-focus, the light passing through detection pinhole reaches maximum, because the detection pinhole aperture blocks most amount of light coming from above, below or beside that focal point. Applying ray tracing analysis in geometrical optics, the light coming from different position related with focal point is indicated as follow:

- When the measured surface (PO1) of a sample is behind the focal point PO, as illustrated in figure 3.3 (a) and (b), the spot area is larger than that from the focal point. The spot size is proportional to the distance between focal point and measured surface. Suppose the lens aperture is large enough and the measured surface PO1 is ideally perpendicular to the optical axis, the light, from the edge of incident area on the surface PO1 (see fig.3.3 (a)), reflects along the path of dash line. After the beam-splitter's diversion, reflected light reaches the detection pinhole with a large area and much amount is blocked before the pinhole P2. So, only small amount of light is collected by photodetector. If the measured surface tilts a small angle at the incident spot edge from PO1 to PO'1, light may reflect along the path of dotted line as shown in fig. 3.3 (b). Then after the beamsplitter diversion, only part of reflected light passes through the pinhole P2. Therefore, the intensity response is smaller.
- Considering the measured surface (PO2) of a sample is placed before the focal point PO, as illustrated in figure 3.4 with assumption that both the lens aperture and beamsplitter are large enough. Most of incoming light from the edge of incident area on

the surface P02, upon returning along the path of dash lines is blocked before the pinhole P2.

- And when the light, from the point (A1) beside the focal point (AO) on the focal plane PO, as illustrated in figure 3.5, passes through lens system and reflected by the beamsplitter, is focused beside the pinhole P2 at point A1'.

Luminance is approximately inversely proportional to square of the spot size on the specimen. The intensity distribution on unit area is thus approximately inversely proportional to square of the defocus distance as illustrated in figure 3.6. Thus optical sectioning is achieved by the combination of two related effects:

- Firstly, the illumination is brought to a sharp focus on a single point within the object. The illumination above and below the point of focus is, therefore, defocused and these regions have low luminance.
- Secondly, the light emanating from that point of focus is collected and focused sharply on to a detection pinhole which is placed before the detector.

With this arrangement, the light which originates from various parts of the object that lie above, below or to one side of the point of focus is focused behind, in front of or to one side of the aperture respectively and is, therefore, defocused in the plane of the pinhole. Because of this only the visibility of specimen features of-interest positioned in the focal point is enhanced. Hence, confocal principle only allows sharp 3D imaging of object.

The confocal system configuration and its performance are analyzed in the following section.

3.2 Confocal system configuration and analysis

3.2.1 Basic configuration

A complete confocal system consists of light source, pinhole, lens system, beamsplitter, photodetector, scanning system, and imaging processing system.

3.2.2 Light source

In confocal system, light source is either white light or laser (including laser diode) light. Laser light is commonly used. Since an image obtained from a broadband light source gives a potential disadvantage as it creates inherent axial aberration in the optical system. This will increase the width of the depth response and thus degrade the resolution of the confocal system. Laser diode is used in the study of confocal system. When selecting a laser as an illuminator, some of important performance specifications considered include intensity, stability, pointing, speckle noise, wavelength stability and Gaussian, output spectrum.

(1) Stability of illuminator

Intensity stability is a strict requirement, because a change in the source intensity can be interpreted as a change in reflected intensity of the sample. Any intensity variation will be recognized as distance variation even though the specimen is not moved. In addition to intensity stability, laser is specified by their pointing stability. The pointing stability is a critical factor when a spatial filter, or a pinhole, is used in the beam expander. In this case instability in the pointing direction of the laser will be converted into intensity changes of the light at the sample. When no pinhole is used in the illumination system, on the other

hand, pointing instability can change the apparent position of the spot on the sample. In a properly designed instrument, the change of position is generally small compared to the spot size of the beam on the sample. Speckle noise is another aspect of intensity stability to be considered. Laser is a high coherent light source. Speckle occurs when an optically rough surface (rough on the scale of the wavelength of light) is measured. Speckle noise leads to adding in or out of phase at the detector. Phase variation modifies the intensity at the detector. Also the feedback of the reflected beam into the laser can cause intensity fluctuation. Wavelength stability is less important than intensity or pointing stability. A small change in the source wavelength will have little effect on the image.

In order to appreciate the influence of light source and indeed other components, it is important to understand the basic properties of Gaussian beam.

(2) Gaussian beam

A beam emitted from a laser with $\text{TEM}_{00}^{[74]}$ mode output is a perfect plane wave with a Gaussian transverse irradiance profile as shown in figure 3.7, in which the transverse coordinate represents contour radius and the column represents irradiance percentage. Light with pure TEM_{00} mode allows a beam expander to illuminate the objective lens uniformly without adding the pinhole P1 (in fig. 3.1) to the illumination path to form a spatial filter (see fig. 3.8).

Unfortunately, coherent Gaussian beams have peculiar transformation properties that require special consideration. The output from real-life lasers is not truly Gaussian although helium neon lasers and argon-ion lasers are a very close approximation. To accommodate this variance, a quality factor, M^2 (called the M-square factor) has been defined to describe the deviation of the laser beam from a theoretical Gaussian.

The M-square factor is a dimensionless beam propagation parameter, which is defined by^[76]

$$M^2 = \frac{w_{0R}\theta_R}{w_0\theta} \quad (3.1)$$

where w_{0R} and θ_R are the beam waist (beam diameter of the focus) and far-field divergence of the real beam, respectively, w_0 and θ are the beam waist and far-field divergence of the fundamental Gaussian beam.

For a theoretical Gaussian, $M^2=1$, while for a real laser beam, $M^2>1$. Helium neon laser typically has an M^2 factor that is less than 1.1. For ion laser the M^2 is typically between 1.1 and 1.3. Collimated TEM₀₀ laser diode beams usually have an M^2 factor ranging from 1.1 to 1.7. For high-energy multimode lasers, the M^2 factor can be as high as 3 to 4. In all cases, the M^2 factor, which varies significantly, affects the characteristics of a laser beam.

In general, laser beam propagation can be approximated by assuming that the laser beam has an ideal Gaussian intensity profile, corresponding to the theoretical TEM₀₀ mode. Laser diode beams are asymmetric and often astigmatic, which causes their transformation to be more complex. Laser diode beam needs to be collimated in order to obtain good quality of the beam. Therefore the illumination pinhole can not be neglected. Laser diodes can eliminate feedback of the reflected beam into the laser, in return, which reduces the intensity fluctuation, factor.

(3) Beam waist and its divergence

Confocal system demands light source to be perfectly collimated. But diffraction causes light waves to spread transversely as they propagate, and it is therefore impossible to have

a perfectly collimated beam. Also for this reason, any perfect lens could not focus light to a spot with zero size or unlimited small diameter. Under ordinary circumstances, the thinnest beam of spreading is called Gaussian waist. Even if a wavefront of Gaussian TEM₀₀ laser beam was made perfectly flat at some plane, with all elements moving in precisely parallel direction, it would quickly acquire curvature and begin spreading (see fig. 3.9) in accordance with^[77]

$$R(z) = Z \left[1 + \left(\frac{\pi w_0^2}{\lambda Z} \right)^2 \right] \quad (3.2)$$

And

$$w(z) = w_0 \left[1 + \left(\frac{\lambda Z}{\pi w_0^2} \right)^2 \right]^{\frac{1}{2}} \quad (3.3)$$

with Z being the distance propagated from the plane where the wavefront is flat, λ as the wavelength of light, w_0 , the radius of the $1/e^2$ irradiance contour at the plane where the wavefront is flat, $w(z)$ as the radius of the $1/e^2$ contour after the wave has propagated a distance Z, and $R(z)$ as the wavefront radius of curvature after propagating a distance Z. $R(z)$ is infinite at $Z=0$, passes through a minimum at some finite Z, and rises again toward infinity as Z is further increased, asymptotically approaching the value of Z its self.

The plane $Z=0$ marks the location of a Gaussian waist, in which the plane of the wavefront is flat, and w_0 is called the beam waist radius. A waist occurs naturally at the mid-plane of a symmetric confocal cavity.

When the laser beam is converged by focusing singlet, the focal point is just the same as Gaussian waist. If a uniform irradiance distribution had been presumed at $Z=0$, the pattern

at $Z=\infty$ would be the well known Airy pattern. Airy pattern is a name given to the transmitted beam field after a uniform beam passes through a circular clear aperture.

The diameter of laser beam, is the distance between axial and the point at which the beam irradiance (intensity) has fallen to 13.5% ($1/e^2$) of its peak.

(4) Energy distribution

In light propagation, some energy is spread outside the region predicted by rectilinear propagation. This effect, known as diffraction, is a fundamental and inescapable physical phenomenon.

Diffraction effects are traditionally classified into either Fresnel^[78] or Fraunhofer types.

Fraunhofer diffraction is the light spreading effect of an aperture when the aperture (or object) is illuminated with an infinite source (planewave illumination) and the light is sensed at an infinite distance (far field) from this aperture. A lens or lens system of finite positive focal length with planewave input maps the far field diffraction pattern of its aperture onto the focal plane. Therefore, it is Fraunhofer diffraction that determines the limiting performance of confocal optical system. More generally, at any conjugate ratio, far field angles are transformed into spatial displacements in the image plane.

The diffraction pattern resulting from a uniformly illuminated circular aperture actually consists of a central bright region, [see fig.3.10 (a)], surrounded by a number of much fainter rings known as the Airy pattern. Each ring is separated by a circle of zero intensity.

The irradiance distribution in this pattern can be described by^[77]

$$I_x = I_0 \left[\frac{2J_1(x)}{x} \right]^2 \quad (3.4)$$

Where I_0 is the peak irradiance in image and

$$J_1(x) = x \sum_{n=1}^{\infty} (-1)^{n+1} \frac{x^{2n-2}}{(n-1)!n!2^{2n-1}} \quad (3.5)$$

Where $J_1(x)$ is Bessel function of the first order, and x is the position shown in figure fig.3.10 (b) and is determined by

$$x = \frac{\pi D}{\lambda} \sin \theta \quad (3.6)$$

where λ is the wavelength, D is the aperture diameter, and θ is the angular radius from pattern maximum. This formula demonstrates the far field irradiance distribution from a uniformly illuminated circular aperture of diameter, D .

The table 3.1 shows the major features of pure (aberration free) Fraunhofer diffraction patterns of circular apertures. The table lists the position, relative intensity, and percentage of total pattern energy corresponding to each ring or band. The position x is expressed in terms of angle θ after rearranging equation 3.6, that is

$$\sin \theta = \frac{\lambda x}{\pi D} \quad (3.7)$$

where D is the aperture diameter. D and λ are in the same unit.

Table. 3.1 Energy distribution in the diffraction pattern of a circular aperture

Ring	Position (x)	Relative Intensity (I_x/I_0)	Energy (%)
Central Maximum	0.0	1.0	83.8
First Dark	1.22π	0.0	0
First Bright	1.64π	0.0175	7.2
Second Dark	2.23π	0.0	0
Second Bright	2.68π	0.0042	2.8
Third Dark	3.24π	0.0	0
Third Bright	3.70π	0.0016	1.5
Fourth Dark	4.24π	0.0	0
Fourth Bright	4.71π	0.0008	1.0

The total width (d , at the base level) of the central maximum of the diffraction pattern is

$$d = \frac{1.22\lambda}{\sin \theta} \quad (3.8)$$

which dictates the fundamental diffraction limits of performance for circular lenses.

In optical lens system, numerical aperture is defined to be

$$NA = n \cdot \sin \theta \quad (3.9)$$

In this expression, n is the refractive index of the medium between the lens and the sample,

θ is the half-angle subtended by the lens at its focus, as illustrated in figure 3.11.

When the medium is air, the function becomes

$$NA = \sin \theta \quad (3.10)$$

The larger the angle is, the more light that can be collected. Hence, the numerical aperture is a measure of both the resolution and the light gathering ability of the lens.

Substitute formula (3.10) into (3.8),

$$d = \frac{1.22\lambda}{NA} \quad (3.11)$$

which is known as spot size of the lens system. Spot size is also expressed as

$$d = 2.44\lambda f / \# \quad (3.12)$$

Notice that it is the f-number of the lenses ($f/\#$) that determines the limiting spot size. f-number of the lens is defined to be the effective focal length divided by system clear aperture, that is

$$f/\# = \frac{f}{a} \quad (3.13)$$

where a is the clear aperture of a lens.

Spot size (eqn 3.11) is one of the most important parameters in a confocal system since it not only affects image quality but also affects the spatial resolution.

3.2.3 Lens system

Lens in confocal system serves two functions. It acts as a condenser to illuminate the light source to the object surface, while the other function is as an objective to collect the object reflected or scattered light. Since the lens is used for both illumination and receiving the reflected light, the negative effect of lens system must therefore be kept to an absolute minimum. Proper spot size focused by objective lens, short focus depth and minimum aberrations especially minimum spherical aberration are the keys to having adequate imaging performance.

(1) Condenser and objective

The function of condenser is to gather light from the light source and concentrate it into the specimen with uniform intensity over the entire view field. Either objective or condenser has singlet form or multi-lens. Objective is responsible for primary image formation and plays a central role in determining the quality of images that the microscope is capable of producing. Objective is also instrumental in determining the magnification of a particular specimen and the resolution under which fine specimen detail can be observed in the microscope.

For conventional microscope, condenser and objective is arranged in separate structures (figure 3.2). The illumination quality on the specimen is very important. One of the most critical aspects in optical microscopy is to ensure the specimen illuminated with light that is bright, glare-free, and evenly dispersed in the field of view. To keep enough luminance on the specimen, large aperture cone of the condenser is necessary.

The practical aspects of adjusting a microscope for proper illumination are to optimize the intensity and the angle of light entering in the objective front lens. On the other hand,

because separation arrangement of condenser and objective, the conjunction should be even. That is matching the parameters of NA and focal length of two lens systems. Each time when the objective is changed, a corresponding adjustment must be performed on the condenser to provide a proper light cone for the numerical aperture of the new objective.

Research-level microscopes contain one of several light-conditioning devices such as iris and diaphragm that are often positioned between the illuminator and condenser, to adjust the illumination cone onto the specimen to match objective cone and to increase the image quality^[79,80].

The parameters: focal length, numerical aperture, field of view and depth of focus are most important features affecting optical performance. The lens designs also should be considered eliminating most optical aberrations.

In confocal microscope, condenser and objective lens are arranged in the same path, in which condenser and objective share the same lens system (fig. 3.1). The lens system not only condenses the light onto the specimen, but also produces the image onto the detector, which simplifies system construction. For confocal system, field of view of the objective loses its action, and is substituted by focusing spot size of the objective. Chromatic aberration is not important problem using high coherent light source as illuminator, but spherical aberration should be considered to eliminate for the sake of keeping good resolution.

(2) Resolution parameters

The depth of field and depth of focus are two important parameters and reflect system resolution in a confocal system. In an imaging system, the depth of field refers to a distance Δ in object space over which the system delivers an acceptably sharp image on the

image plane I (figure 3.12). The depth of field generally is determined by the lens design, lens specifications and the required image quality. Because the criterion of image quality also depends on the propagation of light wave and energy receiver, depth of field is also defined by the distance resolution of the intensity response^[25,26]. No agreed standard is used to estimate the depth of field. From the view of physical optics, depth of field describes the depth resolution with the distance d_z between half-power points (3-dB points) of the intensity response given by^[25,26]

$$d_z = \frac{0.9\lambda}{NA^2} \quad (3.14)$$

The depth resolution is also affected by another parameter, depth of focus. From the view of geometrical optics, the depth of field estimates as

$$\Delta = \frac{4f \cdot NA \cdot \epsilon}{4 \cdot NA^2 - \epsilon^2} \quad (3.15)$$

where f is the focal length of lens L1 (Fig.3.12), NA is numerical aperture of the lens, ϵ is the limited resolution angle acceptable of the lens system to obtain the sharp image. The criterion for what is acceptably sharp image is decided by the factor ϵ and chosen by the property of the image system. ϵ is chosen as the limited recognition angle. Usually, 1' (one minute radian) can be recognized by human eye and 10" (ten second radian) can be recognized by a detector.

If the measured spot is within the depth of field, the image system recognizes a clear image and if the measured spot of specimen outside the depth of field, the image is blurred and weak. Thus for a spot within the depth of field, the image detector response does not change much. It is very clear that the depth of field of the objective lens affects the image resolution. The longer the depth of field is, the lower the resolution will be. Focal depth is the other factor affecting the system resolution. For an imaging system, which is illustrated

in figure 3.13, depth of focus ($\pm\Delta Z$) is the range in image space over which the system delivers an acceptably sharp image. In other words, this is the amount that the image surface (such as a screen or piece of photographic film or a photodetector) could be moved while maintaining acceptable focus. Again, criteria for acceptability are defined arbitrarily. That is the range in image space over which the focused spot diameter remains below an arbitrary limit, which can be derived from the formula (3.2). The image plane is at the waist plane which value is at $Z=0$, to solve for $Z = \Delta Z$, the result is

$$\Delta Z = \pm \frac{\pi w_0^2}{\lambda} \sqrt{\left(\frac{w_z}{w_0}\right)^2 - 1} \quad (3.16)$$

where w_0 is the smallest image size, w_z is the size in the plane of which the system delivers a limited sharp image.

The next step in performing a depth-of-focus calculation is to set the allowable degree of spot size variation, within this variation, the detector can not recognize the changing. Normally, a typical value is of 5%, that is $w(z)=1.05 w_0$,

Then

$$\Delta Z = \pm \frac{0.32\pi w_0^2}{\lambda} \quad (3.17)$$

Since the depth of focus is proportional to the square of focal spot size, and focal spot size is directly related to f-number, the depth of focus is proportional to the square of the f-number of the focusing system. The relationship of f/# with signal response, focal spot size (R_s), depth of focus (ΔZ) and depth of field (d_z) is shown in figure 3.14. Depth of focus and depth of field increase with increasing f-number. In order to keep small focal spot size and high resolution, it is necessary to decrease f-number.

(3) Aberration

The most common aberrations that affect the resolution of confocal system are spherical aberration and axial chromatic aberration. In this project He-Ne laser and laser diode are used in experiments as light source, which have a single wavelength and narrow bandwidth. Chromatic aberration is not an important factor. In the paraxial region, all rays originating from an axial point again pass through a single point on the axis after traversing lens system. But for large angles of divergence, rays do not pass through the same point on the axis. This phenomenon is called spherical aberration. Spherical aberration is caused by lens shape and becomes significant at large divergence angle. Large $f/\#$ causes small spherical aberration. However, in confocal system, large $f/\#$ increases focal spot size, depth of field and depth of focus, and lowers system resolution. Spherical aberration can be minimized or eliminated by selecting and testing high-quality lens or designing multi-lens system.

3.2.4 Pinhole

Confocal system rejects not only the stray light from the specimen but also scattered light from within the optical instrument itself, resulting in increased contrast and signal-to-noise ratio (SNR) in the final image. This function is most, merited from pinholes. The pinhole is an important component for determining both axial and transverse resolutions of confocal system. To select a pinhole, both reflective property of the sample and required resolution should be considered. The tradeoffs are simple. A larger size of the pinhole transmits more light to the detector, generating a higher intensity of the signal but with lower resolution. A smaller pinhole has theoretically better resolution, but transmits lower light intensity to the

sample, so the SNR decreases. In practice, the pinhole diameter should have approximately the same size as the half-power width of the Airy pattern produced by the pinhole lens.

Usually a spatial filter pinhole (illuminating pinhole) is incorporated in the beam expander in order to produce a uniform illumination beam, although this is not strictly necessary.

The radiation from laser is expanded, if the laser beam is noisy, however, it can be “cleaned up” by focusing it onto a pinhole somewhat smaller than the spot size of the focused beam.

3.2.5 Photo detector

After passing through the pinhole the light impinges on the photodetector that generates an electrical signal whose amplitude is proportional to the light intensity. There are different types of photodetectors available for light intensity measurement such as vacuum-tube photodetectors, semiconductor photodiodes, and semiconductor photoconductive devices. The choice of a particular detector depends on the wavelength of the light, the sensitivity needed, the speed of response required, and so forth. Wavelength is especially significant because many photodetectors respond only in certain regions of the spectrum. An ideal detector that is used for confocal measurement should have following properties:

- A large responsivity at the wavelength to be detected;
- A small noise equivalent power, that is, noise introduced by the detector;
- And sufficient speed of response to follow variations in detected light intensity signal.

Several conventional quantities are often used to describe these characteristics including: responsivity, spectral response, noise equivalent power, specific detectivity, quantum efficiency, linearity and response time.

(1) Responsivity

Responsivity is specified as the ratio of the detector output to the light input, which gives a measure of the detector's sensitivity to radiant energy. For a detector that generates a current output, the responsivity "R" is given by

$$R = I/\Phi_e = I/(E_e \cdot A_d) \quad (3.18)$$

where I is the root mean square (RMS) signal with current output of the detector measured in amperes (A) and Φ_e is the incident radiation power measured in watts (W). E_e is the incident irradiance in W/cm² and A_d is the irradiated area of the detector in cm².

For a voltage output detector the responsivity is expressed as,

$$R = V_d/\Phi_e = V_d/(E_e \cdot A_d) \quad (3.19)$$

where, V_d is RMS signal with voltage output of the detector measured in volts (V).

Thus the responsivity is essentially a measure of the effectiveness of the detector for converting electromagnetic radiation to electrical current or voltage. Responsivity will vary with changes in wavelength, bias voltage, and temperature. Responsivity changes with wavelength since the reflection and absorption characteristics of the sensitive material in detector change with wavelength. Temperature changes affect both the optical constants of the detector material and its collection efficiency. In this project, a red laser (or laser diode) is selected as light source. Thus the higher responsivity at $\lambda=630\sim650\text{nm}$ is required. Semiconductor photoconductive devices are suitable at high level illumination, but confocal signal is usually very low. Hence, the photoconductive detector is not a good choice for confocal signal measurement.

(2) Response time

Response time^[81] normally refers to the time that the photocurrent generated by photodetector rises to 63.2% of the final or steady-state value. The recovery time^{''}] is the time it takes for the photocurrent to fall from its steady-state value to 36.8% of its steady-state value. Rise time^[81] is used to describe the speed of response of the detector. Rise time is the time difference between the 10% point and the 90% point of the peak amplitude output on the leading edge of the pulse. Fall time^[81] is measured between the 90% point and the 10% point of the trailing edge of the pulse waveform. Rise time and fall time are the most significant parameters and often quoted by manufacturers in their catalogue. Ideally, a detected signal will be with a rise time, which is less than or equal to 1/10 of the rise time of the photodetector. In confocal system a continuous wave light source is used. The detected signal is changed with the defocused distance. Thus the confocal scanning speed affects processing of the image.

Photomultiplier tube (PMT) and vacuum photodiode tube are two kinds of vacuum-tube photodetectors. Because the response time of photodiode is too slow (1ms), it is not suitable for fast speed measurement.

(3) Quantum efficiency and noise equivalent power

Quantum efficiency (QE) is the ratio of countable events (such as photoelectrons or electron-hole pairs) produced by the incident photons to the number of incident photons. It is expressed as

$$QE = R(\lambda) \cdot h \cdot c / (e \cdot \lambda) \quad (3.20)$$

where $R(\lambda)$ is the responsivity of detector at λ ; h is Planck's constant; c is the velocity of light.

The responsivity defined above gives a measure of how much output from a given detector for a specified input. But it does not specify the minimum recognized output. In confocal system, the light passing through the detection pinhole is small and sometimes may be even as low as the noise. In this case to separation of the signal from the random fluctuations that make up the noise becomes important. Noise equivalent power (NEP) is to describe the amount of optical power incident on the surface of a photodetector that produces a signal at the output of the detector just equal to the noise generated internally by the detector. This is usually the minimum detectable signal level. Noise can be divided into two broad categories: externally induced noise, and internally generated noise. The NEP is related to the internal noise generated within the photodetector. The lower NEP, the better the photodetector is.

For confocal system, to realize high speed high resolution measurement, the best choice of detector is low power input, high responsivity, high QE, low rise time and low NEP.

Figure 3.15 shows the spectral response curves of some typical PMT and photodiodes detectors^[82].

Figure 3.16 shows QE curves of some typical PMT and photodiode detectors^[83~85].

Photomultipliers have higher responsivity than photodiodes but QE of available PMT is only 1-5% at 620~650nm, which limits the SNR of the instrument. Photodiodes on the other hand have high quantum efficiencies throughout the visible light but with little internal gain and higher inherent noise than PMT. Table 3.2 gives the comparison of rise time (RT) and NEP among PIN-photodiodes, avalanche photodiodes and enhanced photodiodes. Enhanced photodiodes have long rise time from 0.5ps to 10 μ s and large NEP from 1 to 30 $\times 10^{-14}$ W/ $\sqrt{\text{Hz}}$ depending on different products' model. Most avalanche photodiodes also have higher NEP than that of PIN photodiodes. Confocal system has low

signal input which need low NEP. Thus the best choice of photodetector for fast speed high precision confocal measurement is PIN photodiodes with low NEP value.

Table. 3.2 Comparison RT and NEP of photodiodes

Comparison items	PIN	APD	EPD
Rise Time (ns)	0.4~40	0.18~2	500~10000
NEP (10^{-14} W/ $\sqrt{\text{Hz}}$)	0.1~8	0.8~2	1~30

3.2.6 Profile scanning system

The image obtained by photo-detector needs further calculation to judge whether the measured point is in focus or not. The premise of the judgement is to get a series of images along the optical axis, hence the need for a process of scanning scheme optical axis (vertical scanning). Vertical scanning methods include translation stage movement, tuning fork vibration, varying refractive index of the objective and moving optical sensor.

For confocal principle, only one spot of specimen is detected at one time. Through vertical scanning, relative position of the measured spot on the specimen is then obtained. To obtain the profile of specimen, a surface (X-Y surface) scanning is needed. Moving translation stage, using acousto-optic element such as acousto-optic deflector to realize surface scan, or by rotating reflection mirror realizing surface scanning, etc, are typical methods used.

While choosing a proper scanning method is important to realize fast speed measurement, it is not a major aspect of this project and will not be discussed in detail here. The motor control translation stage is used to realize z-scan in this project.

3.3 Initial experiments and analysis

To have a practical understanding of the confocal system performance and to improve the

design of the confocal system, experiments were carried out using those elements available in lab to study the effect of NA to resolution and intensity distribution. Some problems and methods are discussed.

3.3.1 System setup

Figure 3.17 is a confocal setup. In this setup, light from a laser (He-Ne Laser), passing through an expander (EP), becomes a uniform collimated beam. A polarized beam splitter (PBS) which works at wavelength of 632.8nm, redirects the beam, which is focused on the reference object (M) by an objective lens (L1). Reflected light from the reference object mounted on a manual-control 3D translation stage, then passes through the same focusing lens L1 and PBS to an imaging lens (L2) before converging to a detector pinhole (P1). To ensure the reflected light has the same polarization, a quarter wave plate ($\lambda/4$) is set between lens L1 and PBS. A photoaetector (PD) collects the light signal passing thought the pinhole P1 and converts the optical signal into electrical signal. Power meter (PM) processes the electrical signal, converts to digital signal and displays on a screen. A high precision displacement sensor (DS) records the displacement of translation stage along optical axis (z direction) with resolution of 0.1 μm .

3.3.2 Experiments and results

In this confocal setup, four seta of objective and image lenses were used with NA value of 0.25, 0.40, 0.65 and 0.85 to observe the different phenomena of resolution. Table 3.3 lists some parameters of objectives and their resolution. As noted earlier, pinhole diameter should equal focused beam diameter which in turn is proportional to the NA. In this set up 10 μm size pinhole was available in the lab and was chosen.

After the setup was aligned, the reference object was set near the focal point. The Airy pattern was observed using CCD and PC monitor instead of photodetector and power meter in fig. 3.17. Four images acquired using this setup with 20X objectives are displayed in figure 3.18. Image (a) of fig. 3.18, is Airy pattern when the reference object was at the focal spot; image (b) is Airy pattern when the reference object was about 200 μm beyond the focal point; image (c) is when the reference object is at an axial position of 500 μm away from the focal point; and image (d) is when the reference object is 1000 μm away the focal point.

Table. 3.3 The list of objectives parameters

Objective	Working distance (mm)	NA	Spot size d_s (μm)	Resolution (3-dB points) d_z (μm)
10X	5.5	0.25	3.1	9.1
20X	1.7	0.40	1.9	3.6
40X	0.6	0.65	1.2	1.3
80X	0.3	0.85	0.9	0.8

The saturated intensity in the image center occurring is because a strong light source. The fringes seen around the edge of Airy pattern are coherent interference generated within reflected light or stray light reflected among optical elements, which may degrade signal quality and embody fluctuation thus reduce the resolution of system.

After the Airy pattern was observed, the photodetector and power meter were placed back as configuration shown in fig. 3.17 and the confocal response was observed.

The translation stage was moved along the Z direction step by step at 5 μm interval monitored by the displacement sensor. The data output from power meter are integrated intensity received by photodetector. The total range in this experiment was about 2000 μm .

The data were recorded with different NA and shown in figure 3.19. The horizontal axis is the distance from the focal point and the vertical axis is the intensity distribution and the center column was in the focal point. The numbers showed in the figure are the NA of the objectives. The variation of data with movement of the translation stage along the optical axis was observed. When the reference object was near the focal point, the power meter showed stable results, and when the defocus distance was larger, the digits fluctuated with time. This is because when the defocused distance is large, the intensity collected by photodetector is small. Low signal reduces the SNR. Random noise interfered with low signal causing output fluctuation. In this experiment, the reference object is a mirror, which has a high reflection. Normally, the measured surface is not an ideal reflector. If the SNR is low at the best focus, the fluctuation becomes a problem, which lowers the reliability of measurement.

The side lobe fluctuation is not a serious problem in system design because the peak of side lobe is much smaller than the central peak. However it must be considered in signal processing, in case the higher order diffraction peaks may be recorded as focus-peak by mistake.

It can be seen in the fig.3.19 that the sharper the curve the higher the resolution is. This is also consistent with the confocal theories^[26]. It is also clear that with the higher NA of objective, the resolution of system increases.

When the alignment was not proper, the image of the Airy pattern collected by the CCD was not a circle but part of disk when moving the stage along z direction. Also, the electric signal of the point photodetector abruptly disappeared when scanning along z direction. This also should be considered in the multi-channel confocal system design of the project.

3.4 Discussion and conclusion

In contrast to a conventional microscope, confocal microscope only allows in-focus images to be seen. To realize confocal 3D profile inspection, the basic configuration, components performances, system parameters (spot size, resolution and stability, etc.) are analyzed. The experiments on Airy pattern and confocal response curves are analyzed. In order to realize multi-channel confocal 3D profile measurement system with micro-size resolution inspection and simplify structure, fiber confocal system is conceived and will be discussed in the following chapter.

Figures

Fig. 3.1 Basic principle of confocal technique.

Fig.3.2 Simplified schematic diagram of conventional microscope.

(a) The measured surface PO1 is perpendicular to the optical axis, the light, from the edge of incident area on the surface PO1 reflects along the path of dash line.

(b) If the measured surface tilts a small angle at the incident spot edge, light reflects maybe along the path of dot line.

Fig. 3.3 In confocal principle, light from the plane away focus point.

Fig. 3.4 In confocal principle, light from the plane before focal point.

Fig. 3.5 In confocal principle, light beside focus point.

Fig. 3.6 Defocused luminance distribution with uniform illumination.

Fig. 3.7 Irradiance profile of a Gaussian TEM_{00} mode.

Fig. 3.8 Ideal TEM_{00} mode as light source in confocal system no need pinhole P1.

Fig. 5.9 Growth in $1/e^2$ contour radius with distance propagated away from Gaussian waist.

(a) Airy pattern.

(b) Cross section of the Airy pattern.

Fig. 3.10 Typical diffraction pattern for a circular aperture.

Fig. 3.11 The relationship of parameters of lens.

Fig. 3.12 depth of field in confocal system.

Fig. 3.13 Depth of focus in image space of confocal system.

Fig. 3. 14 Parameters relationship with f/#.

Fig.3.15 Typical response curves of PMT and PD.

PIN-PD-- PIN photodiodes
 APD--avalanche photodiodes
 EPD--enhanced photodiodes
 PMT--photomultiplier tube

Fig.3.16 QE curves of some typical PMT and photodiode detectors.

PD--photodiode

PMT--photomultiplier tube

Fig. 3.17 One-arm confocal setup.

Fig.3.18 Airy pattern obtained from setup fig. 3.i7.

Fig.3.19 Relationship between intensity distribution and the distance of defocus.

Chapter 4 Fiber confocal system

Optical fiber and fiber coupler have specific properties that can be used to construct confocal 3D profile measurement system. The fiber confocal system is built and analyzed. System evaluation is discussed and some techniques to improve system performance are elaborated.

4.1 Optical fiber analysis

4.1.1 Fiber optics

The optical fiber for transmission of light has many attractive advantages such as:

- Immune to environmental noise such as radio frequency interference (RFI) and electromagnetic interference (EMI), potentially resistant to ionizing radiation,
- Its small size, flexibility, and light weight, allows accessibility into normally inaccessible areas, and offered portability and compactness,
- Solid-state Reliability. Since light is confined within the solid structure of the fiber, thus eliminating interference from dust and air turbulence as in the case when light passes in air.
- Tolerance of extreme environmental conditions,
- Passive and non-electrical, and does not generate heat.

An optical fiber consists of a central core surrounded by a layer of material called cladding, which in turn is covered by a jacket. The core transmits the light waves while cladding

cladding keeps the light waves within the core by total internal reflection and provides some strength to the core. The jacket protects the fiber from moisture and abrasion.

The fiber “mode” is used to describe the propagation property of electromagnetic waves. Fiber is classified according to the mode: single-mode fiber and multimode fiber. Simply, a single mode fiber has only one path for the light while multimode means several paths through the fiber.

Single-mode fiber has a small core diameter from 3.6 to 10 μm and a cladding diameter of 88 μm or 125 μm , while multimode fiber has a core diameter above 10 μm .

Most fibers are step-index fibers, the refractive index between core and cladding is different, which make the light ray bend at the interface from one medium to the other medium (illustrated in figure 4.1).

According to Snell’s Law when light from medium with refractive index n_0 is incident on the fiber core, the refracted beam follows path given by

$$n_1 \cdot \sin \theta_1 = n_0 \cdot \sin \theta_0 \quad (4.1)$$

where n_1 is refractive index of fiber core, in air, $n_0 = 1$. θ_0 is the incident angle, and θ_1 is the angle of refraction. The light ray then passing through the fiber core reaches point P2 which is at the interface of the core and cladding. The ray at the interface transmission follows Snell’s Law again and gives that that

$$n_1 \cdot \sin \varphi_1 = n_2 \cdot \sin \varphi_2 \quad (4.2)$$

where n_2 is refraction index of fiber cladding, φ_1 is incident angle from the fiber core at the interface, and φ_2 is refractive angle in the medium of the fiber cladding.

When light transmitting from one medium to another medium of different refractive indices, reflection as well as refraction takes place. However, when light propagates from a

medium of higher refractive index to a medium of lower refractive index, refraction (the ray of P2 to P4 in fig. 4.1) depends on the incident angle. When the incident angle reaches a critical value. $\varphi_1 = \varphi_c$, beam is reflected back into the same medium. This phenomenon is called total internal reflection (TIR) and φ_c is the critical angle. Fiber can keep selective rays travel in total internal reflection. In optical fibers, the refractive index of the core (n_1) is greater than the index of the cladding (n_2). According to Snell's Law at the critical angle, we have

$$n_0 \cdot \sin \theta_0 = n_1 \cdot \sin \theta_1 = n_1 \cdot \sin(\pi/2 - \varphi_c) = \sqrt{n_1^2 - n_2^2} = NA \quad (4.3)$$

The quantity $n_0 \cdot \sin \theta_0$ is defined as Numerical Aperture (NA) of the optical fiber.

The area bounded by the angle $2\theta_0$ is known as the acceptance cone as shown in fig. 4.2.

When light rays strike the end surface of an optical fiber at different angles, only those rays within the acceptance cone can propagate through the fiber core. Other rays (like ray2, as shown in fig. 4.2) will refract into the cladding and eventually lost by radiation. For greater efficiency of light transmission and the resolution of objective lens system a larger acceptance cone of fiber is preferred.

When fiber is used as light intensity detection sensor, the detected intensity depends on the distance between reflected target and fiber probe, also depends on the fiber bundle configuration^[86]. Single fiber sensor has a higher resolution compared to fiber bundles. Thus single fiber sensor is the best choice for high resolution 3D profile inspection system.

4.1.2 Fiber coupler

Coupler is a device to provide mutual coupling between multiple fibers. The light

transmission path in 2X2 fiber coupler is illustrated in figure 4.3 in which arm 1 and 2 are input ports, arm 3 and 4 are output ports. When input beam passes through fiber coupler, at the interconnection, the beam is split up into two beams and reaches to arm 3 and 4 respectively. In this way, the fiber coupler behaves as a beam-splitter as well as a transmission line.

4.2 Fiber confocal system configuration and the analysis

4.2.1 System configuration

From the above introduction, optical fiber has attractive advantages as below:

- A transmission line of light source,
- A small fiber core diameter,
- An acceptance cone for rays selection,
- Directional fiber coupler can perform as a beam-splitter.

All these advantages make it possible to construct fiber confocal system in which fiber and fiber coupler are used to replace pinhole and beam splitter.

(1) Setup

A 2X2 fiber coupler is used to construct a 3 ports and 4 ports fiber confocal system as illustrated in figure 4.4 and figure 4.5 respectively.

One of the two input fiber arms marked “1” is used to couple source light into the system. The other input fiber arm “2” is used for unbalanced detection of light back reflected by the specimen and connects to a photodetector. Output fiber arm “3” is used as the sensing arm of the system. The beam leaving arm 3 is tightly focused on a specimen via a 4f-lens

system. In fig.4.4 fiber arm 4 is not used while in fig.4.5 fiber arm 4 is used for source fluctuating detection.

(2) Components

In this section, components for constructing a one-channel confocal system and a multi-channel confocal system are described.

• Fiber

When single-mode fiber is used in confocal system, single mode and smaller core diameter make spot size smaller but lower signal response compare with multi-mode fiber confocal system. Both single-mode and multi-mode fibers are used to construct the fiber confocal system. A 125 μm cladding diameter and 10 μm core (125/10) single-mode fiber and (125/50) multi-mode fiber are selected. The fiber NA ($\text{NA}_f=0.11$) as decided by fiber refractive index of core and cladding mediums is an inherent property of fiber. 2X2 multi-mode fiber coupler and single-mode fiber coupler were fabricated using JW2000 model fiber coupler production system bought from Photonik Technologies Company.

• Laser diode

In fiber confocal system configuration, laser diode had a wavelength of 650nm with the output power of 200~300 μW bought from Comate Electro Optics Pte Ltd.

• Lens

To synthesize lens properties, system configuration and performance, gradient index (GRIN) lens and aspherical (DVD) lens are selected as lens system (L2 and L3 in fig. 4.4 and fig. 4.5).

The NA of DVD lens is 0.65 and other parameters are illustrated in figure 4.6.

The GRIN lens is a radial index gradient lens model W18-S0250-083-ABC from NSG

Micro Optics company which has 1.8mm diameter. The index of refraction is highest at the center of the lens and decreases radially outwards. The distribution of the refractive index^[87], $N(r)$, satisfies the equation

$$N(r) = N_0 \left[1 - \frac{(\sqrt{A})^2}{2} r^2 \right] \quad (4.4)$$

where r is the radial distance from the axis, $\sqrt{A}$ is the gradient constant^[87], determined by

$$\sqrt{A}(\lambda) = 0.3238 + \frac{5.364 \times 10^{-3}}{\lambda^2} + \frac{2.626 \times 10^{-4}}{\lambda^4} \quad (4.5)$$

Thus $\sqrt{A}(650) = 0.33797$.

The refractive index on the center axis, $N_0(r)$, is determined by

$$N_0(\lambda) = 1.5868 + \frac{8.14 \times 10^{-3}}{\lambda^2} \quad (4.6)$$

Thus, the refractive index of GRINlens on the axis is $N_0(650) = 1.606$.

The numerical aperture is varying along the radius of GRIN lens and is given as

$$NA = N_0 \sqrt{A(r_0^2 - r^2)}^{1/2} \quad (4.7)$$

When input light is aligned with the central axis of GRIN lens, it has a NA of

$$N_0 \sqrt{A(r_0^2 - r^2)}^{1/2} = N_0(650) \sqrt{A} r_0 = 0.49$$

• Photodetector

A point PIN-FET photodetector integrates PIN and discrete transimpedance amplifier. The detector principle is shown in fig. 4.7. The optical signal is converted to electrical current by PIN photodiode after amplifier the signal output is

$$V_s = A \cdot R \cdot \Phi_e \quad (4.8)$$

where A is the magnitude of amplifier, R is the responsivity and Φ_e is the incident radiation power.

The photodetector model is S10E series bought from Comade Electro Optics Pte Ltd. The responsivity of the detector is $15000\text{mV}/\mu\text{W}$ at wavelength of $0.65\mu\text{m}$. The rising time of the detector is less than $20\mu\text{s}$ and the RMS noise in output is less than $400\mu\text{V}$.

- **Translation stage**

A MELES GRIOT Nanostep three-axial motor controlled translation stage was used in the experiments. It has a resolution of 50nm . The movement and speed of the stage can be preset and controlled by a PC. In measurement study, the stage movement was moved along the z-axis alone.

- **Acquisition board**

The data acquisition section uses National Instruments NI 6040E DAQ board with 500kHz/s single channel acquisition and 12-bit resolution with preset range. 12-bit digital signals give a resolution of 0.0244% of full scale. The analog signal acquired from PD is transmitted through BNC-2110 Adapter to DAQ board and converted to a digital signal by DAQ. The DAQ board has an interface with PC and is programme controlled by LabVIEW™ software.

- **Programme**

LabVIEW™ is a software package in the development of the device and quick changes can be made for various measurement conditions. It also provides a user-friendly interface with many features to collect and analyze the data. The programme was written using LabVIEW™ environment for controlling one-channel and multi-channel confocal system experiments and signal processing.

4.2.2 System analysis

Based on theoretical analysis described in chapter 3, this section gives a calculation on spot

size and resolution for fiber confocal system constructed in this research.

(1) Spot size

The spot size on the specimen can be calculated using the equation 3.11 (shown below)

$$d = \frac{1.22\lambda}{NA}$$

In this equation, the NA is neither fiber NA nor lens (GRIN/DVD) NA. The definition of lens NA needs to be reviewed again. NA of a lens is defined to be as

$$NA = n \cdot \sin \theta$$

here, n is the refractive index of the medium between the lens and the sample and θ is the half-angle subtended by the lens at its focus as illustrated in fig. 3.11. This θ is the half-angle subtended by the actual light incident to the lens from its focus. It is an effective NA (NA_e) for a lens system. In fiber confocal system, NA_e is defined by the fiber NA (NA_f), and lens NA (for GRIN lens, it is NA_g , for DVD lens it is NA_d).

The DVD lens assembly for confocal sensor is illustrated in fig. 4.6 (b). The distance between fiber and DVD lens is about 2mm. The effective NA_{ed} can be estimated according fig. 4.6 (c)

$$NA_{ed} = 2NA_f / 0.4 = 0.55$$

If the wavelength of LD is $\lambda=650\text{nm}$, the spot size is $d_s=1.4\mu\text{m}$.

For a GRIN objective lens, when the input light is aligned with the central axis of GRIN lens, the effective NA does not change with actual illumination. Thus if the NA_{eg} is 0.49, the spot size is $1.6\mu\text{m}$.

(2) Resolution

It is usual to estimate depth resolution using the half-power intensity response as in

equation 3.14 (shown below).

$$d_z = \frac{0.9\lambda}{NA^2}$$

For the DVD lens, the resolution is $d_{zd}=1.9\mu m$. For the GRIN lens, the resolution is

$$d_{zg}=2.4\mu m$$

4.3 System evaluation

There are many parameters to describe the instrument performance, such as resolution, accuracy, precision, error, reliability, repeatability, and stability, etc. To evaluate the performance of a measurement instrument, quantitative and qualitative studies are used. Resolution, accuracy, precision, error are defined as quantitative parameters, while reliability, repeatability, and stability are defined as qualitative parameters though sometime the repeatability needs a quantitative definition^[88]. At present, system noise is qualitatively analyzed as the basis for study other parameters and improving system function. The resolution as quantitative parameter is studied in comparison with theoretical estimation. Reliability is studied as qualitative parameter.

4.3.1 System noise analysis

The confocal response curve is smooth and the experimental resolution can be determined by the resolution of A/D acquisition for a noise free system. However there is no perfect--noise free system. Noise is present in every system. It is the noise that makes the response curve fluctuation and lowers the resolution.

Noise can be classified as: systematic noise and random noise.

Systematic noise has a specific signature that can be studied and by proper design reduced to any level, such as crosstalk which will be discussed in chapter 5.

Light noise derived from light source or generated during transmission and finally changed into electrical noise is a kind of random noise. Light source analysis was discussed in chapter 3. The important random noise is light source fluctuation which will be discussed in section 4.4.

Other random electrical noise includes circuit design for the photodetector and A/D acquisition system, electrical heat noise, and 50Hz /100Hz ambient light noise.

The important factor that determines the tolerance of noise and signal quality is the amount of noise in the signal ,i.e. the SNR. Random noise level is the main factor that affects the system resolution.

4.3.2 Resolution

From the resolution description in chapter 3, the depth of field and the depth of focus of a lens system are two main parameters that reflect system resolution. In an imaging system, there is no agreed standard to estimate system resolution. It can be defined from the view of physical optics or geometrical optics. The physical optics definition is common used which describes the depth resolution as the distance between 3-dB points and is used as the theoretical estimation in this project research.

For a practical instrument, the resolution, defines the lower limit on the magnitude of the change in the input which produces an observable change in the instrument output^[89].

System resolution reflects the ability of the system to recognize the smallest of measurand.

To evaluate the input resolution, the output resoition should be analyzed and evaluated.

Two methods are used to evaluate system resolution. One is static method (static

resolution) the other is dynamic method (dynamic resolution).

A fiber confocal setup (shown in fig. 4.8) is built to do experimental evaluation.

(1) Signal resolution

• Theoretical analysis

For confocal 3D profile measurement system, the depth is the input signal. The depth variable is changed into optical intensity variable through confocal sensor and then converted into an electric signal through photodetector. In this confocal system, the output signal is voltage. So the SNR^[82] can be expressed as:

$$SNR = \frac{\sqrt{V_s^2}}{\sqrt{V_n^2}} \quad (4.9)$$

where V_s stands for the signal voltage and V_n stands for the noise voltage.

For ideal situation, when there is no any signal input, the output is zero. However the zero offset and noise make the output at a base level with random noise fluctuation when there is no signal input. Thus, without signal input, the expected value^[82, 83] (mean value) of the output is at base output

$$\bar{V}_o = \frac{\sum_{i=1}^N V_i}{N}$$

(4.10)

where V_i stands for the i^{th} output signal.

The noise signal fluctuates around the base level randomly. The standard deviation, σ_n , is used to estimate the average uncertainty of the noise.

$$\sigma_n = \sqrt{\frac{1}{N} \sum_{i=1}^N d_i^2} = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_i - \bar{V}_o)^2} \quad (4.11)$$

Where d_i is the deviation of V_i from $\overline{V_o}$, that is

$$d_i = V_i - \overline{V_o}$$

(4.12)

Thus with this definition, the standard deviation can be described as the RMS deviation of the noise signal. This is called the population standard deviation and is noted here as

$$\sigma_{np}$$

There is another definition to describe the average uncertainty of the measurement, that is sample standard deviation, defined by

$$\sigma_{ns} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N d_i^2} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (V_i - \overline{V_o})^2} \quad (4.13)$$

The definition of equation (4.13) is more conservative than the previous definition of equation (4.11).

Because noise is random signal, using a conservative definition can improve the reliability of the measurements. In this project study, the last definition of equation (4.13) is used.

The standard deviation σ_{ns} represents the average uncertainty in the individual measurement V_i . Thus

$$V = V_i \pm \sigma_{ns} \quad (4.14)$$

For the voltage noise source, the mean value of a noise is $\overline{V_n} = 0$ but because there is a zero offset, the mean value of the noise signal output is not zero. The mean of deviation d_i satisfies $\overline{d_i} = 0$. Thus the noise is described using its mean square deviation

σ_{ns}^2 and RMS deviation (sample standard deviation) σ_{ns}

Thus, an output signal V , which includes measured signal V_s , zero offset V_o and noise signal V_n satisfies that

$$Y - V_o = V - \bar{V}_o = V_s + V_n \quad (4.15)$$

Because the noise and signal are uncorrelated the mean square of $(V - \bar{V}_o)$ is

$$\overline{(Y - \bar{V}_o)^2} = \overline{V_s^2} + \overline{V_n^2} \quad (4.16)$$

The minimum detectable signal power is the power require to obtain a SNR of 1: that is an electrical signal as strong as the noise.

$$SNR = \frac{\sqrt{\overline{V_s^2}}}{\sqrt{\overline{V_n^2}}} = 1 \quad (4.17)$$

This is called NEP and can be used to describe the signal resolution. Thus

$$\sqrt{\overline{V_s^2}} = \sqrt{\sigma_{ns}^2} = \sigma_{ns} \quad (4.18)$$

For measured signal V_s , it has

$$\sqrt{\overline{V_s^2}} = \bar{V}_s \quad (4.19)$$

Thus signal resolution satisfies

$$\bar{V}_{sR} = \sigma_{ns} \quad (4.20)$$

where $\bar{V}_{sR}$ stands for the signal resolution.

• Experimental analysis of signal resolution

To test noise level, there are two procedures:

First the photodetector (PD) noise was tested without any input light. The output from PD was acquired by an A/D card and processed by PC. When the PD sensor was covered by a black sheet, the output is the noise signal with the mean square deviation and RMS deviation are as follows:

$$\sigma_{ns}^2 = 0.0000043429 ;$$

$$\sigma_{ns} = 0.002084V = 2.084mV .$$

The resolution without input is $\bar{V}_{sR} = 2.1mV$.

In the second step, the system is setup as shown in fig. 4.8, in which single-mode fiber with a DVD lens and a reference object (M) are used. The output signal was evaluated when the object position was around the focal point of the system with a constant light input. When the photodetector is fixed, the output is displayed in figure 4.9. The mean square deviation and RMS deviation are as follows:

$$\sigma_{ns}^2 = 0.0000480409 ;$$

$$\sigma_{ns} = 0.006931V = 6.931mV$$

The resolution with constant input is $\bar{V}_{nR} = 6.9mV$

Because of every component has a contribution to noise of the system, the noise value of the whole system is larger than that of the first step. Thus signal resolution of the whole system is 6.9mV.

(2) System static resolution and step move experiment

• Static resolution

The static resolution is based on statistics and obtained by evaluating the output signal changes before and after input signal changes. It reflects the static quality of measurement system.

To evaluate static resolution, there are two assumptions. One is that before and after object-in-focus position changes, signal output is stable, only random noise affects system resolution and can be eliminated using statistical method; the other is that a specific

amount of sampling points are acquired before and after object-in-focus position changes respectively.

For this static resolution study, 500 points were set as a specific sampling number with 500kHz sampling rate.

The system setup configuration is the same as shown in fig. 4.8.

After system setup alignment, the reference object was set around the focus of the system.

First, the acquisition was run continuously without moving stage. Then the stage was moved a specific distance, and data acquired continuously for another 500 points. The mean values before and after translation of the stage are calculated. When the difference of these two mean values is equal or nearest the noise level, the amount of translation stage changes along z-axis is the static resolution.

The flow chart of the experiment is shown as chart 4.1.

Figure 4.13 is a typical output trace for a 5 μm step displacement. The mean value was -1.3345V before the step jump and -1.1890V after the step jump. The difference is 145.4mV.

Then the experiments were finished with different size of steps and illustrated in Table 4.1.

Table 4.1 Mean value before and after different steps movement

size of step (μm)	mean value (V)		difference (mV)
	before the step	after the step	
2	-1.4345	-1.3267	107.8
1	-1.4245	-1.3452	79.3
0.5	-1.4023	-1.3637	38.6
0.2	-1.4025	-1.3945	8

Table 4.1 shows that when the stage movement is 200nm. The difference between two mean values before and after the step jump is 8mV which is comparable with the system resolution of 6.9mV. Thus, the static resolution is better than 200nm.

- **Continuous step movement**

The same system configuration as static resolution study is used but the height changed continuously. The experimental test procedure is illustrated in Chart 4.2. The operation is controlled by programme with 500kHz sampling rate. For each step jump the translation stage was fixed. After the acquisition is completed with a preset sampling and averaging numbers, the translation stage was moved by a specific step. This is continued for subsequent steps.

Figure 4.11 shows a 10-step acquisition with 5pm step interval and 500 sampling data in each step. The translation stage position was moved from 2.155004mm to 2.210005mm and the accumulated error of the stage movement was 1nm.

Figure 4.12 shows 10-step experiment with 1 μ m/step and 500 sampling data/step data acquisition. The translation stage position was moved from 2.005mm to 2.015999mm and the accumulated error of the stage movement was 1nm.

The translation stage is motor controlled stage with 50nm resolution. An accumulated error of the stage of 1nm can be neglected compared to the 200nm resolution of the confocal system.

Figure 4.11 and 4.12 show that point B was at the maximum response. The response curve indicates that the object was set near focal point and moved from one side to the other side and point B was at the focus. Since this static method can eliminate random noise, the response curve is smooth and the object-in-focus position is easily found. This method can improve measurement resolution and system measurement stability.

(3) Dynamic resolution of system

Dynamic resolution is found by continuously evaluating the changes of output signal corresponding the change of input signal. Random noise affects dynamic resolution more than to static resolution. When there is no noise, the confocal response curve is smooth. Noise causes fluctuations and reduces the resolution. The resolution based on the mean noise value is not adequate for dynamic real time measurement. To evaluate the dynamic resolution, the following factors have to be considered.

For 12-bit acquisition, the resolution is one in 4096. Suppose V_{Rge} is the input range, then the resolution of A/D acquisition is

$$\Delta v_{AD} = \frac{V_{Rge}}{4096} \quad (4.21)$$

The system resolution is not only determined by the resolution of A/D card but also affected by the output noise. Let Δv_R be the measurement resolution, then

$$\Delta v_R = \text{Max}(\Delta v_{AD}, \Delta v_N) \quad (4.22)$$

where Δv_N is the noise output.

Figure 4.13 shows three different conditions relating acquisition resolution and the output noise. The x-coordinate corresponds to the object-in-focus position, and the y-coordinate stands for the output response. When there is no output noise, the resolution depends on the resolution of A/D acquisition, which is illustrated in fig. 4.13 (a). When the output noise is smaller than the resolution of A/D acquisition, the signal output has smaller fluctuation and the system resolution depends on the resolution of A/D acquisition, which is illustrated in fig. 4.13 (b). In these two cases, the dynamic resolution of the confocal profile measurement is

$$\Delta P_R = P_b - P_a \quad (4.23)$$

When the output noise is larger than the resolution of A/D acquisition, the signal output has larger fluctuation and the resolution depends on the noise output, which is illustrated in fig. 4.13 (c). In fig. 4.13 (c), the solid line stands for the output signal with large noise, and the dash line stands for the fitting curve. Where

$$P_4 - P_3 > P_2 - P_1 \quad (4.24)$$

and the resolution is

$$\Delta P_R = P_4 - P_3 \quad (4.25)$$

In most cases, the resolution of A/D acquisition is smaller than the output noise.

In this evaluation, the setup is similar to fig.4.10 but with different components and is divided into three groups. A single-mode fiber with a DVD lens is **Setup1**, a single-mode fiber with a GRIN lens is **Setup2**, and a multi-mode fiber with a GRIN is **Setup3**.

Chart 4.3 shows the flow chart of dynamic resolution experiment.

- **Setup 1**

In this experiment, the A/D acquisition was set to 6V full-scale range and 0.96μm sampling interval. The resolution of A/D acquisition is thus 1.465mV. The stage movement was set at 0.1 mm/s with a scanning range of 0.5mm.

Figure 4.14 (a) is one characteristic cycle as the object is cycled about the point of the best focus. Figure 4.14 (b) shows the output response as a function of stage position. From the output response, the confocal object-in-focus position is at 1.998mm with respect to initial scanning position. The noise output at object-in-focus was 189.8mV and the system resolution in this test was 6μm.

- **Setup 2**

The experimental parameters were set at 0.1mm/s movement, 0.07mm scanning range and 0.875μm sampling interval.

Figure 4.15 (a) is one characteristic cycle while, fig. 4.22 (b) shows the signal output vs. the stage position. The resolution for this test was $0.7\mu\text{m}$.

- **Setup3**

The experimental parameters were set at 0.1mm/s movement, 1mm scanning range and $0.977\mu\text{m}$ sampling interval.

Figure 4.16 is the signal output vs. the stage position. The resolution for this test loop was $4.1\mu\text{m}$

4.3.3 Reliability

Reliability which reflects the system repeatability and stability is a fundamental property for system performance. If an instrument has low reliability, all the quantitative parameters are no significance. Higher reliability implies higher accuracy and precision, lower error and higher consistency of the measured value with the true value.

The accuracy^[90] of a measuring instrument is a measure of how close an instrument's reading corresponds to the true value of the measured quantity. Accuracy is given in terms of random (unsystematic) and systematic uncertainty. Since uncertainties will be different for different values in the range of the instrument, uncertainty should be specified as a function of the quantity measured. In practice it is common to specify the maximum uncertainty in the range as a fraction of the upper limit of the range. It is best to ensure that errors are as small as possible and to have a reliable estimate of how large they are. The premise of the inevitable uncertainty is to keep errors as small as possible. The reliable estimation for uncertainty depends on analysis the source of all errors. In many cases what is of interest is not the accuracy, but the repeatability^[88] of an instrument. The repeatability study is also based on the system reliability. Reliability^[91] of a test or measuring

instrument is defined as the ratio of the true score variance to the observed score variance. Reliability analysis uses successive repeated measurement of the same value under stated conditions. Thus the reliability reflects the closeness of agreement with the successive measurement of the true value.

(1) Theoretical analysis

Let X_{ij} , $i = 1, 2, 3, \dots, m$; $j = 1, 2, 3, \dots, n$ represents the j^{th} measurement value with the i^{th} parameter setting. Let the error be e_{ij} . The expected value of the i^{th} parameter setting is denoted with τ_i , and the expected value of all experiment setting is denoted with μ . For the i^{th} parameter setting, the experiment is repeated “n” times.

A simple statistical model for a series of measurements of physical quantity has the following form:

$$X_{ij} = \tau_i + e_{ij}$$

(4.26)

In this model, X_{ij} represents the j^{th} measurement with the i^{th} parameters setting. τ_i is the “true” value for the i^{th} parameters setting and e_{ij} is the measurement error associated with X_{ij} .

The expected value is

$$E_j(X_{ij}) = \tau_i$$

(4.27)

The expectations over the whole measurement will be

$$E_{i,j}(X_{ij}) = E_i(\tau_i) = \mu \quad (4.28)$$

where μ is the mean of all possible score of X_{ij} . It follows that

$$E(e_{ij}) = E_j(e_{ij}) = 0 \quad (4.29)$$

The D is denoted the square of standard deviation. It follows that

$$D(X_{ij}) = D(\tau_i) + D(e_{ij}) \quad (4.30)$$

Reliability is thus:

$$R = \frac{D(\tau_i)}{D(X_{ij})} \quad (4.31)$$

This equation is equivalent to

$$R = 1 - \frac{D(e_{ij})}{D(X_{ij})}$$

(4.32)

It is clear from this definition that R is dependent on the standard error of the test and on the variability of the true score being studied.

(2) Experimental analysis

The setup for reliability tests is the same as shown in fig.4.10. Two groups of experiments were conducted. The first group used a single-mode fiber and a GRIN lens, while the second used a sir&-mode fiber and DVD lens. A mirror was used as a reference specimen. The stage movement was preset at 0.1 m/s for all experiments and sampling rate of 10,50, or 90ms was used.

• The system with GRIN lens

For this test, the scanning range was set at 0.07mm. Before inspection, the specimen, the lens and specimen-sensor were aligned.

The acquired data is shown in fig.4.17 at a sampling rate of 10ms. Figure 4.17 (a) is the data for the entire scan period, fig. 4.17 (b) shows the output response as a function of the stage position, fig. 4.17 (c) is the output response as a function of stage position in the 1st loop with the best focus position at 1.9991mm. The best focus position for other loops is shown in Table 4.2.

For a sampling rate of 50ms, the experimental data are shown in fig.4.18. Figure 4.18 (a) shows the data for the entire scan period and fig. 4.18 (b) is the output response as a function of stage position.

Table. 4.2 Reliability calculation of fiber confocal system with GRIN lens

Sampling rate (ms)	Test (loop)	Focus position (mm)	τ_{gi} (nm)	$\sum e_{gij}^2/n$ (mm ²)*10 ⁻⁷	μ_g (mm)
10	1	1.9991	1.9997	2.5523194	1.9990
	2	2.0002			
	3	1.9990			
	4	2.0002			
	5	1.9990			$D(\tau_{gi})$ (mm ²)*10 ⁻⁷
	6	2.0001			
	7	1.9999			2.9721569
	8	2.0000			
	9	1.9991			$D(e_{gij})$ (mm ²)*10 ⁻⁷
	10	2.0000			
	11	1.9997			
	12	2.0004			
50	1	1.9979	1.9985	2.6892117	1.988587
	2	1.9989			$D(X_{gij})$ (mm ²)*10 ⁻⁷
	3	1.9988			
	4	1.9987			
	5	1.9976			
	6	1.9989			4.9607439
90	1	1.9987	1.9987	0.7242314	
	2	1.9987		R=60%	
	3	1.9988			
	4	1.9990			
	5	1.9990			
	6	1.9980			
	7	1.9989			
	8	1.9986			

	9	1.9987			
	10	1.9985			
	11	1.9990			
	12	1.9986			

For a 90ms sampling rate, the experimental data are shown in fig.4.19. Figure 4.19 (a) shows the data for the entire scan period and fig.4.19 (b) shows the output response as a function of stage position.

The focus position in each experiment cycle with different sampling rates and the reliability for the system configuration are analyzed and listed in Table 4.2. It is seen that the reliability is 60%.

- The system with DVD lens

Table 4.3 Reliability calculation of fiber confocal system with DVD lens

Sampling rate (ms)	Test (loop)	Focus position (mm)	τ_{di} (mm)	$\sum e_{dij}^2 / n$ (mm ²)*10 ⁻⁵	μ_d (mm)
10	1	2.0117	2.0150	1.71542053	
	2	2.0184			2.0068
	3	2.0136			
	4	2.0127			$D(\tau_{di})$ (mm ²)*10 ⁻⁵
	5	2.0174			
	6	2.0109			4.59074312
	7	2.0212			
	8	2.0109			
	9	2.0174			
	10	2.0109			$D(e_{dij})$ (mm ²)*10 ⁻⁵
	11	2.0193			
	12	2.0090			
	13	2.0212			1.404665
50	1	2.0042	1.9984	1.57243149	
	2	1.9996			
	3	1.9948			$D(X_{dij})$ (mm ²)*10 ⁻⁵
	4	2.0014			
	5	1.9930			
	6	2.0014			
	7	1.9930			5.99540812
	8	1.9996			

90	1	2.0078	2.0069	0.92614179	R=77%
	2	2.0078			
	3	2.0078			
	4	2.0011			
	5	2.0101			

In this test, the scanning range was set at 0.5mm. Before inspection, the specimen, the lens and specimen-sensor were aligned.

The acquisition data are shown in fig. 4.20 for a sampling rate of 10 ms. Figure 4.20 (a) is the data for the entire scan period, fig. 4.20 (b) shows the output response as a function of stage position.

For a sampling rate of 50ms, the experimental results are shown in fig. 4.21. Figure 4.21 (a) shows the data for the entire scan period and fig. 4.21 (b) shows the output response as a function of stage position.

For a 90ms sampling rate, the experimental results are shown in fig. 4.22. Figure 4.22 (a) is the data for the entire scan period and fig. 4.22 (b) shows the output response as a function of stage position.

The focal position for each experiment cycle with different sampling rate and the reliability for the system configuration are analyzed and listed in Table 4.3. The system reliability is detected to be 77%.

(3) Discussion

The reliability analysis indicates that the fiber confocal system is reliable. The reliability of the system with DVD lens configuration is better than that with GRIN lens. The low reliability indicates that the system standard error is large. For a given test it is assumed in classical test theory that the standard error of measurement is a constant characteristic of a measuring instrument. Reducing system standard error, the reliability will be increased.

From figure (b) of fig. 4.19, fig. 4.21, and fig. 4.22, it is obvious that the peak response for the odd/even scanning loops are around the same expected position. while for figure (b) of fig. 4.17, fig. 4.18, and fig. 4.20, the peak responses in the odd loops have a small shift of expected position from the even loops. Reviewing the system configuration and operation of the experiments, the stage movement is not synchronized with the preset parameters. The stage control is an open loop without feedback. The position is calculated differently from that of by feedback signal. The stage movement of odd loops starts from zero-scan position towards the objective while the even loops reverse the direction. When the stage movement changes the orientation, the stage position lags behind the position calculated by the preset parameters, while the acquisition is continuous. Further, the computer interface of the stage is GPIB, while the interface of the DAQ is PCI. These different interfaces are not synchronized. The sample number of first loop may affect the number of next loop.

In short, the following methods are recommended for reducing the standard errors.

The interface between the translation stage and computer should be the same as that between the DAQ board and the computer, so that the performance of hardware and software can be in synch. Also, the stage position can be monitored when each acquisition is performed if using a stage with feedback control or indicator.

4.4 System improvement techniques

4.4.1 Compensation for light source fluctuation

(1) Introduction

Confocal 3D imaging^[25, 26, 92] uses light intensity variations for profile measurement. The system detects the best focus-position on target. The intensity received by the detector at the best focus-position reaches a maximum while out-of-focus points on the target have lower intensity^[93]. Thus in confocal imaging, stability of the light source is very important^[25, 26, 92]. For an ideal point source with stable properties, the light intensity collected by the photodetector depends on the defocus position; and at the focal point, the value is highest. For high precision 3D inspection using a confocal system, light source stability is critical for system resolution. A variation of intensity response can be regarded as variation in focus-position on target though it may be caused by the light source fluctuation.

Light source fluctuation can also lower the measurement accuracy, repeatability and stability. In order to get high quality data with high resolution, many researchers and commercial products used high quality light source. The light source driver is thus very complex and expensive.

In this project a new method to compensate light source fluctuation is proposed. First, the depth response model function is deduced, then the effect of light source fluctuation to confocal imaging is studied, and finally, system error caused by light source fluctuation is analyzed. A new scheme using dual detectors, to reduce the effects of light source

fluctuation, is proposed. Theoretical analysis and experiment results of light source fluctuation and compensation are presented.

(2) Depth response

Shallow depth of focus is a distinguishing feature of confocal imaging system. That is out-of-focus portions of the sample are not imaged. An important criterion for judging the behavior of an imaging system is based on the reflection of a focused beam from a perfect plane reflector^[94].

The focused point on the sample acts as a reflector and the incident beam has a plane wavefront at the focus point.

Considering the diffraction of a monochromatic beam such as from a laser by a finite aperture, as illustrated in Gg.4.23, a light beam, with a uniform field amplitude U_1 , emerges from the left aperture. The field amplitude at a generic point $P_1(x_1, y_1, 0)$ in this aperture plane is written as $U_1(x_1, y_1, 0)$. Let the observation plane be parallel to the aperture plane at a normal distance z . The distance between P_1 and P is Rz . It has

$$Rz = \sqrt{z^2 + (x_o - x_1)^2 + (y_o - y_1)^2} = z \sqrt{1 + \left(\frac{x_o - x_1}{z}\right)^2 + \left(\frac{y_o - y_1}{z}\right)^2} \quad (4.33)$$

The field amplitude at point $P(x_o, y_o, z)$ in the observation plane is written as $U(x_o, y_o, z)$.

According to Huygens-Fresnel principle^[95], the field amplitude $U(x_o, y_o, z)$ is

$$U(x_o, y_o, z) = \iint_{-\infty}^{\infty} h(x_o, y_o, z; x_1, y_1, 0) U_1(x_1, y_1, 0) dx_1 dy_1 \quad (4.34)$$

where

$$h(x_o, y_o, z; x_1, y_1, 0) \cong \frac{1}{j\lambda} \frac{\exp(jkRz)}{Rz} \quad (4.35)$$

where λ is wavelength, k is wave number and j is virtual unit. Because it is a far field diffraction application, the value Rz in the denominator of eqn. 4.35 can be approximated to z .

Then to consider a thin lens with a clear aperture (a) placed at the position of the Aperture, let the optical axis of the lens be perpendicular to the plane of the Aperture and the observation region and coincides with the z -axis. If the observation plane is placed near the focal plane, the Fresnel approximation can be used in the weighting function, as,

$$h(x_o, y_o, z; x_1, y_1, 0) = \frac{\exp(jkz)}{j\lambda z} \exp\left[j \frac{k}{2z} (x_o - x_1)^2 + (y_o - y_1)^2\right] \quad (4.36)$$

For the thin lens the coordinates on the entrance face can be assumed to be the same as the coordinates on the exit face.

The phase transformation of a lens is:

$$t(x_1, y_1) = \exp(jkn\Delta_0) \exp\left[-j \frac{k}{2f} (x_1^2 + y_1^2)\right] \quad (4.37)$$

where Δ_0 is the lens thickness, f is the focal length of the lens, and n is the refractive index of the lens.

The field amplitude at point P (x_o, y_o, z) for this configuration becomes

$$U(x_o, y_o, z) = \iint_{-\infty}^{\infty} U_1(x_1, y_1, 0) t(x_1, y_1, 0) h(x_o, y_o, z; x_1, y_1, 0) dx_1 dy_1 \quad (4.38)$$

or

$$U(x_o, y_o, z) = \frac{\exp(jkz) \exp(jkn\Delta_0)}{j\lambda z} \exp\left[j \frac{k}{2z} (x_o^2 + y_o^2)\right] \iint \left\{ U_1(x_1, y_1, 0) \exp\left[j \frac{k}{2} (x_1^2 + y_1^2) \left(\frac{1}{z} - \frac{1}{f}\right)\right] \exp\left[-j \frac{k}{2z} (x_o x_1 + y_o y_1)\right] \right\} dx_1 dy_1 \quad (4.39)$$

The factor $(kn\Delta_0)$ is a constant phase delay which can be neglected. When $z \rightarrow f$,

the factor $\exp \left[j \frac{k}{2} (x_1^2 + y_1^2) \left(\frac{1}{z} - \frac{1}{f} \right) \right] \rightarrow 1$.

The uniform field amplitude $U_1(x_1, y_1, 0)$ for a finite aperture can be expressed by a normalized pupil function $P(x_1, y_1)$ which is defined by

$$U_1(x_1, y_1, 0) = P(x_1, y_1, 0) = \begin{cases} 1 & \text{inside the aperture} \\ 0 & \text{otherwise} \end{cases} \quad (4.40)$$

So the final expression is

$$U(x_o, y_o, z) = \frac{\exp(jkz)}{j\lambda z} \exp \left[j \frac{k}{2z} (x_o^2 + y_o^2) \right] \iint \left\{ P(x_1, y_1, 0) \exp \left[-j \frac{k}{2z} (x_o x_1 + y_o y_1) \right] \right\} dx_1 dy_1 \quad (4.41)$$

This is the point spread function of the lens^[96] denoted as $\phi(x_o, y_o, z)$.

Now, the standard confocal imaging system configuration (Fig.3.1) is reviewed again. The light illuminates the lens L2 uniformly. The optical response at the specimen is $U(x_o, y_o, z)$. The uniform light comes from the source S. The illumination pinhole P1 acts as a pupil of the imaging system and can be described by $P(x_1, y_1)$ as in eqn 4.40. A simplified confocal imaging system is illustrated in fig.4.24 (a). Thus illumination light source with a pupil function $P(x_1, y_1)$ generates the point spread function of the lens at the object plane.

Considering the object is as a perfect plane reflector, the Configuration of fig. 4.24 (a) is equivalent as the configuration of fig.4.24 (b) with the same parameters for lenses L1 and L2. The photodetector plane is set behind the detection pinhole P and collects all the light passing through it. The optical response at the object O becomes a new excitation source.

The point spread function of the collector lens L2 is the same as the lens L1. Expressing

amplitude of the light in the detection plane as $U(x_2, y_2)$, the response at the detection pinhole can be written

$$U(x_2, y_2) = \iint \phi^2(x_o, y_o, z) dx dy \quad (4.42)$$

The depth response of the signal is the response of variable z , noted with $V(z)$. So equation (4.42) is written as

$$V(z) = \iint \phi^2(x_o, y_o, z) dx dy \quad (4.43)$$

To normalize it with the focal point response, then

$$A(z) = \frac{\iint \phi^2(x_o, y_o, z) dx dy}{\iint \phi^2(x_o, y_o, z_0) dx dy} \quad (4.44)$$

where $z_0 = f$.

Invoking the Fourier transform, the amplitude response can be solved as:

$$|A(z)| = \frac{\sin[k(z - z_0)(1 - \cos \theta_0)]}{k(z - z_0)(1 - \cos \theta_0)} \quad (4.45)$$

where θ_0 is the half angle from objective lens to focal point and gives the numerical aperture of the objective as $NA = \sin \theta_0$. k is the wave number.

If the initial point of z -axis is set at the focus of the confocal system, eq. (4.45) is expressed as

$$|A(z)| = \frac{\sin[kz(1 - \cos \theta_0)]}{kz(1 - \cos \theta_0)} \quad (4.46)$$

This is the depth response model function of confocal imaging. It accurately predicts the defocus response shape at the central lobe.

The depth of focus is given by the 3-dB points of the central lobe in eq. (4.46):

$$\Delta z|_{3dB} = \frac{0.45\lambda}{1 - \cos \theta_0} \quad (4.47)$$

which is used to estimate resolution of confocal system.

For a confocal system with wavelength at 670nm and NA = 0.6. The ideal depth response is shown in fig. 4.25. The estimated resolution is $1.5\mu\text{m}$.

(3) Light source fluctuation and error analysis

The intensity $I(z)$ detected by the photodetector is proportional to square of the amplitude response. That is

$$I(z) \propto |A(z)|^2 \quad (4.48)$$

In confocal system, the intensity $I(z)$ reaches maximum at the focus, denoted by I_0 . Thus the distribution of axial intensity response $I(z)$ is

$$I(z) = I_0 |A(z)|^2 = I_0 \left| \frac{\sin[kz(1 - \cos\theta_0)]}{kz(1 - \cos\theta_0)} \right|^2 \quad (4.49)$$

When the light source fluctuates, the central lobe fluctuates correspondingly. The fluctuation of light source is a random signal. The ideal optical signal overlaps with a random fluctuation signal may give rise to two peaks [fig.4.26(b)], peak shift [fig.4.26(c)], or widening of peak at the central lobe [fig.4.26(d)].

The light source fluctuation amplitude $S(t)$ is considered to be random and varying with time. When the fluctuation output is lowest at focus, i.e.,

$$I'_0 = S(t)_{\min} \quad (4.50)$$

and light intensity has a maximum at a defocus distances dz , can be written as

$$I'(dz) = S(t)_{\max} |A(dz)|^2 \quad (4.51)$$

If $I'_0 \leq I'(dz)$, the error occurs. Thus

$$\frac{S(t)_{\min}}{S(t)_{\max}} = |A(dz)|^2 \quad (4.52)$$

To study the fluctuation of light source, an experiment was done using a 670-710nm laser diode with confocal NA of 0.6. The experiment lasted about one hour and recorded a series of signals without environment illumination. Table 4.4 gives the record and the calculation of the error dz. Sa and Si stand for $S(t)_{\max}$ and $S(t)_{\min}$ respectively.

Table 4.3 Fluctuation of light source with its error

Sa (V)	Si (V)	Sa-Si (V)	dz(um)
0.125	0.07812	0.04088	0.618~0.655
0.14	0.07812	0.06188	0.685~0.725
0.1406	0.09375	0.04685	0.576~0.610
0.156	0.09375	0.06225	0.642~0.680
0.1406	0.078	0.0626	0.688~0.729
0.125	0.09375	0.03125	0.488~0.5 17

Table 4.4 shows that the maximum error caused by fluctuation of light source is $dz_{\max}=0.729\mu\text{m}$, a large error when compared to the resolution of $1.5\mu\text{m}$. It is clear that the light source fluctuation can decrease the resolution, lower the measurement stability and repeatability.

(4) Compensation technique used in experiments

In order to improve system stability, reduce error caused by light source fluctuation, a dual detector confocal system is constructed, as shown in fig. 4.27 and fig. 4.5. In both

configurations, PD1 is used to collect the measured signal and PD2 is the compensation detector.

Light source fluctuation affects both the compensation and measured signals correspondingly. Supposing that the beamsplitter has a reflective and transmissive coefficient as k_r and k_t respectively, and the output of the LD has a time varying fluctuation, $S(t)$. The compensation signal is

$$I_2 = k_t S(t) \quad (4.53)$$

The measured signal is

$$I_1 = k_r k_t S(t) |A(z)|^2 \quad (4.54)$$

Neglecting the loss of reflection from the target, then

$$\frac{I_1}{I_2} = k_r |A(z)|^2 \quad (4.55)$$

k_r is a constant which does not effect the depth response. Equation 4.55 is also suitable for the fiber confocal system with dual detector scheme as shown in fig. 4.27, only the value of the constant, k_r , is different. Thus using a divider circuit, the light source fluctuation can be reduced.

An experiment is conducted out using the fiber confocal system shown in fig. 4.27. In this configuration, single-mode fiber and DVD lens are used. The confocal response is recorded on Ch1, the compensation detector output is recorded on Ch2. The compensation result is shown as Ch3. After system is aligned, the resolution test was performed and shown in fig.4.28. Before compensation, the signal resolution for Ch1 is 2mV, the signal

resolution of the compensation detector output is 2.4mV. After compensation, the signal resolution for the system is 1.5mV.

For the experimental compensation experiment, the object was set around the focus position and the parameters were 20ms sampling rate, 0.05mm range and 0.1mm/s translation stage movement.

Figure 4.29 shows the output response as function of stage position. The analysis indicates that resolution is 0.26 μ m before compensation and 0.17 μ m after compensation. The confocal system resolution becomes better using compensation technique.

4.4.2 Fast scan algorithm

(1) Introduction

It is known that the normal response of light intensity detected by a confocal imaging system is the function of the defocus and given by

$$I(z) = \left| \frac{\sin[kz(1 - \cos\theta_0)]}{kz(1 - \cos\theta_0)} \right|^2 \quad (4.56)$$

where z is the defocus distance.

Figure 4.30 is an illustration of depth response of confocal system for $\lambda=650\text{nm}$ and $\text{NA}=0.49$. The practical resolution can be obtained from the results of the experiments.

To measure three-dimensional shapes at a required resolution-- ΔZ_R in the Z direction (optical axis), the conventional method must, at least, acquire confocal images at ΔZ_R intervals and perform the image processing on many confocal images, which will be time consuming. For rapid inspection, a fast algorithm is necessary and described herein:

(2) Theoretical analysis

The relationship of power response with defocus distance in a confocal imaging system is a Gaussian curve which is not easy to solve analytically. However, numerical analysis is a powerful tool to study, develop and analyse algorithms for obtaining solutions to various mathematical problems.

The intensity of confocal imaging at the in-focus position is highest. Since the confocal images are acquired by sampling within a large amount of measuring points, the maximum value is not exactly the in-focus position but rather one having a prescribed accuracy. The ideal situation is that the in-focus position of confocal images is at the peak of Gaussian curve. Thus the depth response function of confocal imaging system is further studied.

Now to find the zero points from the formula (4.56), that is $I(z)=0$, i.e.,

$$kz(1 - \cos \theta_0) = \pm \pi \quad (4.57)$$

The solution is

$$z_1 = \frac{\pi}{k(1 - \cos \theta_0)} \text{ and } z_2 = \frac{-\pi}{k(1 - \cos \theta_0)} \quad (4.58)$$

Thus the width of central lobe is

$$wd = z_1 - z_2 = \frac{2\pi}{k(1 - \cos \theta_0)} = \frac{\lambda}{(1 - \cos \theta_0)} \quad (4.59)$$

In fig.4.30, the width of central lobe is $5.1 \mu\text{m}$.

In practice confocal imaging system, inherent zero offset of the system shifts two zero points away from zero. The sampled values and the value of central peak within the acquired data depends on the properties of sensor response and surface properties of measured object so that the imaging data does not show the typical Gaussian distribution .

Neglecting errors, the output response can be expressed as

$$V(z) = \frac{\sin^2[k_1(z-a)]}{k_2(z-a)^2} + k_3 \quad (4.60)$$

Where k_1 is a constant which is a function of the wavelength and numerical aperture; k_2 , and k_3 are unknown constants.

The next step is to study an algorithm so that acquiring confocal images at much larger intervals and still maintain the required resolution, ΔZ_R .

Curve fitting and interpolation are two methods which can be exploited to obtain the functional relationships between the defocus distance and acquired intensity and then find the position of the central peak.

Mathematically, the curve fitting^[97] is, given enough data points $P_k(x_k, y_k)$, so that statistical laws reduce the errors introduced by inaccuracies in the measuring instrumentation. For a confocal imaging system, curve fitting demands acquiring enough data points to satisfy the resolution requirement; hence this is not faster than the conventional method. When the experiment values are within acceptable error and the values can be assumed to be accurate, an interpolation method can be used. In a confocal system a minimum of three points are needed.

The interpolation methods which can be used to analyze confocal images are quadratic interpolation^[97], Lagrange interpolation^[97~99], Newton interpolation^[97~99], and direct model formula.

The quadratic interpolation is to find a quadratic function $f(x)$ for three consecutive points P_1, P_2, P_3 . That is to find a quadratic function

$$f(x) = Ax^2 + Bx + C \quad (4.61)$$

which passes through these three points P_1, P_2, P_3 .

In Lagrange interpolation, the Lagrange polynomial is

$$L(x) = \sum_{j=1}^n f_j l_j(x) \quad (4.62)$$

where $\prod$ is the sign of continuous multiplication, $l_j(x)$ satisfies

$$l_j(x) = \frac{\prod_{i=1, i \neq j}^n (x - x_i)}{\prod_{i=1, i \neq j}^n (x_j - x_i)} = \begin{cases} 1 & \text{if } x = x_j \\ 0 & \text{if } x = x_i \end{cases}; \quad (j=1, 2, \dots, n) \quad (4.63)$$

and $f_j = f(x_j)$.

In Newton interpolation, the function is given by n points (x_i, f_i)

$$N(x) = D_1 + \sum_{k=1}^{n-1} D_{1+k} \prod_{i=1}^k (x - x_i) \quad (4.64)$$

where

$$D_1 = f_1 \quad (4.65)$$

$$D_2 = f[x_i, x_{i+1}] = \frac{f_{i+1} - f_i}{x_{i+1} - x_i} \quad (4.66)$$

and

$$D_{1+k} = f[x_i, x_{i+1}, \dots, x_{i+k}] = \frac{f[x_{i+1}, \dots, x_{i+k}] - f[x_i, \dots, x_{i+k-1}]}{x_{i+k} - x_i} \quad (4.67)$$

The theoretical model of confocal response is a kind of Gaussian curve. There is no analytical solution for a sinc function. So quadratic interpolation can be used and Taylor series is exploited before interpolation.

Exploiting three points interpolation in confocal measurement, there has to, at least, have three points within the central lobe. Assume $P_1(V_1, x_1)$, $P_2(V_2, x_2)$, $P_3(V_3, x_3)$ are three measured points in the central lobe. In order to satisfy the requirement, equal spaced abscissa sampling method is used, ie

$$\Delta x = x_2 - x_1 = x_3 - x_2 \quad (4.68)$$

The abscissa value of the central peak in confocal response $P_a(V_a, x_a)$ should be kept within the given interval $x_a \in (x_1, x_3)$.

The three coefficients **A**, **B**, **C** satisfy the quadratic function (eqn. 4.61) and

$$A = \frac{V_1 - 2V_2 + V_3}{2\Delta x^2} \quad (4.69)$$

$$B = \frac{-(2x_1 + 3\Delta x)V_1 + 4(x_1 + \Delta x)V_2 - (2x_1 + \Delta x)V_3}{2\Delta x^2} \quad (4.70)$$

$$C_n = \frac{(x_1^2 + 3x_1\Delta x + 2\Delta x^2)V_1 - 2(x_1^2 + 2x_1\Delta x)V_2 + (x_1^2 + x_1\Delta x)V_3}{2\Delta x^2} \quad (4.71)$$

Thus, the in-focus position is

$$x_c = \frac{x_1 + x_2}{2} + \frac{(V_1 - V_2)\Delta x}{V_1 - 2V_2 + V_3} \quad (4.72)$$

The truncation error of the confocal response at the central peak is

$$e_c = |x_c - x_a| \quad (4.73)$$

The relative error of the system resolution is thus

$$\varepsilon_c = \frac{|x_c - x_a|}{\Delta Z_R} \quad (4.74)$$

The processor, which calculates the height of an object using this algorithm will decrease the sampling numbers by $\frac{wd}{3\Delta Z_R}$ times and still maintain the required resolution.

In a confocal measurement system with $\lambda=0.65\mu\text{m}$, $\text{NA}=0.49$, the three points interpolation curve and theoretical curve is illustrated in Fig. 4.31. The solid line is an ideal curve and the dash line is a three points interpolation curve. The error is $0.2\mu\text{m}$.

Multi-point (more than three points) interpolation method can also be used to calculate the peak position. When using interpolation method, the interval of sampling must be smaller so that at least three sampling points fall within the center lobe.

(3) Experiment

To test the speed of the algorithm with three-point interpolation method, an experiment using the fiber confocal system with single-mode fiber and the GRIN lens was conducted.

The experimental parameters were as follows:

Wavelength: $0.65\mu\text{m}$,

The central NA of the GRIN: 0.49,

The stage velocity: 0.1mm/s ,

Sampling interval: $0.85\mu\text{m}$,

Scanning range: $70\mu\text{m}$.

The three points of the interpolation method was extracted from the acquired data at

$x_1 = 1.9923\text{mm}$,

$x_2 = 1.9983\text{mm}$,

$x_3 = 2.0043\text{mm}$.

The experiment results are compared with multi-point tracing, three-point interpolation, and theoretical Gaussian curve, which are shown in fig.4.32. In fig.4.32, the Ch1 is the experiment result of multi-point tracing, the Ch2 is the three-point interpolation curve, and the Ch3 is the theoretical Gaussian curve. The central peak of the theoretical curve is at 1.99939mm , the interpolation curve is at 1.99937mm , and the tracing curve is at 1.99991mm . Assuming the theoretical curve to be correct, the error of the interpolation

curve is 0.02nm, and the tracing curve is 0.52nm. The difference of central peak between interpolation curve and tracing curve is 0.54nm.

When the moving range is $70\mu\text{m}$, to realize z-scan with same resolution, exploiting three-point interpolation method, there are 12 sampling points with 6pm sampling interval, while for tracing method, there has 82 sampling points. For three-point interpolation method, the sampling points are fewer, which not only save the sampling time but also save the signal processing time. The sampling speed is thus faster.

4.5 Conclusion

Fiber confocal 3D profile measurement system is successfully constructed and system configuration is analyzed. A detailed theoretical and experimental analysis of system resolution is presented. Cases studies demonstrated that the resolution can be better than 200nm. Reliability study indicates that system reliability can reach 77% for a single-mode fiber and DVD lens confocal configuration. The compensation study on light source fluctuation shows that a $0.26\mu\text{m}$ resolution before coincompensation can be reduced to $0.17\mu\text{m}$ after compensation. The fast algorithm to process data shows that higher speed with same resolution is possible by using interpolation. In the experiment, the interpolation curve was 0.02nm difference from theoretical curve at the central peak position, while 0.54nm difference from the tracing curve.

Following the successes of this single channel fiber optical confocal system, a multi-channel system is proposed and developed in the next section for increasing measurement speed and realizing online inspection.

Flow charts

Chart 4.1 Procedure for static resolution study.

Chart 4.2 Procedure for step-movement measurement.

Chart 4.3 Procedure for dynamic resolution experiment.

Figures

Fig. 4.1 Fiber transmission properties.

Fig. 4.2 Optical fiber's acceptance cone angle.

Fig. 4.3 2X2 fiber coupler

Fig. 4.4 One-channel fiber confocal setup.

Fig. 4.5 One-channel fiber confocal setup with light source fluctuation compensation.

(a) The parameters of the DVD lens

(b) The assembly of confocal sensor. The working distance between fiber and DVD lens is about 2mm.

(c) The relationship of parameters with NA_{ed}

Fig. 4.6 DVD lens and its configuration parameters.

Fig4.7 The principle of PIN detector.

Fig. 4.8 Fiber confocal system configuration with DVD lens.

Fig.4.9 Confocal system signal output when the object position was around the focus.

Fig.4.10 Signal output before and after the step movement with 5 μ m.

Fig.4.11 10-step movement with 5pm step and 500 sampling datdstep and a list of average signal output for each cycle respectively.

A—Initial step; B—Highest response; C—Last step

Fig. 4.12 10 cycles step movement acquisition with 1 μ m step and 500 sampling data/step and a list of average output for each cycle respectively.

A—Initial step; B—Highest response; C—Last step

(a) The resolution of smooth signal output $\Delta P_R = P_b - P_a$

(b) The resolution of the signal output with lower output noise.

$$\Delta P_R = P_b - P_a$$

(c) The resolution of signal output with the case $\Delta V_{PDn} > \Delta V_{AD}$

$$\Delta P_R = P_4 - P_3$$

Fig. 4.13 Resolution for different SNR.

Fig.4.14 (a) One characteristic cycle.

(b) The output response with the relation of scanning position.

Fig.4.14 The acquisition output using components of single-mode fiber and a DVD lens.

Fig.4.15 (a) Data output of one characteristic cycle.

(b) The signal output vs. the stage position.

Fig.4.15 The acquisition output using components of single-mode fiber and GRIN lens.

Fig.4.16 The signal output vs. the scanning position using components of multi-mode fiber and GRIN lens.

(a) The data for the entire scan period.

Fig.4.17 Signal output of confocal sensor with single-mode fiber and GRIN lens at the sampling rate of 10ms.

Fig.4.17 (b) The output response in relationship to stage position.

Fig.4.17 (c) The output response in relationship to stage position in the 1st loop.

(a) The data for the entire scan period.

Fig.4.18 Signal output of confocal sensor with single-mode fiber and GRIN lens at the sampling rate of **50ms**.

Fig.4.18 (b) The output response in relationship to stage position.

(a) The data for the entire scan period.

Fig.4.19 Signal output of confocal sensor with single-mode fiber and GRIN lens at the sampling rate of 90ms .

Fig.4.19 (b) The output response in relationship to stage position.

(a)The data for the entire scan period.

Fig.4.20 Signal output of confocal sensor with single-mode fiber and DVD lens at the sampling rate of 10ms.

Fig.4.20 (b) The output response in relationship to stage position.

(a) The data for the entire scan period.

Fig.4.21 Signal output of confocal sensor with single-mode fiber and DVD lens at the sampling rate of 50ms.

Fig.4.21 (b) The output response in relationship to stage position.

(a) The data for the entire scan period.

Fig.4.22 Signal output of confocal sensor with single-mode fiber and DVD lens at the sampling rate of 90m.

Fig.4.22 (b) The output response in relationship to stage position.

Fig. 4.23 diffraction of finite aperture illumination.

Fig.4.24 (a) A simplified configuration

(b) An equivalent configuration.

Fig.4.24 Confocal configuration.

Fig. 4.25 depth response at wavelength of 670nm and $\text{NA}=0.6$

Fig.4.26 The effect of light source fluctuation on output signal. a is ideal signal; b-d are discrepant signals with fluctuation of light source.

Fig.4.27 Double detectors compensate the fluctuation error of light source.

Fig.4.28 System resolution test.

Fig.4.29 The result of one characteristic cycle in system compensation experiment.

Fig. 4.30 Depth response of confocal system with $\lambda=650\text{nm}$ and $\text{NA}=0.49$.

Fig.4.31 Three knots interpolation curve with the Gaussian curve the error is $0.197\mu\text{m}$.

Fig.4.32 Three knots interpolation curve, multi-point tracing curve and theoretical Gaussian curve.

Chapter 5 Multi-channel confocal system

In this chapter, a brief overview of the development of 3D profile inspection system and its problem fast speed and online inspection is presented. Multi-channel confocal systems with different configurations are developed. The system layout is analyzed. The crosstalk problem is then discussed and studied thoroughly both in the time and frequency domains using theoretical and experimental analysis. Solutions to eliminating the cross-talk are also presented.

5.1 Introduction

Laser scanning systems are widely used in high precision triangulation and confocal systems for fast 3D profile inspection. Though the resolution is good for some commercial products, measuring speed is still an important problem. Many profile scanning systems can not realize real time online inspection. Current triangulation scanning devices and confocal devices scan the sample sequentially point by point or line by line and then assemble the pixel information up to a single profile image. Since triangulation methods do not need to scan in the Z direction, image construction speed is faster than that for confocal systems.

An example of triangulation measurement system is the Model LC-2420 products of Keyence Corporation. This kind of device has a resolution of $0.01\mu\text{m}$, sampling frequency of 50 kHz and response time of $100\mu\text{s}$ with a minimum spot size of $20 \times 12\mu\text{m}$. However, this is for a single point measurement. For every sample, the detector has a response time of $100\mu\text{s}$ and takes an additional $20\mu\text{s}$ data sampling. Thus each data is acquired in $120\mu\text{s}$.

To measure a 50mm specimen with a 12 μ m sampling interval 4167 data points have to be acquired. Therefore, it takes 0.5s to profile a single line. For a 50mm² specimen, the data acquisition is 1250s. This is more than 20mins! When the time of translation stage movement from one scanning line to the next is considered, data acquisition can take more than 20min. Actually, the mechanical movement is slower than response time of the electrical signal. To get a whole profile, the inspection will take a very long time for the large size object with high resolution such as wafer, disc, etc. Reviewing the analysis of previous chapters, the depth resolution of triangulation device is not as good as spatial resolution. The resolution and accuracy are also not as good as confocal scanning system.

For confocal devices, additional depth scanning is necessary. To find the best focus position axial scanning over a range of 200 μ m with 1 μ m step size takes 200 times longer than that for triangulation, assuming the sampling frequency and response time are same as that of the latter.

To realize an area scan with a size of $l_x \times l_y$ and an interval of $(\Delta x, \Delta y)$, noted with

$$m = \frac{l_x}{\Delta x} \quad \text{and} \quad n = \frac{l_y}{\Delta y},$$

using single point inspection method, there need a number of $m \times n$

times of X-Y scan while using a multi-channel inspection system with an array of $m \times n$, there does not need X-Y scan. Thus with the same inspection method, a $m \times n$ multi-channel inspection system is approximately $m \times n$ times faster than single point inspection system.

In order to increase the measuring speed, point-array measuring system is introduced and multi-channel confocal 3D profile inspection system is developed.

5.2 System configuration methods

The one-channel fiber confocal 3D profilometer has been developed and described in detail in chapter 4. A novel multi-channel 3D profilometer based on fiber confocal principle is developed. Different configurations are conceived to solve different problems.

5.2.1 Basic configuration

The basic configuration of multi-channel fiber confocal system consists of light source, fiber coupler array (FCA), lens system, detector array, depth scanning system and image processing system.

One configuration is illustrated in figure 5.1 (a) and (b). In fig. 5.1 (a), the system consists of laser diode array (LDA), FCA, GRIN lens, photodetector array (PDA), translation stage (TS), A/D acquisition board and PC. The LDA is used in the present project, though it is not the only light source. A laser array is not necessary in this configuration and can be replaced by a single beam. A DVD lens can replace the GRIN lens as the objective lens as shown in fig. 5.1 (b). However, a single objective lens can be replaced by a micro-lens array. The FCA can be fabricated using single-mode fiber or multi-mode fiber. A translation stage performs the depth scanning and can be replaced by tuning fork as shown in figure 5.2 or by a PZT as shown in figure 5.3 with a 4f lens system configuration.

The basic configuration uses fewer components comparing with the configuration that without fiber. However, the basic Configuration can not reduce or eliminate, if have, light source fluctuation and crosstalk problems. The system parameters such as resolution, precision, stability and noise may not be satisfactory if have these problems. To solve the above problems, new and improved schemes are developed.

5.2.2 Configuration with double detector array

A double detector array is configured to compensate for light source fluctuation, which is shown in figure 5.4. The PDA1 is used for specimen detection while the PDA2 is used for compensating the fluctuation of the light source. The principle for compensation of light source fluctuation is discussed in section 4.3. In the present configuration, the scanning system can be replaced by a tuning fork or a PZT. The lens system can be a GRIN lens or a DVD lens. An array of laser diodes is not necessary and can be replaced by one beam. The requirements of other components are same as that of the basic configuration.

However, this configuration can not reduce or eliminate, if have, crosstalk problem. In order to eliminate crosstalk problem the configuration with signal generator array is constructed.

5.2.3 Configuration with signal generator array

A signal generator array (SGA), used to eliminate or reduce the crosstalk problem, is illustrated in figure 5.5. In this configuration, each signal generator in the SGA produces a signal with a central frequency which is different from other generators. Each signal generator drives the corresponding laser diode resulting in a modulated laser diode. The confocal response collected by PDA passes through a demodulator (DEM) before acquisition and signal processing, which includes filter and amplifier. The demodulator can be replaced by a signal processing programme which will be discussed in section 5.4. After demodulating or filtering, one channel signal is kept from other channels, thus the crosstalk is eliminated. Because each LD is driven at different frequencies, laser array is necessary. The requirement of other components is the same as that for basic configuration. However, the compensation of light source fluctuation is not considered in this configuration. Full

function realization is discussed in the following section.

5.2.4 Multi-function configuration

The multi-function configuration is illustrated in figure 6. In this configuration, signal generator array SGA with demodulator DEM are used to eliminate or reduce the crosstalk problem, while the PDA2 is used to compensate light source fluctuation.

5.2.5 Summary

This section presents different configurations to satisfy different requirements which are listed in Table 5.1. The sensor array is linear. Actually the array style is as flexible as the fiber's and which can be arranged as a linear array, square array, rectangle array, circular array, etc. The number of sensor array can be large to detect a bigger area. The sensor arrangements can also be different from light source array and photodetector array.

To realize multi-channel fiber confocal system, the system layout and system performance is analyzed in the following section.

Table 5.1 Multi-channel confocal system with different configurations

Configuration	Function
Basic configuration	Realize multi-channel inspection
Double detector array	Realize multi-channel inspection and eliminate or reduce light source fluctuation
Configuration with signal generator array	Realize multi-channel inspection and eliminate or reduce cross-talk
Multi-function configuration	Realize multi-channel inspection, eliminate or reduce light source fluctuation and cross-talk

5.3 Layout analysis

This section discusses the construction of multi-channel linear array confocal system, system design, components selection, and factors affecting system performance.

5.3.1 Fiber array arrangement

As a case study for a multi-channel confocal system, the single-mode fiber used has a core diameter of $10\mu\text{m}$, a cladding diameter of $125\mu\text{m}$ and the NA of 0.11. Figure 5.7 is a photograph of a five-sensor linear fiber array taken using a Nikon Microscope with a 3X objective. Figure 5.8 shows the schematic of fiber-array layout. a_f is the fiber core, and the pitch of the array, P , is $125\mu\text{m}$. A ray emits from A to B then to C at the edge of acceptance cone of fiber with refraction at the fiber-end B. The ray BC appears to emerge from point A' which is the backward-extension of ray BC intersecting with the fiber axis. The distance, dp , from point A' to the end of fiber tip surface TT' is

$$dp = \frac{a_f}{2\text{tg}\theta} \approx \frac{a_f}{2NA_f} = 45\mu\text{m} \quad (5.1)$$

This gives the minimum distance between the fiber sensor and the objective lens.

5.3.2 Photodetector array configuration

Each photodetector is connected to one arm of fiber coupler in multi-channel fiber confocal system. The position of photodetector array with fiber coupler array should be designed properly in case that on the one hand, one channel output from fiber port were collected by other channel's photodetector to cause crosstalk, on the other hand, the output from fiber leaks out to lower efficiency of photodetectors.

In figure 5.9, the dashed cylinders are the photodetectors. h_1 is the distance between photodetectors and fibers. The acceptance cone of the adjacent fibers intersects at point D. The distance from D to the end surface of fibers is h_2 .

First, the distance, h_2 , can be obtained as

$$h_2 = \frac{P_d}{2 \cdot \tan \theta} - dp \quad (5.2)$$

where, θ and dp are shown in fig.5.8. Because the flexibility of fiber, the pitch P_d of photodetector array can be any value either equal to or larger than the sensor pitch. It is sufficient to keep $h_1 < h_2$. Once the distance h_1 is fixed, the active area of photodetector can be calculated afterwards.

5.3.3 Two spots recognition and spatial resolution

For multi-channel sensors, fig. 5.10 shows the relationship between two points on the specimen with their respective image points using ray-tracing for a typical 4f system. F12 is the confocal plane of the two lenses, F1 is front focal plane of lens L1, and F2 is the back focal plane of lens L2. Image spots IO and I1 are images of object spots O0, O1 respectively. Assuming that L1 and L2 are large enough for all possible light vectors to pass through, it can be seen that irrespective of the illumination direction, each object has only one ideal image neglecting the lens aberration.

Assuming that there are two spots O0, O1 of an object on the focal plane F1, their images are IO and I1 respectively in the focal plane F2. The ray (solid line) is shown in the fig. 5.11. If the object surface at the point O0 and O1 has a small tilt δ , with the axis of focal plane F1, the reflected light from these two points deviates by an angle 2δ as illustrated by the dashed line in fig.5.11. The deviated rays still obey the law of reflection and images at

I0 and I1 respectively. If the distance of two points at object or at image can be distinguished (resolved), cross-talk does not exist for an ideal system. Thus, to resolve adjacent image points, the pitch and the lateral resolution have to be considered.

The smallest pitch is limited by the lateral resolution. For incoherent imaging, according to Rayleigh criterion, the transverse resolution is the distance between the two points greater than the distance, d_R , as illustrated in fig. 5.12, and is given as

$$d_R \geq \frac{0.61\lambda}{NA} \quad (5.3)$$

Here, d_R is the critical value of the lateral resolution. According to this criterion, a point array can be resolved if the pitch of multi-channel sensors on the specimen is larger than d_R . When the pitch of the sensors is at its critical value, cross-talk becomes a serious problem. Since all the detected spots overlap with their adjacent neighbors, the reflected light from each spot is collected by the adjacent detectors. considering diffraction and quality of lens, the cross-talk is even more serious. Further, when the pitch of the sensors is at this critical value, for a confocal system, the overlapped spots make the detection efficiency lower.

To overcome the above problems, the sensor pitch should be larger than the Rayleigh distance. However, a longer pitch means lower spatial-resolution for the system. For diffraction, the zero order has 83.8% of total energy while the first order is 1.34 times the spot size and has 7.2% of the total energy. To ensure transverse detection quality and efficiency, in multi-channel confocal system, the pitch of the sensor should be kept at 5 to 10 times that of the spot size.

Based on equation (5.3), the lateral resolution is $0.8\mu\text{m}$ for GRIN lens and $0.6\mu\text{m}$ for DVD lens. Thus a pitch of $4\sim 8\mu\text{m}$ is desired for the system with GRIN lens and $3\sim 6\mu\text{m}$ for the system with DVD lens.

5.4 Crosstalk study

5.4.1 Introduction

To meet industrial and research requirement, a multi-channel confocal 3D profile measurement system was proposed and the system configurations are discussed in the previous section. Some researchers tried to develop a microlens array confocal 3D profile measurement system^[26, 98]. From the literature survey on confocal techniques and microlens configuration, it is seen that the crosstalk problem has not been considered by any other research work. From the theoretical analysis, it appears that crosstalk problem does not exist. However, the theoretical analysis is for an ideal system and hence not practical. In an actual measurement system the components are not perfect in design, fabrication, and alignment. The aberration problems may often cause the image size and shape to deviate more than for the ideal case. When two adjacent image points are so close that the aberrated part of one image may overlap to the normal field of the other image and crosstalk will thus be a problem. The measured surface is also not an ideal surface, the scattered light, at a measured point from one channel may be picked up by the other channel. If the system alignment is not good, crosstalk can occur. Any crosstalk in a micro-array confocal 3D profile measurement system, will decrease system resolution and accuracy, increase measurement error and uncertainty. This is a heed to address and limit crosstalk.

In order to study crosstalk, light source for each channel should be controlled separately, each channel of confocal 3D profile measurement must be operated and observed separately. In order to solve the problem of crosstalk, the received and transformed signal from one channel should be isolated or filtered from other channels.

This section elaborates theoretical and experimental analysis, and solution about the crosstalk study.

5.4.2 Experiment preparation

In order to study the problem of crosstalk a 9-channel linear array confocal setup was set UP.

To fabricate the fiber sensor array, the cover of the fiber is first stripped off. The bared fibers are aligned in linear array one against the other. A linear 9-sensor array was fabricated as shown in fig. 5.13, which shows the plan and cross section views taken using a Nikon Microscope with 3X objective. The pitch of the fiber sensor is $125\mu\text{m}$. Two sets of sensor array were made out of which one is single-mode fiber array, while the other is multi-mode fiber array.

The fiber coupler was fabricated using JW2000 model Fiber Coupler Production System. The paragraph of the 9-channel fiber coupler array (FCA) (shown in fig. 5.14) was configured as multi-channel light transmitting path and beamsplitter. Two sets of FCA, multi-mode and single-mode FCA were exploited to study the crosstalk. Each of the nine channels was coded as Ch1, Ch2, ..., Ch9.

A single objective lens, gradient index (GRIN) lens or DVD lens, was used to focus the light array onto a reference object. The reference object was fixed on a translation stage to realize a z-scan and to adjust the object position to the sensor.

The GRIN lens used in the experiments had a diameter of 1.8mm, which had a large enough clear aperture for 9-channel linear array. However, the DVD lens used in the experiments had a 0.83mm clear aperture, which restricts the array size to less than six channels. Therefore only a 5-channel configuration was studied with this configuration.

In order to use the available resources in the laboratory and to display enough phenomena of crosstalk, only signals from two channels were acquired. Two laser diodes were used as light source instead of a LDA and two photodetectors were used to collect signals instead of a PDA.

Other instruments include DL 1520L Digital Storage Oscilloscope (DSO), HP 35670A dynamical signal analyzer (DSA), 8023 series 50MHz arbitrary waveform/function generators (SG), which were used to provide a modulated signal for display, signal analysis, etc.

Experiments were carried out with different configurations. The configuration of multi-mode fiber with GRIN lens is denoted as Config.1, multi-mode fiber with DVD lens is denoted as Config.2, single-mode fiber with GRIN lens is Config.3, and single-mode fiber with DVD lens is Config.4. as illustrated in Table 5.2.

Setup Configurations	GRIN lens	DVD lens
Multi-mode fiber	Config. 1	Config.2
Single mode fiber	Config.3	Config.4

The experiment procedure is separated into three groups as given below:

- o One-channel signal tests

To fix a photodetector at the output leg of one channel, move a laser diode to each of 9-channel input leg, and observe the output signal from the photodetector. This is to test how many channels have crosstalk problem.

- o Two-channel signal tests

The experiments use two photodetectors to observe two-channel output signals and to show how the crosstalk affects each other.

- **Three-channel signal tests**

Two photodetectors are used to study the crosstalk problems within three adjacent channels.

These analyses are processed with time domain and frequency domain methods.

5.4.3 Time domain analysis

5.4.3.1 Constant illumination input

(1) One channel crosstalk study

This experiment uses a multi-mode fiber and GFUN lens, as setup configuration (Config.1).

The connections are shown in figure 5.15. A photodetector (PD) was fixed at the output leg of the channel 1 (Ch1). The signal output of the PD was monitored by channel 1 of the DSO. A LD was connected with the input leg of the Ch1, Ch2, Ch3, ..., Ch9 one by one. After the system was aligned, the signal output from different channels was studied.

- **Self-channel confocal response**

The self-channel in this section implies the LD and the PD connected to be in the same channel. First, connect the LD to Ch1 and switching off power of the LD, the average value of signal was 0, with a resolution lower than 2.0mV.

Next, setting the object at the focus position of the system, when the LD was switched on, the response value at focus position was -884mV.

Then, by moving the translation stage manually in steps of $5\mu\text{m}$ or $10\mu\text{m}$, the confocal response was obtained and illustrated in fig. 5.16. The confocal resolution in this experiment was around $1.0\mu\text{m}$.

- **Other channel crosstalk response**

Let the LD offer light source to channel 2 and the PD collect signal from channel 1. This configuration is written as

LD->Ch2; Ch1->PD

The object was set at the “focus” position.

An output response was observed when the LD was switched from “off” to “on” position.

When the LD was switched on, the “focus” signal was 44 mV while the “defocused” ($100\mu\text{m}$ away the “focus”) output was -30mV.

Figure 5.17 synthesizes the changes in Ch1 when the LD was switched from “off” to “on” and then the object was moved from “focus” position to some “defocused” position. It is obviously that the signal in the Ch2 can affect the output in the Ch1. The experiments indicate that the crosstalk exists.

The response difference of PD between “focus” and “defocused” is 14mV. Comparing the resolution of 2.0mV, the crosstalk is a serious problem.

Next, the setup was configured as following:

LD->Ch3; Ch1->PD

The “focus” and the “defocused” output were 46mV and 34mV respectively. The difference is 12mV. Thus this channel also shows crosstalk.

When LD is connected to Ch4, the configuration is

LD->Ch4; Ch1 -> PD

To observe the PD response, the signal output kept the value around 44mV with the changes less than 1mV when the object was moved from the "focus" to the “defocused” position. Thus, this channel had no crosstalk problem.

Similarly, connecting the LD to Ch5, Ch6, ..., Ch9, respectively, the signal output was not detectable when the object was moved from the “focus” to the “defocused” positions.

Thus, these channels had no crosstalk problem.

These experiments indicate that the crosstalk problem spans three adjacent channels.

(2) Two channels crosstalk study

The experiments with Config.1 indicate that only three adjacent channels showed crosstalk problem. This system setup was aligned using Config.2--multi-mode fiber with DVD lens to study the crosstalk with two-channel phenomena. In this configuration, Ch5 was set around the optical axis. Two laser diodes (LD1, LD2) and photodetectors (PD1, PD2) were used.

First, LD1 and PD1 were connected with Ch5 input and output ports respectively, LD2 and PD2 were connected with Ch4 input and output ports respectively. Thus the configuration is:

LD 1->Ch5->PD 1; LD2->Ch4->PD2

The object was set around focus position. When the LD1 and the LD2 were switched "on" and “off”, the output response from the Ch4 and the Ch5 were observed and recorded.

Table 5.3 The output response from the Ch5

Channel i	LD1	LD2	PD1 (mV)
Ch5	off	off	72
	off	on	60
	on	off	-408
	on	on	-476

Table 5.4 The output response from the Ch4

Channel i	LD1	LD2	PD2(mV)
Ch4	off	off	-36
	on	off	-52
	off	on	-264
	on on		-348

Table 5.3 shows the output response from Ch5 when LD1 and LD2 were switched "on" and "off". It indicates that part of the signal from Ch4 was collected by PD1. The signal from Ch4 affected the output response in Ch5.

The Table 5.4 shows the output response from Ch4 when LD1 and LD2 were switched "on" and "off". It indicates that the signal from Ch5 interfered with the output response of Ch4.

Next, keeping LD1 and PD1 connected to Ch5 input and output ports respectively, LD2 and PD2 were connected to Ch3 input and output ports respectively. This configuration is LD1 → Ch5 → PD1; LD2 → Ch3 → PD2

When LD1 and LD2 were switched "on" and "off", the output response from Ch3 and Ch5 were observed but no obvious difference was seen in these two channels, which indicates that these two channels do not have crosstalk problem.

Then, two-channel crosstalk test was carried out again using Ch5 with Ch6, and Ch5 with

Ch7. The crosstalk occurred between Ch5 and Ch6 but there was no obvious crosstalk problem between Ch5 and Ch7.

Thus, for Config2, only two adjacent channels had a crosstalk problem.

5.4.3.2 Signal analysis

(1) General description

In order to eliminate the problem of crosstalk, the signal properties have to be studied. There are two types of signals, continuous-time signal and discrete-time signal^[99]. A finite number of discrete-time signals are called digital signals. The continuous time and amplitude signals are called analog signals. By sampling a continuous time signal, discrete-time signal is obtained. Data-acquisition and conversion devices link the real world of analog signals to the computational world of digital data processing. Like signal classification, the system can be classified as continuous-time system and discrete-time system. Confocal 3D profile measurement system is a continuous-time system. Sampling converts an analog signal changes into a digital signal. The data analysis devices used in the experiments such as DSO and DSA employ data-acquisition and conversion techniques that convert the analog signals to the digital signal, performing signal processing, reconvert the digital signal to the analog signals and then displaying results.

One of the most important signals is the sinusoidal signal, that is

$$x(t) = A \sin(\omega t + \alpha), t \geq 0 \quad (5.4)$$

which is a function of time that frequently is encountered in the study of power systems and electronic systems. The quantity A is the amplitude, ω is the frequency in radians per second, and α is the phase in radians. The sinusoidal signal is easy to obtain using the signal generator.

In common confocal 3D profile measurement system, the illumination device i.e. the laser offers a constant power. The normal depth-response of confocal imaging satisfies the equation,

$$|A(z)| = \frac{\sin[k(z - z_0)(1 - \cos\theta_0)]}{k(z - z_0)(1 - \cos\theta_0)} \quad (5.5)$$

where k is wave number, θ_0 satisfies $\text{NA} = \sin\theta_0$, z_0 is the position of focus, and z is the position of the detected point. From the view of control theory, the normal depth-response is a transfer function. If the input signal from LD is a variable signal i.e. a sinusoidal signal, the output signal still satisfies confocal depth-response, the multi-channel crosstalk can be reduced or eliminated by exploiting modulation, filtering, demodulation techniques and Fourier analysis.

(2) The depth response to a sinusoidal input

An ideal confocal system is a linear time-invariant continuous-time system. When the LD output is constant, the depth response of the system will be as given by equation (5.5). This system is the steady-state response.

Denoting the depth response function as $h(z) = |A(z)|$, its transfer function is $H(s)$, using the analysis of Laplace-transform technique^[99],

$$H(s) = \frac{1}{s} h(z) \quad (5.6)$$

When the input is sinusoidal as in equation (5.4), its Laplace-transform is

$$X(s) = \frac{A\omega \cos \alpha}{s^2 + \omega^2} + \frac{A \sin \alpha \cdot s}{s^2 + \omega^2} \quad (5.7)$$

Then the Laplace-transform of the system output is

$$Y(s) = X(s) \cdot H(s) = \frac{A\omega h(z) \cos \alpha}{s(s^2 + \omega^2)} + \frac{Ah(z) \sin \alpha}{s^2 + \omega^2} \quad (5.8)$$

Exploiting inverse Laplace transform, the system output is

$$\begin{aligned}
 y_{ss}(t) &= L^{-1}\{Y(s)\} = L^{-1}\{X(s) \cdot H(s)\} \\
 &= L^{-1}\left\{\frac{A\omega h(z) \cos \alpha}{s(s^2 + \omega^2)}\right\} + L^{-1}\left\{\frac{Ah(z) \sin \alpha}{s^2 + \omega^2}\right\} \\
 &= \frac{Ah(z) \cos \alpha}{\omega} [1 - \cos(\omega t)] + \frac{Ah(z) \sin \alpha}{\omega} \sin(\omega t) \\
 &= \frac{Ah(z) \cos \alpha}{\omega} + \frac{Ah(z)}{\omega} \sin\left(\omega t + \alpha - \frac{\pi}{2}\right), t \geq 0
 \end{aligned} \tag{5.9}$$

This shows that, the confocal imaging system response to the sinusoidal input has two components, DC and AC components. The DC component is scaled by the normal depth-response $h(z)$, the phase factor of input signal, $\cos(\alpha)$, and the frequency of input signal, ω . The AC component has the same frequency as the input but is phase shifted by an amount $\angle H(j\omega) = -90^\circ$. The amplitude of the AC component is scaled by the normal depth-response $h(z)$ and depends in general on the frequency ω of the input sinusoid.

It can be concluded that for confocal imaging system, when the LD output is a sinusoid, the magnitude of DC component and the amplitude of the AC component in system output are functions of the defocused-position which can be used to determine the object-in-focus position in confocal imaging system.

The following experiments were conducted to test the above theory analysis.

(3) Confocal response with sinusoid input

A signal generator (SG) provides a sinusoidal signal with a frequency of 50Hz and an amplitude of 500mV to drive a LD. The signal output from LD was a DC component of 221mV and a sinusoidal signal with a frequency of 50Hz and an amplitude of 56.5mV.

It is known that a constant illumination input to confocal imaging system satisfies the depth response equation (5.5). However, a constant illumination input can not be used to

solve the crosstalk problem. The following experiments were done to test the relationship between the amplitude of input signal and depth-response of confocal imaging.

The experiment setup configuration was set with Config.3—the single-mode fiber with GRIN lens. The LD and a PD were connected with Ch5 input and output respectively. A SG generated a sinusoid signal output at 2kHz frequency and 400mV amplitude, which was used to drive the LD. The magnitude of the amplitude response was observed using a DSO.

After system alignment, the translation stage was moved from the focus to a defocused position. The AC-component signal response is shown in fig. 5.18. Figure 5.18 (a) is the focus response of the AC component and fig. 5.18 (b) is the defocused response of the AC component.

Moving the stage in steps of $5\mu\text{m}$ or $10\mu\text{m}$, the magnitude of the amplitude output was recorded. Fig. 5.19 displays the amplitude value of the output signal response versus the object-in-focus position. It shows that the amplitude of output signal changes with defocused position. The closer to be best focus the object was, the larger the output amplitude. The amplitude response of the output signal of the AC component satisfies the confocal principle.

5.4.3.3 Illuminatioo with sinusoid signal input

(1) Experiments using the Config.1

For a sinusoidal input signal, the crosstalk phenomenon was tested further. In this experimental study the DC component of the output was filtered and only the AC component was analyzed.

- **One-channel crosstalk response**

A PD was connected to the output leg of Ch5. A LD was connected to the input leg of Ch6 and driven by a SG. The configuration is

SG->LD->Ch6; Ch5->PD

After the system was aligned, the signal output from the PD was monitored using a DSO.

First, switching off the SG, the AC component of the signal output response from the PD was observed. Since there was no AC signal input, there was no change in output when the object was moved from focus to defocused position along optical axis.

Next, the SG was set to give sinusoidal signal at a frequency of 5KHz and an amplitude of 300mV and used to drive the LD. When the object was set the focus and 100 μ m away the focus, the peak to peak (P-P) value response was 14mV at the focus position and 9mV at the defocused position. This experiment displays the crosstalk response detected from Ch5 when the sinusoid input was used to drive the LD in Ch6. The difference is 5mV P-P value from the focus position to the defocused position.

- **Two-channel crosstalk response**

In this experiment, the output of two channels, Ch5 and Ch6 was observed simultaneously.

Two laser diodes (LD1, LD2) and photodetectors (PD1, PD2) were used along with two signal generators (SG1 and SG2).

LD1 was connected to Ch5. PD1 and PD2 were connected to the output port of Ch5 and Ch6 respectively. The output of two detectors was monitored using the two channels of the DSO. The configuration is

SG1->LD 1->Ch5->PD 1->DSO (channel 1);

Ch6->PD2->DSO (channel 2)

The sinusoidal output from SG1 was set to operate at a frequency of 2KHz and an amplitude of 100mV. Moving the object from the focus position to $100\mu\text{m}$ away the focus position, the output response from two channels is displayed in fig. 5.20. The lower signal was acquired from channel 1 of the DSO and the upper signal was acquired from channel 2 of the DSO. In channel 2 of the DSO, the P-P value was 13mV, which indicates that Ch6 has a crosstalk response. The crosstalk was not obvious at the focus position in this experiment.

Now, without changing the SG1, LD1 and PD1, the SG2, LD2 and PD2 were connected to Ch7. The output of PD2 was monitored using channel 2 of the DSO. The configuration is:

SG1->LD1->Ch5->PD1 ->DSO (channel 1);

SG2->LD2->Ch7->PD2->DSO (channel 2)

The sinusoidal output from SG1 was set to operate at a frequency of 2KHz and an amplitude of 100mV. The sinusoidal output from SG2 was set to operate at a frequency of 12KHz and an amplitude of 200mV. When SG1 was switched on and SG2 was switched off, moving the object from the focus position to $100\mu\text{m}$ away the focus position, the response was acquired and is shown in fig. 5.21. Fig. 5.21 (a) displays the focus response, in which the P-P value was 180mV of Ch5 but no obvious crosstalk output from Ch7. Fig. 5.21 (b) displays the defocused response, in which the P-P value of the crosstalk response from Ch7 was 13mV.

Then SG2 was turned and the object placed around the focus position. The response is displayed in fig.5.22. It shows the focus response, in which the P-P value was changed to 200mV in Ch5. Comparing with fig. 5.21 (a), there was 20mV difference in Ch5, which indicates that the output signal from Ch5 was affected by the signal from Ch7.

Next, switching off SG1, the object was set at the defocused position and the response is shown in fig. 5.23. The crosstalk signal in Ch5 was about 22mV in this experiment.

These experiments indicate that three adjacent channels have a crosstalk problem and the crosstalk problem is higher at defocused position than that of at the focus position.

- **Three channels crosstalk response**

in this section, Ch5, Ch6 and Ch7 output response were simultaneously analyzed. The LD1 was connected to Ch5. LD2 and PD1 were connected to the input port and output port of Ch6. PD2 was connected to Ch7. SG1 and SG2 were used to drive LE1 and LD2 respectively. PD1 and PD2 outputs were monitored and displayed on channel 1 and channel 2 of the DSO respectively. Thus the configuration is:

SC->LD1->Ch5;

SG2->LD2->Ch6->PD1->DSO (channel 1);

Ch7->PD2->DSO (channel 2)

The sinusoidal output from SG1 was set to operate at a frequency of 12KHz and an amplitude of 200mV. The sinusoidal output from SG2. was set to operate at a frequency of 2KHz and an amplitude of 100mV. Moving the object to the focus position, no obvious crosstalk effect was observed. When the object was moved 100 μ m away the focus position, the output response is shown in fig. 5.24. In this figure, Ch7 and Ch6 output signals show two main frequencies, a high frequency modulated by a lower frequency, indicating that Ch7 was affected by Ch5 and Ch6.

The experiments indicate that the crosstalk interfere three adjacent channels.

(2) Experiments with Config.2

In this section, the multi-mode fiber with DVD lens (Config.2) system was used. The AC component response was observed and studied for a sinusoid signal input at Ch3, Ch4, and Ch5. Two sets of signal generator, laser diode and photodetector were used identified as SG1, SG2, LD1, LD2, PD1, and PD2 respectively.

- **Two channels crosstalk response**

LD1 and PD1 were connected to Ch5 input and output port respectively, and LD2 and PD2 to Ch4. SG1 and SG2 were used to drive LD1 and LD2 respectively. Channel 1 and channel 2 of the DSO were used to monitor the output response from PD1 and PD2 respectively. That is:

SG1→LD1→Ch5→PD1→DSO (channel 1);

SG2→LD2→Ch4→PD2→DSO (channel 2)

After aligning the setup, the sinusoidal output from SG1 was set to operate at a frequency of 2KHz and an amplitude of 500mV. The sinusoidal output from SG2 was set to operate at a frequency of 5KHz and an amplitude of 300mV.

Figure 5.25 shows the output response when SG1 is switched on and SG2 is switched off for the object at the focus position and 100μm away the focus position respectively. Figure 5.25 (a) displays the signals output for the object in the focus position. Figure 5.25 (b) displays the signals output when the object was at the defocused position. Figure 5.25 (b) clearly shows that part of the signal from Ch5 entered Ch4 and the P-P value was 72mV.

Next, SG2 is switched on and SG1 is switched off. The output response is shown in fig. 5.26 for the object at the focus and 100μm away the focus position respectively. Figure 5.26 (a) displays the output when the object was at the focus. Figure 5.26 (b) displays the output when the object was at a defocused position. Figure 5.26 (b) clearly shows that part

of the signal from Ch4 entered Ch5 and the P-P value was 20mV. It indicates that there was crosstalk problem within two adjacent channels.

- **Three channels crosstalk response**

In this experiment, LD1 and PD1 were connected to Ch5. LD2 and PD2 were connected to Ch3. SG2 was used to drive LD2 with a sinusoidal frequency of 12KHz and an amplitude of 300mV. The DSO is used to observe the crosstalk between Ch3 and Ch5. In this experiment, no crosstalk was observed.

For the setup of Config.2, crosstalk was observed only for two adjacent channels.

(3) Experiments using the Config.3 and the Config.4

Crosstalk problem was studied further using three adjacent channels for the setup of Config.3 and Config.4 respectively. Table 5.5 summarizes the results using Config.3 and Table 5.6 summarizes the results using Config.4.

Table 5.5 and Table 5.6 indicate that Ch7 was affected by Ch6 but was not affected by Ch5. The crosstalk phenomena only showed up within two adjacent channels.

Table 5.5 Crosstalk study of three adjacent channels using Config.3

Object position Setup connections	focus position	100 μ m away the focus position
(12KHz, 350mV)SG1 $\rightarrow$ LD1 $\rightarrow$ Ch5 Ch6 $\rightarrow$ PD1 $\rightarrow$ DSO(ch1) Ch7 $\rightarrow$ PD2 $\rightarrow$ DSO(ch2)	no crosstalk	There is 12KHz, 50mV signal observed in ch1 but no signal in ch2
(12KHz, 350mV)SG1 $\rightarrow$ LD1 $\rightarrow$ Ch5 (2KHz, 200mV)SG2 $\rightarrow$ LD2 $\rightarrow$ Ch6 $\rightarrow$ PD1 + DSO(ch1) Ch7 $\rightarrow$ PD2 $\rightarrow$ DSO(ch2)	no crosstalk	There are 12KHz and 2KHz signals observed in ch1 with amplitude about 55mV. but in ch2, there is 2KHz signal observed only with amplitude about 5mV.

Table 5.6 Crosstalk study of three adjacent channels using Config.4

Object position Setup connections	focus position	100 μ m away the focus position
(12KHz, 350mV)SG1 $\rightarrow$ LD1 $\rightarrow$ Ch5 Ch6 $\rightarrow$ PD1 $\rightarrow$ DSO(ch1) Ch7 $\rightarrow$ PD2 $\rightarrow$ DSO(ch2)	no crosstalk	There is 12KHz, 48mV signal observed in ch1 but no signal in ch2
(12KHz, 350mV)SG1 $\rightarrow$ LD1 $\rightarrow$ Ch5 (2KHz, 200mV)SG2 $\rightarrow$ LD2 $\rightarrow$ Ch6 $\rightarrow$ PD1 $\rightarrow$ DSO(ch1) Ch7 $\rightarrow$ PD2 $\rightarrow$ DSO(ch2)	no crosstalk	There are 12KHz and 2KHz signals observed in ch1 with amplitude about 50mV. but in ch2, there is 2KHz signal observed only with amplitude about 5mV.

5.4.3.4 Summary

The experimental results are summed up in Table 5.4 displaying the crosstalk problem occurred in different configuration. It indicates that there are total three adjacent channels have the problem of crosstalk.

Table 5.7 The crosstalk problem for different configurations

Setup	Configuration	Crosstalk problem at each side
Config.1	MMF + GRIN lens	Adjacent three channels
Config.2	MMF + DVD lens	Adjacent two channels
Config.3	SMF + GRIN lens	Adjacent two channels
Config.4	SMF + DVD lens	Adjacent two channels

5.4.4 Frequency domain experiments method and analysis

5.4.4.1 General description

The crosstalk problem can be solved by simultaneously modulating the input light into a particular channel and demodulating the specimen signal. This section discusses how this strategy has been reached.

Filters are employed to extract useful properties and separate the noise from a signal.

If the input signal in confocal 3D profile measurement system can be modulated, the output signal needs to be demodulated. When the demodulated signal complies with the confocal response curve, the crosstalk problem can be resolved. That means, if the input is modulated with a signal which has a constant amplitude and frequency, the amplitude of the output signal will change with the position of the object-in-focus and comply with the confocal response curve. Extracting the amplitude from the complex signal gives the

confocal response curve. Thus, if different input channels are modulated with different frequencies, using a proper filter will resolve the crosstalk problem.

Use of the SG to drive the LD with a sinusoid signal to test for the crosstalk problem as described in the previous section is the modulation method. The above experiments were analyzed in the time-domain for crosstalk observation and analysis. Frequency domain analysis is required for the modulation signal selection, filter design, and the Fourier transform techniques to solve the crosstalk problem.

5.4.4.2 Experimental and theoretical analysis

(1) Sinusoidal signal output from the SG

A sinusoidal signal with a frequency of 2KHz and an amplitude of 400mV can be written as

$$s_V(t) = 400\sin(4000\pi t + \theta) \quad (5.10)$$

The output from the SG was tested using the DSO. The P-P value was 812mV and the fundamental frequency was 2kHz.

This experiment indicates that the output signal from the SG only has the fundamental frequency with some low noise.

(2) Sinusoidal signal output from the LD

Loading this signal into a LD, the modulated signal output from the LD was monitored. The P-P value was 248mV and the fundamental frequency was 2kHz. In the time domain, there is 200mV DC component. The DC component power has a higher ratio than the modulated sinusoid signal. Compared to the original signal from the SG with the output signal from the LD, the noise in the LD modulated signal is higher than that of the original

signal.

(3) Sinusoid signal output from the confocal system

In this section, the experiments with sinusoidal input signal into confocal system were observed in order to analyze confocal system modulation signal output.

- **One channel sinusoid signal output using the Config.1**

The confocal system was used a multi-mode fiber and GRIN lens (Config.1). The configuration of the LD, the PD, the DSO and the SG is

SG→LD→Ch5→PD→DSO

Considering the same sinusoidal output signal from the SG modulates this one channel confocal system. For the object at the focus, the output from the PD was monitored and displayed in fig. 5.27. Fig. 5.27 (a) is time domain response and fig. 5.27 (b) is frequency domain response. The P-P value is 308mV and the DC component is 234mV in the time domain figure. The fundamental frequency is 2kHz in the frequency domain with higher noise than the input signal and the LD output.

- **One channel sinusoid signal output using the Config.3**

This experiment setup used a single-mode fiber with GRIN lens (Config.3). The configuration of the LD, the PD, the DSO and the SG is

SG→LD→Ch4→PD→DSO,

For the object at the focus and 500 μ m away the focus position, the modulated response of the PD was monitored and displayed in fig. 5.28 (a) and (b) respectively. The P-P value was 1.9V at the focus position and 190mV at the defocused position. Compared to fig. 5.27 (a), noise was higher for a single-mode fiber confocal system. The Fourier Transform of fig. 5.28 (b) using a DSA is displayed in fig. 5.28 (c) and (d). Figure 5.28 (c) displays the

full spectral information of the acquired data and fig. 5.28 (d) zooms in to highlight the harmonics. It shows that the response signal from the PD has a DC component, the 2KHz fundamental frequency and harmonics at, 4kHz, 6kHz, etc. Comparing to fig. 5.28, a confocal imaging system, using single-mode fiber has more harmonic components than a multi-mode fiber system. The harmonic noise is not stable. The occurrence of harmonics causes the shape change of the fundamental wave. Therefore the harmonic noise can cause signal output distortion and degrade the system stability and resolution.

(4) The analysis of the sinusoidal signal output from the confocal system

The above experiments indicate that confocal imaging system has more noise than the input signal and the LD output. The 2kHz sinusoidal signal output from the confocal imaging system can be expressed as

$$s_v(t) = A_0 + C_1 \sin(4000\pi t + \theta_1) + \sum C_k \sin(4000\pi k t + \theta_2) + n(t), \quad k = 2, 3, \dots \quad (5.11)$$

Where

A_0 : the DC response in confocal imaging system,

C_1 : the amplitude response of the fundamental wave,

C_k : the amplitude response of the harmonics,

$n(t)$: the noise fluctuation with the time.

The amplitudes of the fundamental and its harmonic waves depend on the best focus position of object and also on the frequency. This means that the depth response is modulated. If only the amplitude of fundamental wave is extracted, i.e., the DC component, higher harmonics and noise are filtered, and following demodulation, the signal output will be given by

$$s_{\nu}(t) = C'_1 \frac{\sin[k(z - z_0)(1 - \cos \theta_0)]}{k(z - z_0)(1 - \cos \theta_0)} \quad (5.12)$$

where C'_1 is a constant.

Thus modulating the input signal to confocal system does not change the depth response expression.

In the time domain analysis, two or three adjacent channels have crosstalk with each other, which means that if the pitch of the sensor array is less than $250\mu\text{m}$ using Config.1 or $125\mu\text{m}$ using Config.2 to 4, the crosstalk will be present. If the pitch is smaller than $125\mu\text{m}$, crosstalk will affect more channels. If the three-channel crosstalk problem is solved, it's easier to solve multi-channel crosstalk and develop multi-channel sensor. Here three-channel linear array crosstalk is studied as specific case.

Considering three channel sensors Ch1, Ch2, Ch3 that are modulated with sinusoidal signals of different frequencies, denoted as f_1 , f_2 , and f_3 . The modulated sinusoidal input signals can be written as

$$s_{\nu 1i}(t) = C_{10} \sin(2\pi f_1 t + \theta_{10}) \quad (5.13)$$

$$s_{\nu 2i}(t) = C_{20} \sin(2\pi f_2 t + \theta_{20}) \quad (5.14)$$

$$s_{\nu 3i}(t) = C_{30} \sin(2\pi f_3 t + \theta_{30}) \quad (5.15)$$

The amplitude of the three fundamental waves, C_{10} , C_{20} , C_{30} are constant and do not vary with the environmental conditions.

Without crosstalk, the output signal from the three channels will be

$$s_{\nu 1o}(t) = A_{11} + C_{11} \sin(2\pi f_1 t + \theta_{11}) + \sum C_{1k} \sin(2k\pi f_1 t + \theta_{1k}) + n_1(t) \quad (5.16)$$

$$s_{V2o}(t) = A_{21} + C_{21} \sin(2\pi f_2 t + \theta_{21}) + \sum C_{2k} \sin(2k\pi f_2 t + \theta_{2k}) + n_2(t) \quad (5.17)$$

$$s_{V3o}(t) = A_{31} + C_{31} \sin(2\pi f_3 t + \theta_{31}) + \sum C_{3k} \sin(2k\pi f_3 t + \theta_{3k}) + n_3(t) \quad (5.18)$$

In these three equations, the amplitude of the three fundamental waves, C_{11} , C_{21} , and C_{31} are functions of defocused position and depend on the fundamental frequencies, f_1 , f_2 , and f_3 respectively. The magnitude of DC components, A_{11} , A_{21} , and A_{31} , are the functions of defocused position, also depend on the fundamental frequencies of f_1 , f_2 , and f_3 and phases $\cos\theta_{10}$, $\cos\theta_{20}$, and $\cos\theta_{30}$ respectively.

When these three channels have crosstalk, they can be expressed as

$$\begin{aligned} s'_{V1o}(t) = & A'_{11} + C_{11} \sin(2\pi f_1 t + \theta_{11}) + \sum C_{1k} \sin(2k\pi f_1 t + \theta_{1k}) \\ & + C''_{21} \sin(2\pi f_2 t + \theta''_{21}) + \sum C''_{2k} \sin(2k\pi f_2 t + \theta''_{2k}) \\ & + C'_{31} \sin(2\pi f_3 t + \theta'_{31}) + \sum C'_{3k} \sin(2k\pi f_3 t + \theta'_{3k}) + n'_1(t) \end{aligned} \quad (5.19)$$

$$\begin{aligned} s'_{V2o}(t) = & A'_{21} + C_{21} \sin(2\pi f_2 t + \theta_{21}) + \sum C_{2k} \sin(2k\pi f_2 t + \theta_{2k}) \\ & + C'_{11} \sin(2\pi f_1 t + \theta'_{11}) + \sum C'_{1k} \sin(2k\pi f_1 t + \theta'_{1k}) \\ & + C''_{31} \sin(2\pi f_3 t + \theta''_{31}) + \sum C''_{3k} \sin(2k\pi f_3 t + \theta''_{3k}) + n'_2(t) \end{aligned} \quad (5.20)$$

$$\begin{aligned} s'_{V3o}(t) = & A'_{31} + C_{31} \sin(2\pi f_3 t + \theta_{31}) + \sum C_{3k} \sin(2k\pi f_3 t + \theta_{3k}) \\ & + C''_{11} \sin(2\pi f_1 t + \theta''_{11}) + \sum C''_{1k} \sin(2k\pi f_1 t + \theta''_{1k}) \\ & + C'_{21} \sin(2\pi f_2 t + \theta'_{21}) + \sum C'_{2k} \sin(2k\pi f_2 t + \theta'_{2k}) + n'_3(t) \end{aligned} \quad (5.21)$$

In these three equations, C'_{11} and C''_{11} are the crosstalk amplitude of the fundamental wave of f_1 , C'_{21} and C''_{21} are the crosstalk amplitude of the fundamental wave of f_2 , and C'_{31} and C''_{31} are the crosstalk amplitude of the fundamental wave of f_3 .

The magnitude of DC components, A'_{11} , A'_{21} , and A'_{31} , are the functions of defocused position. The DC component from each channel can interfere with each other. Each

channel signal output includes its own fundamental wave, harmonics generated by its own fundamental wave (self-harmonics), other channels' fundamental waves and their harmonics (crosstalk-harmonics), DC component from its own and other channels, and other noise. The noise degrades the signal and makes the signal distortion, which includes the low-frequency fluctuation, harmonics noise and the crosstalk.

5.4.4.3 Discussion

The experiments in this section indicate that a fundamental wave signal generated from a SG after passing through a component, a LD, or passing through system. a confocal system, the output signal will be degraded by harmonics and white noise.

Theoretical analysis indicates that in multi-channel confocal system, the crosstalk make one channel signal output more complex than single channel confocal system. It includes fundamental wave and harmonics not only from its self-channel, but also from crosstalk channels. In order to extract the useful signal, reduce signal distortion and eliminate or reduce the crosstalk affection, filtering is employed.

5.4.5 Crosstalk problem solution

This section gives the crosstalk solution by filter and experiments analyzing. Band-pass filter is used in confocal system. Experiments analyses give the filter parameters as a demonstration. Software filter is realized to eliminate crosstalk.

5.4.5.1 Filters in a confocal system

A filter is a frequency selective device that allows certain frequencies to pass through and blocks or attenuates others. Whether a signal is passed or blocked, depends on the system function which can be described as

$$H(e^{j2\pi f}) = |H(e^{j2\pi f})| \angle \phi(2\pi f) \quad (5.22)$$

The amplitude $|H(e^{j2\pi f})|$ of frequencies in the pass-band is relatively large and ideally is a constant. A stop-band is characterized by small ideally zero magnitude $|H(e^{j2\pi f})|$. A filter can be classified as low-pass filter, high-pass filter, band-pass filter and notch (band-stop) filter^[100~102]. The frequency between the pass-band and the stop-band is the cutoff frequency. In a practical case, the pass-band and stop-band are not clearly demarcated and are referred to as the cut-off frequency corresponding to the -3dB point of the frequency f_c . A band-pass filter combines features both the low-pass and high-pass filters. It is described by a low cutoff frequency, f_{c1} , and a high cutoff frequency, f_{c2} . Many filters are designed by first designing a low-pass filter and then using a frequency transformation to obtain the desired filter^[100].

Crosstalk can be resolved by setting the signal from Ch1 to pass through a low-pass filter, the signal from Ch3 to pass through a high-pass filter and the signal from Ch2 to pass through a band-pass filter. Theoretical analysis and experiment results show that low frequency distortion and DC components from three channels can interfere with the response from Ch1, thus low-pass filter will not produce a satisfactory output response from Ch1. To reduce distortion caused by low-frequency fluctuation and to eliminate the factor of crosstalk caused by DC components, DC component cannot be used as part of signal in multi-channel system configuration. Thus low frequency and DC component have

to be filtered. Further, the self-harmonics and the crosstalk-harmonics can cause distortion of the output signal in Ch3. Therefore, to eliminate the crosstalk and harmonic distortion, band-pass filters have to be used in each channel. To remove DC component and low frequency noise, interference (crosstalk) and harmonic noise, the bandwidth should be narrower. White noise exists at all the frequencies of the spectrum, so narrow band-pass filter can filter most of white noise too. Subsequently, narrow band-pass filter can greatly reduce the total noise.

To determine the cut-off frequency and bandwidth of band-pass filter, an experimental analysis about frequency spectrum distribution was done. Some of the experimental data used earlier are analyzed using DSA.

5.4.5.2 Crosstalk experiments and analysis

Reviewing fig. 5.25 (a) and (b) obtained using the setup of Config.2, Channel 1 displays the response from Ch5, and Channel 2 displays the response from Ch4. Ch5 was the self-channel response and Ch4 was the crosstalk response. These time domain response from Ch4 and Ch5 are analyzed and converted to frequency domain using the FFT technique and the DSA device.

The frequency response of Ch5 is shown in fig. 5.29 and fig. 5.30.

Fig. 5.29 (a), (b) and (c) display the frequency response of Ch5 when the object is at the best focus position. Fig. 5.29 (a) is the full spectrum of Ch5; fig. 5.29 (b) zooms in to the harmonics; and fig. 5.29 (c) zooms in further to highlight the bandwidth of the fundamental frequency and the low frequency noise.

Fig. 5.30 (a), (b), and (c) display the frequency response of Ch5 when the object *was* at a defocused position. Fig. 5.30 (a) is the frequency response of the full spectrum, fig. 5.30

(b) zooms in to highlight the harmonics; and fig. 5.30 (c) zooms in further to highlight the bandwidth of the fundamental frequency and low frequency noise.

Fig. 5.29 and fig. 5.30 show that for frequencies larger than 350Hz, the low frequency noise is very low. For the fundamental frequency, the -3dB bandwidth is 60Hz. From 350Hz to the fundamental frequency $(2k-60)\text{Hz}$, and from $(2k+60)\text{Hz}$ to the first harmonic frequency $(4k-60)\text{Hz}$ the noise is very low.

Figure 5.31 and figure 5.32 show the frequency response of the crosstalk Ch4.

Fig. 5.31 (a), (b) and (c) are the frequency response of Ch4 when the object was at the best focus position. Fig. 5.31 (a) is the full spectrum of Ch4; fig. 5.31 (b) zooms in to indicate that there are no higher order harmonic in this spectrum; and fig. 5.31 (c) zooms in further to highlight the bandwidth of the fundamental frequency and low frequency noise.

Fig. 5.32 (a), (b) and (c) are the frequency response of Ch4 when the object was at the defocused position. Fig. 5.32 (a) is the full spectrum of Ch4; fig. 5.32 (b) zooms in the fundamental frequency and its harmonic frequency; and fig. 5.32 (c) zooms in further to highlight the bandwidth of the fundamental frequency and low frequency noise.

Figure 5.31 and 5.32 show that bandwidth of the low frequency noise is wider than that of the fundamental frequency. For frequencies greater than 400Hz, noise is very low. For the fundamental frequency, the -3dB bandwidth was 60Hz. From 400Hz to the fundamental frequency $(2k-60)\text{Hz}$, and from $(2k+60)\text{Hz}$ to the first harmonic frequency $(4k-60)\text{Hz}$, noise is very low.

To eliminate or reduce the crosstalk problem, harmonics noise and white noise, a narrow band filter is used and sampling theorem is studied for the filter design.

5.4.5.3 Sampling theorem

To design a software filter, the continuous-time waveform should be sampled and converted to discrete-time waveforms. One critical mathematical preliminary for the processing of discrete-time waveforms, which originates from sampling continuous-time waveforms, is the issue of sampling frequency and aliasing.

According to Whittaker-Shannon sampling theorem^[103], when the sampling frequency is twice the value of the highest frequency existing in the signal, all the information contained in the analog signal is kept. That sampling frequency is called Nyquist frequency and is given by:

$$f_s \geq f_n = 2f_h$$

(5.23)

where f_s is the real sampling frequency, f_n is the Nyquist frequency, and f_h is the highest frequency existing in the signal. Failure to obey the Nyquist sampling theorem results in

The Nyquist frequency is the theoretical limit that should be used as a guide when sampling a function and should not be taken as a sacred or absolute value. In actual practice, a sampling frequency of five times the Nyquist frequency is usually recommended so as to avoid any problems caused by noise or other signal degradation. We call this sampling frequency ($f_s = 5f_n$) the real-world sampling frequency^[103].

5.4.5.4 Filter analysis

Band pass filter is used to extract useful signal from its-self channel and filter the affection of crosstalk and some noise. A program was designed under the LabView environment to

analyze signals before and after narrowband band pass filter. The continuous signal was acquired using the DSO and processed using the designed program.

Fig. 5.33 shows the output from single-mode fiber confocal setup modulated by a 2KHz sinusoidal signal. The data was analyzed in time and frequency domains before and after passing through a narrow band filter.

Figure 5.34 is the time domain signal and its frequency domain signal before filtering.

Figure 5.34 (a) is the time domain response within 5 to 10ms period, and fig. 5.34 (b) is the frequency spectrum of the time domain response. The fundamental frequency 2KHz and its harmonics 4KHz, 6KHz, 8KHz, 10KHz and 12KHz are present in the spectrum.

After passing a narrow band filter with 2KHz central frequency, the signal output is displayed in fig. 5.35. Fig. 5.35 (a) is the time domain response within 5 to 10ms period, while fig. 5.35 (b) is the frequency spectrum of the time domain response. Compared to fig. 5.34 (a), fig. 5.35 (a) shows a more pure sinusoidal response. This is confirmed by comparing fig. 5.34 (b) with fig. 5.35 (b), which indicates no higher harmonic or noise in the frequency response after the filter. Figure 5.36 shows the frequency response of fig. 5.34 (b) and fig. 5.35 (b) amplified by the same amount. Figure 5.36 (a) displays the frequency signal spectrum before narrow band filter and fig. 5.36 (b) displays the frequency signal spectrum after the narrow band filter, which shows that there is no harmonics noise and the white noise is reduced too.

Figure 5.37 displays a crosstalk signal for a two-channel single-mode fiber confocal setup modulated by 5kHz sinusoid signal in Ch5 and a 2KHz crosstalk signal from Ch6. Fig. 5.37 (a) is the time domain signal before filter, while fig. 5.48 (b) is after filter within a 1 to 2ms. Comparing these two figures, the signal after filtering has a more smooth sinusoidal form. Figure 5.37 (c) and (d) are the frequency responses before and after

filtering respectively. Fig. 5.37 (c) shows the full frequency spectrum of fig. 5.37 (a), which shows the 5KHz fundamental frequency, 2KHz crosstalk frequency and their harmonics at 4KHz, 6KHz, 8KHz, 10KHz, etc. and white noise. After the narrowband filter, the full spectrum shows in fig. 5.37 (d), in which the signal consists of 5kHz with low harmonics and white noise. Figure 5.37 (e) and (d) zoom in the frequency spectrum with same ratio from 3KHz to 7KHz before and after filtering respectively, which show that after filtering [fig. 5.37 (d)], noise is decreased much.

5.4.5.5 Summary

Time and frequency domains analysis show that crosstalk and harmonic noise make the signal coarse and distorted. Bandwidth of filter is obtained by frequency spectrum analysis. The filter analysis indicates that after the filter, the harmonics and crosstalk are eliminated and the white noise is reduced.

5.5 Conclusion

With fast speed 3D profile inspection requirement for industries, multi-channel confocal 3D profile inspection system is conceived with different configuration to solve the problem of measuring speed, light source fluctuation, and crosstalk. The basic rules for system layout are discussed. Multi-channel fiber confocal setup is successfully built for crosstalk study and problem solution.

The illumination with constant input and sinusoidal input indicate that the crosstalk still exists. Experimental analysis found that the crosstalk can affect upto a length of $250\mu\text{m}$. Frequency analysis indicates that sinusoidal input will increase harmonic problem but not crosstalk problem. Thus multi-channel confocal system with modulation input signal not

only has crosstalk problem but also include harmonic problem. Filter analysis gives the case study a success in eliminating the crosstalk and harmonics problems.

With the successful contribution of techniques discussed in chapter 4 and chapter 5, a basic fiber array configuration of three-channel 3D profilometer is constructed and applied in MOEMS components inspection, which will be discussed in the next chapter.

Figures

Fig. 5.1 The schematic of multi-channel 3D profile measurement system.

Fig. 5.2 The schematic of multi-channel 3D profile measurement system with tuning fork as scanning system.

Fig. 5.3 The schematic of multi-channel 3D profile measurement system with PZT as scanning system.

Fig. 5.4 Multi-channel 3D profile measurement system with double photodetector array and translation stage configuration.

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Fig. 5.22 The focus response from the Ch5 and the Ch7 when the SG1 and the SG2 were switched on.

Fig. 5.23. The defocus response from the Ch5 and the Ch7 when the SG1 was switched off and the SG2 was switched on.

Fig. 5.24 The crosstalk response from the Ch6 and the Ch7, when the SG1 and the SG2 offered signal to the Ch5 and the Ch6 respectively.

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(b) Defocus response from the Ch4 and the Ch5

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(a) The focus response from the Ch4 and the Ch5.

(b) Defocus response from the Ch4 and the Ch5.

Fig. 5.26 The response from the Ch4 and the Ch5 when the SG1 was switched'off and the SG2 was switched on.

(a) Time domain output from the PD 1

(b) Frequency domain output from the PD.

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Fig. 5.33 The output response from single-mode fiber coupler system setup modulated by 2kHz sinusoid signal.

(a) The time domain signal within 5-10ms period

(b) The Frequency spectrum response

Fig. 5.34 The analysis of the signal output response from single-mode fiber coupler system setup with 2kHz sinusoid modulated signal before filter.

(a) The time domain signal within 5~10ms period.

(b) 300Hz band width
1000Hz stop band
width

Fig. 5.35 The analysis of the signal output response from single-mode fiber coupler system setup with 2kHz sinusoid modulated signal after passing a narrow band filter with **2kHz** central frequency.

(a) Zooming in
frequency signal
spectrum before the
narrow band filter.

(b) Zooming in
frequency signal
spectrum after the
narrow band filter.

Fig. 5.36 Zooming in the frequency signal spectrum of the Fig.5.34 and the Fig. 5.35 with the same proportion before and after the narrow band filter.

(a) The time domain of **5kHz** sinusoid signal interfered by 2kHz sinusoid signal before filter.

(b) The time domain of **5kHz** sinusoid signal interfered by 2kHz sinusoid signal after filter.

Fig. 5.37 A crosstalk signal with 5kHz sinusoid signal interfered by 2kHz sinusoid signal in two-channel single-mode fiber coupler system setup.

(c) Frequency domain of 5kHz signal interfered by 2kHz signal before filter.

(d) Frequency domain of 5kHz signal interfered by 2kHz signal after filter.

(e) Zoom in 5kHz signal interfered by 2kHz signal before filter.

(f) Zoom in 5kHz signal interfered by 2kHz signal after filter.

Fig. 5.37 A crosstalk signal with 5kHz sinusoid signal interfered by 2kHz sinusoid signal in two-channel single-mode fiber coupler system setup.

(a) The full spectrum of the Ch5

(b) Zoomed in for observing the harmonics

(c) Zoomed in for observing the low frequency spectrum

Fig. 5.31 The frequency domain of the Ch4 when the object was at the focus position.

Fig. 5.32 The frequency domain of the Ch4 when the object was at the defocus position.

Fig. 5.33 The output response from single-mode fiber coupler system setup modulated by 2kHz sinusoid signal.

(a) The time domain signal within 5–10ms period.

(b) The frequency spectrum response.

Fig. 5.34 The analysis of the signal output response from single-mode fiber coupler system setup with 2kHz sinusoid modulated signal before filter.

(a) The time domain signal within 5~10ms period.

(b) 300Hz band width
1000Hz stop band width

Fig. 5.35 The analysis of the signal output response from single-mods fiber coupler system setup with **2kHz** sinusoid modulated sign21 after passing a narrow band filter with **2kHz** central frequency.

(a) Zooming in frequency signal spectrum before the narrow band filter.

(b) Zooming in frequency signal spectrum after the narrow band filter.

Fig. 5.36 Zooming in the frequency signal spectrum of the Fig.5.34 and the Fig. 5.35 with the same proportion before and after the narrow band filter.

(a) The time domain of 5kHz sinusoid signal interfered by 2kHz sinusoid signal before filter.

(b) The time domain of 5kHz sinusoid signal interfered by 2kHz sinusoid signal after filter.

Fig. 5.37 A crosstalk signal with **5kHz** sinusoid signal interfered by 2kHz sinusoid signal in two-channel single-mode fiber coupler system setup.

(c) Frequency domain of 5kHz signal interfered by 2kHz signal before filter.

(d) Frequency domain of 5kHz signal interfered by 2kHz signal after filter.

(e) Zoom in 5kHz signal interfered by 2kHz signal before filter.

(f) Zoom in 5kHz signal interfered by 2kHz signal after filter.

Fig. 5.37 A crosstalk signal with 5kHz sinusoid signal interfered by 2kHz sinusoid signal in two-channel single-mode fiber coupler system setup.

Chapter 6 MOEMS component fabrication and inspection study

In micro-optical communication systems, V-grooves are an important MOEMS component for fiber and laser diodes embedding. For passive optical alignment of micro-optical communication system, the fabrication of V-groove and their inspection are important. In this chapter, a three-channel fiber confocal 3D profilometer is built and used for MOEMS components' measurement.

6.1 Introduction

6.1.1 MOEMS background

Micro-electro-mechanical systems (MEMS) is a new manufacturing technology, to produce high performance three-dimensional structures and mechanical components with micron sized features, accurately and at low cost. It is a combination of miniature mechanical and electronics components integrated into a system. The late 1970's was the start of serious micromachining activity. The paper "Silicon as a mechanical material"^[104] published by K. Peterson in 1982 is regarded as the beginning of the MEMS era.

MEMS technology is seen amongst the leading technologies for this century^[105, 106]. It has drawn intensive interests due to its wide applications and large market potential. Its impact on the society is predicted to be considerable in many fields, such as increased safety, environmental protection, improved health systems, increased comfort and worldwide

communication system. Continuous achievements have been made in the research and development of microsensors, microdevices and microsystems. Futuristic microsystems have been prophesied which carry out manipulations inside the human body as miniature robots^[106].

In certain areas, MEMS has already stepped out of the research lab into the real world. Pressure sensors for measuring e.g. patients' blood pressure or the pressure in car have so far achieved the biggest market share. Micro acceleration sensors for airbag systems are widely employed in cars and gyroscopes for navigation and stability control. The printheads of inkjet printers consist of small micromachined nozzles and microactuators which control the flow of ink. Micro-telecommunication system and MOEMS are recent packing architecture which are a major driving force behind the development of high performance, high reliability integrated opto-electro or opto-electro-mechanical components^[7, 107].

6.1.2 MEMS technology and MOEMS application

The interest in MEMS originates partially in the advantages which can be gained from miniaturization. On the one hand, microsystems can simply replace conventional systems, while on the other new applications arise. Generally, it has been recognized that simple down-scaling of mechanical parts, which exist in the microworld, does not usually work. Microstructure technology allows mechanical, fluidic, optical structures to have very small dimensions and be implemented on a substrate. Silicon based sensors are already available commercially. Silicon is presently still the most important material for MEMS fabrication. The main reason is the existing expertise and fabrication tools in the successful and well-

established in the silicon-based microelectronic industry. The prospects of new sensor and device concepts together with a possible cheaper manufacturing process are the driving factors. The standard processes to fabricate MEMS are similar to the ones used in the fabrication of integrated electronic circuits.

A common classification scheme divides MEMS technologies into bulk micromachining, surface micromachining and LIGA/HARMS^[106].

For typical surface micromachining, structures are fabricated on silicon-based surface and combined with integrated circuits on one chip. Together with bonding techniques they are essential for new MEMS applications and to develop better and cheaper sensors, actuators and microsystems.

Bulk micromachining is widely used in MOEMS applications. Bulk micromachining is the term applied to devices processing in which part of the silicon substrate is dissolved away to produce mechanical elements, such as beams, membranes, grooves, and other structures. The main principle of bulk micromachining is to selectively remove material from a substrate by various etching methods.

In MOEMS application, laser-fiber module is fabricated on single wafer using bulk micromachining technology to realize miniaturization and multi-data communication. This new packaging architecture integrates on a MOEMS chip a silicon micromachined submount. The silicon submount has a central recess for the MOEMS chip, V-grooves for optical fibers, and micropits for micro laser diodes. All bulk micromachined shapes use a single anisotropic wet etching step.

6.1.3 Micro optical alignment

For communication systems, the optical alignment between fibers or fiber and micro LD is

significant factor for optimal system operation. For fiber-fiber alignment, a $1\mu\text{m}$ axis to axis misalignment can cause power losses greater than 3dB, which degrades the information of communication data^[108].

Optical alignment technology can be classified into passive and active alignment method. Active optical alignment method requires extra components or techniques to enhance coupling efficiency. This method gives precise alignment, however there is the additional need for extra components in the system, equipment to monitor the alignment result and experienced operator for good alignment, which makes it time consuming and expensive. For instance, partially metal-coated (PMC) fiber is a novel fiber alignment method^[109]. Rotating the PMC fiber in a silicon V-groove, the core position can be aligned. But this operation is complex and time consuming, and PMC fiber is costly, and not suitable for industrial application.

Passive alignment method is a low cost alternative. However, for passive alignment, a precision better than $1\mu\text{m}$ is essential, which requires high precision anisotropic wet etching control. To realize passive alignment, photolithography, anisotropic and etching of material should be studied in detail. The profile of etched shape should be constantly inspected to improve fabrication process.

6.1.4 V-groove inspection

Currently, the scanning electron microscope (SEM) is the most common technique used to inspect the etched V-groove. Figure 6.1 is a photograph of a V-groove with embedded fiber taken using the SEM. However, the etched surface is not perfect because of inaccuracy in the alignment and lithography process, which may cause the depth of V-groove to change along the length of the groove. The SEM has been used to inspect the V-

groove profile but this is destructive technique and one cannot get the profile over the entire length. Multi-channel confocal system can satisfy the requirement of V-groove inspection. It is easy to measure V-groove at any cross section and realize fast profile measurement. This system is applied to inspect anisotropic wet chemical etching process for V-groove fabrication. The three-channel fiber confocal 3D profilometer is used as a demonstration of a general multi-channel confocal 3D profile measurement system.

For passive optical alignment application, the V-groove size is a critical requirement, which depends on material properties, etching technology and anisotropic properties. In order to control the anisotropic wet chemical etching, these technologies have to be studied.

6.2 Mask design

MOEMS application provides the possibility to put optical systems on a single silicon chip. MOEMS have miniaturized devices that are designed to manipulate light in the same fashion as large-scale optics. They offer advantages in terms of mass, volume, electrical power consumption and cost, but they also present significant design challenges because creating an integrated circuit and optical components on a silicon wafer needs a mask fabricated with the specific pattern. The micromaching methods and chemical methods used to fabricate this pattern on the wafer or on the mask. 3-D mechanical structures have to be converted into two dimensions in order to be able to transfer them to the wafer or the mask using photolithography.

Mask design is the initial step of photolithography. The depth of the V-groove is highly dependent on the width of the channel (V-groove) since the wall of the etched silicon is fixed at an angle of 54.7° due to the crystal lattice of the silicon^[106]. The measurement is

calculated using the sine rule of basic trigonometry shown in fig. 6.2 and given as

$$\frac{A}{\sin A^\circ} = \frac{B}{\sin B^\circ} = \frac{C}{\sin 90^\circ} \quad (6.1)$$

Thus the different sizes of the V-groove can be obtained by

$$\frac{A_1 \pm A_2}{\sin 54.7^\circ} = \frac{B}{\sin(90^\circ - 54.7^\circ)}$$

(6.2)

where A_1 is the distance from the horizontal center axis of the fiber to the bottom of the V-groove, A_2 is the distance from the horizontal center axis of the fiber to the top of the V-groove and B is the distance from the vertical center axis of the fiber to the top edge of the V-groove. Figure 6.3 shows this relationship between depth and width of the V-groove.

6.3 V-groove inspection method and experimental setup

To evaluate the suitability of design and manufactured process, the fabricated pattern on the wafer or the mask has to be inspected. There are many profile inspection systems used for testing the fabricated pattern on the wafer or the mask such as interferometry, confocal method, AFM, SEM and stylus method. Confocal method is a new technique applied in the field of 3D profile measurement.

Conventional confocal 3D method is a single point detection method, which needs to be scanned over the surface to get the entire 3D profile. Speed is thus a serious problem. In this section, to demonstrate the ability of the multi-channel fiber confocal system for area detection, a three-channel 3D profilometer is built to inspect the depth of V-groove.

The schematic of three-channel fibre confocal 3D profilometer is shown in fig. 5.1, and fig. 6.4 shows the photograph of the actual system. In this system configuration, a multi-mode fiber and GRIN lens were employed (Config.1). Figure 6.5 shows the micro-

photograph of the three-sensor linear fiber array, taken using a Nikon Sc113 Microscope with 20X objective. The pitch of the sensor array is $125\mu\text{m}$. Figure 6.6 shows the photograph of three-channel fiber coupler array.

During experiment, the motorized translation stage carries a sample and allows scanning along optical axis. The three-channel signals were transmitted to a DAQ board through BNC adapter. A data analysis programme was designed with a user-friendly interface under LabVIEWTM environment.

6.4 Experiments and results

In the experiments, a two-channel confocal system was used to measure the depth of a single V-groove and its profile. Then a three-channel confocal system was used to measure the depth of a double V-groove.

After confocal system is aligned, the reference object is placed at the best focus position, and the calibration data is acquired. Following calibration, the measured sample, single or double V-grooves, is placed at the object position. The specimen is aligned, so that sensors can detect both the bottom and the top of the V-groove (or V-grooves) respectively. After setting the measured point at the best focus position, the data acquisition is started. The object scanned is from the starting position towards GRIN lens.

The following experimental parameters were selected:

Sampling interval: 10ms,

Depth scanning range: 0.4mm, and

Scanning rate: 0.1mm/s.

A mask design for a single V-groove is showing in the fig. 6.7. The width of the V-groove

is $222\mu\text{m}$ and the depth is $156\mu\text{m}$. Following this mask design, the single V-groove was fabricated on a silicon wafer and a fiber was embedded, whose photograph, fig. 6.1, was taken using SEM. After the fiber was removed, the single V-groove was inspected using different measurement instruments available in laboratory, including a Nikon Microscope, Veeco Interferometer, the Form Talysurf Series system (It is a stylus method. The profile is obtained using a stylus probe contacting and following the measured surface), and the newly developed three-channel 3D profilometer.

Fig. 6.8 is the single V-groove photograph which was taken using Nikon Microscope with 10X objective. The depth at this cross section is $140\mu\text{m}$.

For depth measurement using SEM or Microscope, it is necessary to cut the V-groove at the desired cross section. Because misalignment problem and etching skill difficulty make the depth of the V-groove may not the same at all cross sections along the length.

The profile of the V-groove at the same cross section tested using Veeco Interferometer. But the profile is vague and not easily recognizable because of the sharp surface gradient. This suggests that the Veeco interferometer is not suitable to inspect the V-grooves.

The profile of the V-groove at the same cross section then measured using the Form Talysurf Series system is shown in Fig. 6.9. The measured depth of the V-groove is $137.7\mu\text{m}$. The clear V-groove profile indicates that the stylus method can measure at any cross section of the V-groove depth. However, there has to be contact between the probe and object, which may damage the surface.

The novel three-channel 3D profilometer can measure the V-groove depth at any cross section without damaging/contacting the specimen. As a comparison and criteria, the Form Talysurf Series system is used to compare and evaluate the result of the novel three-channel 3D profilometer.

Experiments were performed using the novel three-channel confocal profilometer and the results are shown in fig. 6.10 and fig. 6.11.

Fig. 6.10 shows the calibration process with fig. 6.10 (a) displaying one characteristic cycle, during which the translation stage was moved a distance of 0.4mm along the optical axis. The plot of signal output vs. object position is shown in fig. 6.10 (b). The two sensors show a difference in best focus position of $1.467\mu\text{m}$ with the sensor in channel 1 (Ch1) being closer to the object than the sensor in the channel 2 (Ch2).

Following the calibration, the single V-groove replaced the reference object. For this experiment process, the sensor, Ch1, monitored the bottom of the V-groove and the other sensor, Ch2, monitored the top of the single V-groove. Figure 6.11 (a) shows one characteristic cycle during which the translation stage moved a distance of 0.4mm along the optical axis. The detector output vs the object position is shown in the fig. 6.11 (b). The difference in best focus distance from the two channels is $133.96\mu\text{m}$. Subtracting the initial misalignment of $1.467\mu\text{m}$ the corrected depth of the V-groove at this cross section is $135.4\mu\text{m}$.

Comparing this result with that measured using the Stylus instrument, $137.7\mu\text{m}$, a difference of less than 2% is observed.

Next, the X-scan was added to the former experimental setting. The direction of X-scan is illustrated in figure 6.12. The X-scan range is $125\mu\text{m}$ with $5\mu\text{m}$ sampling interval. Figure 6.13 shows the single V-groove profile reconstructed by experiment result.

Following this success, the depth of two V-grooves was measured using three-channel confocal profilometer.

Fig. 6.14 is the photograph of the double V-groove specimen taken using the Nikon Microscope under 3X objective.

Fig. 6.15 shows the final result of double V-groove measurement at one particular cross section. In this measurement, the sensor, Ch1, monitored the top surface of the double V-groove, while Ch2 and Ch3 sensors monitored the bottom of the two V-grooves respectively. From the best focus position for the Ch1, Ch2 and Ch3, the measured depth of the first V-groove was $158.7\mu\text{m}$ and that of the second groove was $157.6\mu\text{m}$.

The double V-groove profile was measured using the Form Talysurf system as shown in fig. 6.16. In this case the depth of the first V-groove was determined to be $154.0\mu\text{m}$ while that of the second groove was measured at $153.5\mu\text{m}$, giving a maximum difference of less than 3%.

6.5 Conclusion

Table 6.1 Depth of V-groove

	Single V-groove	Double V-groove (first/second)
Mask design	$156\mu\text{m}$	---
Form Talysurf Series system	$137.7\mu\text{m}$	$154.0/153.5\mu\text{m}$
Three-channel confocal system	$135.4\mu\text{m}$	$158.7/157.6\mu\text{m}$
Nikon Microscope depth	$140\mu\text{m}$	---
Veeco Interformeter	Vague	---

Table 6.1 shows the depth results of V-grooves. The depth results indicate that there is a difference, albeit small between designed depth and the fabricated depth. Based on the critical nature of the alignment of optical communication systems, this information is valuable to feedback and correct for the V-groove design, increase the accuracy of the V-groove fabrication, and increase the accuracy for passive alignment in communication system.

The novel three-channel 3D profilometer is developed and first successfully demonstrated

for MOEMS component V-groove depth inspection. It can measure the V-groove depth not only at any cross section but also for whole V-groove profile by scanning. It has no directional ambiguity and is an absolute technique for 3D profile inspection. The calibration step only needs to be done once after the setup is built. The comparison of experiment results shows that the difference is very small. The difference is less than 2% for single V-groove depth inspection and 3% for double V-groove depth inspection as compared to the results using Form Talysurf system.

Multi-channel configuration can be extended and further developed to configure more sensors system and thus will be more convenient and more efficient for global profile inspection. It is a suitable tool for inspection of MEMS fabrication.

Figures

Fig.6.1 SEM photograph of a single V-groove with embedded fiber.

Fig. 6.2 The basic trigonometry figure

Silicon V-groove

Fig. 6.3 The relationship of depth with the width of the v-groove

Fig. 6.4 The photograph of three-channel 3D profilometer.

Fig. 6.7 The parameters of mask design, for silicon V-groove etching.

Fig. 6.8 Single V-groove photograph taken using Nikon Microscope with 10X objective

Fig. 6.9 The single V-groove profile measured using the Stylus instrument.

(a) One characteristic cycle of the calibration process.

(b) The signal output vs. the object position for a characteristic cycle.

Fig. 6.10 The calibration process.

(a) One characteristic cycle for the single V-groove detection.

Cursor 0	1.9321	1.3370		*	
Cursor 1	2.0660	1.1752		*	

(b) The output signal from a single V-groove specimen as the function of wave position.

Fig. 6.11 Signal output for the single V-groove.
The peak shift indicates the depth of the bottom from the crest.

Fig. 6.12 Single V-groove X-scan and Z-scan

Fig. 6.13 Single V-groove **profile**

Fig. 6.14 The double V-groove photograph taken using Nikon Microscope with 3X objective.

Fig. 6.15 The final result of the double V-groove measurement at one cross section.

Fig. 6.16 The double V-groove profile measured using the Form Talysurf system.

Chapter 7 Summary and conclusion

In this project a three-channel confocal measurement technology and an experimental setup of the 3D profilometer system have been successfully demonstrated. Based on theoretical analysis and experimental investigation, the developed technology of the three-channel system can be used to build a multi-channel fiber confocal profile measurement system for fast speed 3D surface inspection.

During the thesis research on the high speed 3D profile measurement system, a detailed review and comparison of all commercially available 3D profile measuring systems, which were based on either mechanical, optical or electronic sensing techniques, has been conducted before finally selected the fiber optical confocal measurement technology.. In comparing with the commonly used optical 3D profile measurement techniques, such as triangulation and interferometry, the confocal is advantageous at measurement speed and immunization of environment disturbance. To fully understand the confocal techniques, not only the confocal principle is elaborated in details, but also system construction and key components are anatomized during the study and development of the optical confocal system. For example. in system construction, the beam size and energy distribution of the light source were studied and properly selected because all these parameters would affect the image quality, the measurement resolution, accuracy and stability. Moreover, the objective lens was investigated because its function is one of the greatest challenges affecting system performance. The photodetector was also studied for construction of the confocal system.

The experimental tests and theoretical analysis of the basic configurations, which can be one-arm or two-arm confocal setups, showed that the numerical aperture (NA) influences the Airy pattern and confocal response curve of confocal 3D profile measurement. Pinhole as an important component was studied and its influence on both axial and transverse resolutions of the confocal system was evaluated. Based on theoretical analysis, a novel fiber optical confocal system, in which the optical fiber functions as the pinhole and a fiber coupler functions as a beamsplitter, was invented and an experimental set up of one channel fiber confocal system was built. The experimental results proved that the theoretical analysis is correct and the optical fiber based confocal measurement system can fully meet the required performance. Furthermore, the results of the theoretical analysis and experimental tests can also be used for the development of the multi-channel confocal system.

Since the confocal measurement is based on the detection of light intensity, the fluctuation of light source is critical. To reduce the fluctuation of the light source and its influence to the measurement result, a mathematic compensation model and a double detector configuration system were developed. Due to signal processing speed has an effect on real time display, a fast scanning algorithm was built to increase confocal imaging processing. These two techniques are also applicable to both single channel confocal and multi-channel confocal systems.

To realize high speed on-line inspection, the multi-channel confocal system can be constructed in four different configurations to meet different application requirements. The basic configuration of the multi-channel fiber confocal system has a concise structure which can meet the fundamental measurement needs and is relatively easy to be realized.

To compensate the light source fluctuation, the configuration with a double detector array is conceived. Although the crosstalk is a more serious problem in the multi-channel system, the crosstalk effect can be eliminated or at least reduced by means of a signal generator array. Generally, each of the above mentioned three configurations can overcome some drawbacks of the confocal measurement system, however their performance and effectiveness are still limited. Therefore, an integrated multi-function configuration combining a double detector array and a signal generator array in one confocal system is conceived to eliminate or reduce the influence of the crosstalk and light source fluctuation.

Because the relationship of the selected parameters and the final performance is the fundamental issue for the development of practical confocal measurement system, an in depth investigation and analysis were conducted. Among of all, the crosstalk, which is one of the most critical issues, was investigated by means of different methodologies, such as, the relationship of the number of channels vs. the crosstalk, one-channel, two-channel, and three-channel crosstalk, time domain and frequency domain analysis of the crosstalk; theoretical vs. experimental analysis; different configuration analysis; eliminating crosstalk analysis, etc.

Based on the basic configuration, a three-channel fiber confocal 3D profilometer was built and used for inspection of V-groove, a kind of MOEMS component. V-groove is a miniature mechanical component machined on Silicon wafer used for the alignment of optical fiber and micro optical devices. To realize accurate optical alignment, the depth and shape in V-groove design and V-groove fabrication were studied and the knowledge is useful for gauging the fiber optical passive alignment. Currently in MEMS production, the

V-grooves are inspected by means of commercial instruments, which include SEM, optical microscope, interferometer, stylus technique, but all the methods has very limited capabilities. To test the feasibility, the depth of a single V-groove and a double V-groove are measured using the newly developed three-channel 3D profilometer and a commercial instrument -Form Talysurf system, and the measured results are compared with each other. The comparison results indicate that the deference of ?he measured results by both measurement systems are within the instrument's tolerance and the measurement of the three-channel 3D profilometer is correct. By adding on more channels, the three-channel 3D profilometer can be extended to a multi-channel 3D profilometer for more convenient inspection of global profile V-groove or other MOEMS component inspection.

To develop a multi-channel confocal system for practical inspection, two suggestions are discussed. One is to develop a multi-channel 3D profilometer capable of total eliminating the crosstalk problem and the other is to develop a multi-channel 3D profile spectrometer, which exploits the crosstalk property (discussed in chapter 8).

In short, the main contributions achieved in this project research are listed as following:

1. One-channel fiber confocal 3D shape measurement system is introduced by means of constructing the different optical fibers and micro objective lenses. The system evaluation (including noise analysis, resolution and ieliability) is conducted.
2. Light source fluctuation compensation technique is developed and used in confocal 3D shape measurement system -- proposal, system construction, theoretical analysis and experimental tests.
3. Attempt to develop an algorithm for realizing fast signal processing and error comparison.

4. Multi-channel fiber confocal 3D shape measurement system is proposed and analyzed with different configurations and functions. Then successfully constructed a Three-channel 3D profilometer with basic function.
5. Crosstalk problem study is introduced in multi-channel confocal system. Based on theoretical and experimental analysis, crosstalk problem is solved.
6. Multi-channel confocal system is introduced to inspect MOEMS components' profile and is successfully used in V-groove profile measurement.
7. Extending confocal 3D shape measurement technology and its industrial application.

Chapter 8 Future work

Based on the achievements described in Chapter 4, Chapter 5 and Chapter 6, a one channel 3D profilometer and a multi-channel 3D profilometer can be developed using the findings in this project. In addition, to realize multi-channel 3D profilometer instrumentation, some further research is required. The crosstalk study will bring about more interest in multi-channel confocal system for exploiting or eliminating the crosstalk.

8.1 One channel 3D profilometer completion

A one-channel fiber confocal 3D shape measurement system has been developed. The principle, construction, analysis and evaluation have been discussed. However, for instrumentation, the system performance parameters should be studied in further detail. What has been elaborated in detail is the resolution as a quantitative parameter and system reliability as a qualitative parameter. Also, the system noise has been given as a qualitative analysis. However, as a commercial product, the parameters such as accuracy, precision, sensitivity, error, stability, and repeatability should be studied and quantified in the future study.

8.3 Multi-channel 3D profilometer development

The analysis in chapter 5 indicates that the harmonics, crosstalk and the white noise can be eliminated or reduced by properly designed band-pass filters. A software program was written, which successfully eliminated the harmonics and crosstalk problems, at the same time, it reduced the white noise. For real time inspection, a hardware based filter design is

practical better than software process. The amplification and demodulation have to be considered in the circuit design for band-pass filters. Chart 8.1 shows the basic scheme for the realization of demodulation, filter, and amplification. After passing through the filter and demodulator, the signal can be processed using a DAQ acquisition board and software programme designed using LabVIEW™.

The frequency selection for band-pass filter is the key for the demodulation design. Denoting the frequencies of the three channels, Ch1, Ch2, and Ch3 by f_1, f_2 , and f_3 respectively, letting $f_1 < f_2 < f_3$, and considering the crosstalk and harmonics, the response will consist of the frequency series of the form:

$$\begin{aligned} f_1, 2f_1, 3f_1, \dots \\ f_2, 2f_2, 3f_2, \dots \\ f_3, 2f_3, 3f_3, \dots \end{aligned}$$

According the former analysis, the low frequency noise is acceptable when $f > 400\text{Hz}$.

The frequency f_1 can be set at 1kHz. However, its harmonic noise will consist of the components f_2 and f_3 when f_2 and f_3 are integer multiples of f_1 , which interfere with the original frequencies f_2 and f_3 in channel 2 and channel 3 respectively and cause crosstalk problems. To implement a band pass filter, the frequency, f_1 , has to be different from 1kHz. As an example, let $f_1 = 2\text{kHz}$, $f_2 = 3\text{kHz}$, and $f_3 = 5\text{kHz}$. The response may then consist of the frequency series of $2\text{k}, 3\text{k}, 4\text{k}, 5\text{k}, 6\text{k}, 8\text{kHz}$. The FFT analysis results show that the width of the pass band is 70Hz on each side of the filter central frequency (denoted as $\pm 70\text{Hz}$). If the filter bandwidth is too narrow, the filter circuit becomes very expensive and difficult to realize. The results show that the lowest noise occurred between 400Hz and the lower end of the band pass filter, i.e. 70Hz below 2kHz [denoted as (2k-

70)Hz]. Therefore the bandwidth can be larger than $\pm 70Hz$. Band-pass filters with central frequencies of 2kHz, 3kHz, and 5kHz respectively and $\pm 500Hz$ bandwidth in three channels would be one solution to eliminate the crosstalk problem, harmonic noise and low frequency noise, at the same time white noise would be reduced. This three-channel system will be realized in the future work.

For a multi-channel system, the three-channel crosstalk problem can be resolved by resetting the central frequencies at every fourth sensor, for instance

$$f_1, f_2, f_3, f_1, f_2, f_3, \dots$$

When the pitch of the sensors is shorter the crosstalk will affect more channels. For n-channel crosstalk problem, the frequency can be repeated in turn from the (n+1)th channel. The central frequency in each channel must not match the harmonics from other channels and the pass band frequency of any filter should not overlap. In this way, it is easy to develop a multi-channel area array system such as rectangle array, circle array, polygon array.

8.3 Multi-channel 3D profile spectrometer development

The discussion in last section far developing multi-channel 3D profile inspection system explains how to solve and eliminate the problem of crosstalk and harmonics. This section study proposes an idea for exploiting the crosstalk to realize 3D profile measurement.

When there is a crosstalk problem, the output response from one channel involves the information of other channels. Here, the part from its own channel is called self-channel response: while the part from other channels is called crosstalk response. The crosstalk response can affect many channels. The number of channels creating the crosstalk depends on the pitch of the multi-channel sensor and detected surface shape.

For flat surface detection, the output response curve of self-channel response is that of typical confocal response, and the crosstalk response also has similar confocal response curve. The difference is that the peak response of the crosstalk signal is not at the focal point although it has a distinct maximum with a response similar to the confocal signal. Due to this difference, the detected position at the maximum of the crosstalk signal (point-in-peak-response position) can be determined.

Reviewing the experimental results using Config.1, when the object was at the focus position of the system, the signal output was -884mV. When the crosstalk response was highest, the signal output was 44 mV. Comparing the peak value between the self-channel response and the crosstalk response, the response ratio between the maxima (peak-peak ratio) is 20. Though the crosstalk response for a flat surface is only 5% of peak-peak ratio comparing with self-channel response, it is possible to determine the detected point-in-peak-response position. Reviewing the two-channel and three-channel crosstalk experiments, when one channel confocal response is at the peak value, the other channel crosstalk response might not in the peak value. This means that the peak response of the crosstalk may occur at some defocused position. Thus, when z-scan is performed in the multi-channel system, the peak value of the self-channel response and the crosstalk response may occur at different times, depending on the surface profile.

Exploiting this phenomenon of crosstalk response, the different surface shapes and various difficult shapes can be inspected.

Flow chart

Chart 8.1 The circuit realization for demodulation.

Reference

- [1]. Standard custom wafers, <http://www.virginiasein.com/pdf/BACK%20PAGE.pdf>.
- [2]. Integrated optics & optical communications lab,
<http://iol.ee.nctu.edu.tw/projecte.html>.
- [3]. Hidekazu Sekizawa, Kiyoshi Ymada, and Akito Lwamoto, (1984). Disk-memory Pregroove Inspection. *Applied Optics*, Vol. 23, No16/15 Aug.
- [4]. Eric J. Lerner, (2000). Laser Microscopy Opens a New Dimension. *Laser Focus World Dec.*, Vol. 36, Iss. 12.
- [5]. ConfoCor 2 - FCS available to the Life Scientist.
<http://www.zeiss.de/C12567BE0045ACF1/allBySubject/775A6F2B7439ADF0C12569DD004B3341>.
- [6]. Gary Durack, J.Paul Robinson, (2000). Emerging Tools for Single-Cell Analysis: Advances in Optical Measurement Technologies. A John Wiley & Sons, INC., Publication.
- [7]. Michael R. Matthews, Brian M. Macdonald, and Keith R. Preston, (1990). Optical Components—The New Challenge in Packaging. *IEEE Transactions on components Hybrids And Manufacturing Technology*. Vol. 13, No. 4.
- [8]. Pramod K. Rastogi, (1997). Optical Measurement Techniques and Applications. Artech House, Inc., Boston. London.
- [9]. LT Series Laser confocal displacement meters,
<http://www.keyence.com/products/measuring/lt/lt.html#applications>.
- [10]. Carl Zeiss,
<http://www.zeiss.de/C12567A100537AB9/Inhalt->

Frame/3726ECD8B793CB50C12569000046D9DE?OpenDocument&Highlight=confocal.

- [11]. Edge Roughness. <http://www.asmicro.com/edgerough.htm>.
- [12]. A Primer on Displacement Measuring Interferometers. <http://zygo.com/index.html>.
- [13]. Yan Li, etc, (2000). Displacement Sensing HeNe Laser with $\lambda/8$ Accuracy and Self-calibration. *Tsinghua University, etc, Opt. Eng.* 39(11) 3039-3043.
- [14]. Zhou Wensen, (1999). Optical Triangular Profilometry — Studies of Calibration and Fringe Pattern Processing. *Master thesis, MPE, NTU*.
- [15]. Markus-Christian Amann, etc, (2000). Laser Ranging: A Critical Review of Usual Techniques for Distance Measurement. *Opt. Eng.* 40(1) 10-19.
- [16]. B.Newhall, (1958). Photosculpture. *Image* 7(5), 100-105.
- [17]. Thomas D. Dewitt and Douglas A.Lyon. A Rangefinding Method Using Diffraction Gratings: <http://lyon.bridgeport.edu/Pub/Documentation/osa/osa.htm>.
- [18]. Leonhardt, K., U. Droste, and H. J. Tiziani, (1994). Microshape and Rough-Surface Analysis by Fringe Projection. *Appl. Optics, Vol. 33, 1994, pp. 7477-7488*.
- [19]. Windecker, R., and H. J. Tiziani, (1995). Topometry of Technical and Biological Objects by Fringe Projection. *Appl. Optics, Vol. 34, 1995, pp. 3644-3650*.
- [20]. Gasvik, K., J., (1987). Optical Metrology. *New York: Wiley*.
- [21]. Tiziani, H. J., (1989). Optical Methods for Precision Measurements. *Optical and Quantum Electronics, Vol. 21, 1989, pp. 253-282*.
- [22]. Seitz, K. G., and H. J. Tiziani, (1993). Resolution Limits of Active Triangulation Systems by Defocusing. *Optical Engrg., Vol. 32, 1993, pp. 1374-1383*.
- [23]. Wilson, T. A. (1990). Confocal Microscopy. *London: Academic Press*.

- [24]. Tiziani, H. J., and H. M. Uhde, (1994). Three Dimensional Image Sensing with Chromatic Confocal Microscopy. *Appl. Optics, Vol 33, 1994, pp. 1838-1843.*
- [25]. Timothy R. Corle, etc, (1999). Confocal Scanning Optical Microscopy and Related Imaging Systems. *Academic Press.*
- [26]. C.J.R. Sheppard, D.M. Shotton, (1997). Confocal Laser Scanning Microscopy.
- [27]. Peter de Groot, (1995). Novel Interferometer Based on a Wedge Prism. *Optics & Photonics News, Engineering Lab Notes Supplement, Volume 6, Page 1.*
- [28]. Peter de Grooi and Les Deck, (1995). Surface Profiling by Analysis of White-light Interferograms in the Spatial Frequency Domain. *Journal of Modern Optics, Volume 42, Pages 389-401.*
- [29]. Les Deck and Peter de Groot, (1995). High-speed non-contact profiler based on scanning white light interferometry. *Applied Optics. Volume 33, Pages 7334-7338.*
- [30]. Peter de Groot, Les Deck, James Soobitsky and James Biegen, (1996). Polarization Interferometer for Measuring the Flying Height of Magnetic Read-write Heads *Optics Letters, Volume 21, Pages 441-443.*
- [31]. Peter de Groot, (1996). Grating Interferometer for Flatness Testing. *Optics Letters, Volume 21, Pages 228-230.*
- [32]. Leslie L. Deck and Peter J. de Groot, (1998). Punctuated Quadrature Phase-shifting Interferometry. *Optics Letters, Volume 23, pages 19-21.*
- [33]. Peter de Groot, (1994). Metrology of Transparent Flats. *Meetings Digest, Optical Fabrication and Testing Workshop, Rochester.*
- [34]. Peter de Groot, (1994). Predicting the Effects of Vibration in Phase Shifting Interferometry *Meetings Digest, Optical Fabrication and Testing Workshop, Pages 189-192, Rochester.*

- [35]. Peter de Groot, (1995). Derivation of Phase Shift Algorithms for Interferometry Using the Concept of a Data Sampling Window. *Applied Optics, Volume 34, Number 22, Pages 4723-4730.*
- [36]. James Biegen, (1995). Determination of the Phase Change on Reflection from Two-beam Interference *Optics Letters, Volume 19, Number 21, Pages 1690-1692.*
- [37]. Peter de Groot, (1995). Vibration in Phase Shifting Interferometry. *Journal of the Optical Society of America, Volume 12, Pages 354-365.*
- [38]. Peter de Groot, (1995). Phase-shift Calibration Errors in Interferometers with Spherical Fizeau Cavities. *Applied Optics, Volume 34, Number 16, Pages 2856-2862.*
- [39]. Peter de Groot, (1996). Grating Interferometer for Metrology of Transparent Flats. *Meetings Digest, Optical Fabrication and Testing Workshop, Boston.*
- [40]. Peter de Groot and James Soobitsky, (1995). Interferometer for Measuring Polarization and Birefringence. *Meetings Digest, Optical Fabrication and Testing Workshop, Boston.*
- [41]. Takanori Oshio and Yoshiyuki Sakai, etc, (1987). Observation of Grating Surfaces by the Use of STM. *Application and theory of Periodic Structures, Diffraction Gratings, and Moire Phenomena III, SPIE Vol. 815.*
- [42]. Hua Fan, Hong Zhao and Yushan Tan, (1997). Automated Three-dimensional Surface Profilometry using Dual-Frequency Optic Fiber Phase-shifting Method. *Opt. Eng. 36(11) 3167-3171.*
- [43]. DeWitt, T. and Lyon, D., (1995). Ranging Method using Diffraction Gratings. *Appl. Opt., Vol. 34, No.14, pp. 2510-2521.*

- [44] T.C. Strand, (1985). Optical Three-dimensional Sensing for Machine Vision. *Opt. Eng.*, 24, pp. 33-40.
- [45] X. X. Chen, X. Y. Su, and L.R. Guo, (1991). Automated Measurement Method for 360° Profilometry of Diffuse Objects. *Appl. Opt.*, 30, pp. 1274-1278.
- [46] A. Asundi and M. R. Sajan(1995). Peripheral Inspection of Objects. *Opt. Laser Eng.*, 22, pp. 227-240.
- [47] V. Srinivasan, H. C. Liu, and M. Halioua, (1984). Automated Phase-measuring Profilometry of 3-D Diffuse Objects. *Appl. Opt.*, 23, pp. 3105-3108.
- [48] H. Zhao, W. Chen, and Y. Tan (1994). Phase-unwrapping Algorithm for the Measurement of Three-dimensional Object Shapes. *Appl. Opt.*, 33, pp. 4497-4500.
- [49] M.Takeda and K. Mutoh, (1983). Fourier Transform Profilometry for the Automatic Measurement of 3-D Object Shapes. *Appl. Opt.*, 22, pp.3977-3982.
- [50] P. Saint-Marc, J.-L. Jezouin, and G. Medioni (1991). A Versatile PC-based Finding System. *IEEE Trans. Robotics and Automation*, 7, pp. 250-256.
- [51] R.J.Valkenburg, A.M.McIor, (1998). Accurate 3D Measurement Using a Structured Light System. *Image and Vision Computing*. 16, pp. 99-110.
- [52] Robinson, D.W., and G. T. Reid (eds.), (1993). Interferogram Analysis, Digital Fringe Pattern Measurement Techniques. *Bristol: Institute of Physics*.
- [53] Greath, K., (1988). Phase-Measurement Interferometry Techniques. *Progress in Optics XXVI (E. Wolf, ed.)*, Amsterdam: North-holland, pp. 349-392.
- [54] Takeda, M., H. Ina, and S. Kobayashi, (1982). Fourier-Transform Method of Fringe-Pattern Analysis for computer-Based Topography and Interferometry. *J. Opt. Soc. Amer.*, Vol. 72, pp. 156-160.
- [55] Born, M., and E. Wolf, (1980). Principles of Optics, *New York: Pergamon Press*.

- [56]. Zou, J., Pedrini, G., Tiziani, H.J., (1996). Two-wavelength Contouring with a Pulsed Ruby Laser by Employing TV-Holography. *J. Mod. Optics*, Vol. **43**, pp 639-646.
- [57]. Dandliker, R., K. Hug, J. Politch, and E. Zimmermann, (1995). High-Accuracy Distance Measurements with Multiple-Wavelength Interferometry. *Opt. Engng.*, Vol. **34**, pp. 2407-2412.
- [58]. Murty, M. V. R., (1964). A Compact Radial Shearing Interferometer Based on the Law of Refraction. *Appl. Optics*, Vol. **3**, pp. 853-857.
- [59]. Truax, B.E., (1986). A Phase Measuring Radial Shear Interferometer for Measuring the Wavefronts of Compact Disc Laser Pickups. *Proc. SPIE*, Vol. **661**, p. 74
- [60]. Flournoy, P. A., R. W. McClure, and G. Wyntjes, (1972). White-light interferometric Thickness Gauge. *Appl. Optics*, Vol. **11**, pp. 1907-1915.
- [61]. Hitzengerger, C.K., (1992). Measurement of Corned Thickness by Low Coherence Interferometry. *Appl. Optics*, Vol. **31**, pp. 6637-6642.
- [62]. Caber, P., J., (1993). Interferometric Profiler for Rough Surfaces. *Appl. Optics*, Vol. **32**, pp. 3438-3441.
- [63]. De Groot, P., and L. Deck, (1995). Surface Profiling by Analysis of White-Light Interferograms in the Spatial Frequency Domain. *J. Modern Optics*, Vol. **42**, 389-401.
- [64]. Wang, W. M., k. T. V. Grattan, W. J. O. Boyle, and A. W. Palmer, (1994). Active Optical Feedback in a Dual-Diode Laser Configuration Applied to Displacement Measurements with a Wide Dynamic Range. *Appl. Optics*, Vol. **33**, pp. 1795-1801.

- [65]. Willemin, J. F., R. Dandliker, and S. M. Khanna, (1988). Heterodyne
Interferometer for Submicroscopic Vibration Measurements in the Inner Ear. *J. Acoustical Soc. Amer.*, Vol. 83, pp. 787-795.
- [66]. <http://iygo.com/index.html>.
- [67]. Frank C Demarest, (1998). High-resolution, High-speed, Low Data Rate
Uncertainty, Heterodyne Displacement Measuring Interferometer Electronics.
Measurement Science and Technology, Volume 9, Number 7, pages 1024-1030.
- [68]. G. Dussler et al., (1999). *SPIE Proc.* 3825, 144.
- [69]. P. Corcuff et al., (1999). *SPIE Proc.* 3605, 73.
- [70]. Keyence Corporation of America. <http://www.keyence.com/measure/lt.htm#2>.
- [71]. UBM Corporation. <http://www.ubmusa.com/product/nanosurf.htm>.
- [72]. Albert Michelson: The Pioneer of Interferometry.
<http://sim.jpl.nasa.gov/interferometry/albert.html#albert>.
- [73]. Paula Noaker Powell, (2000). Wavelength-to-depth Encoding Gives 3-D Images.
Laser Focus World.
- [74]. Dickey, Fred M., (2000). Laser beam shaping: theory and techniques. *Marcel Dekker*.
- [75]. Confocal Microscopy: an Overview with a Biological and Fluorescence
Microscopy Bias. *The Quekett Journal of Microscopy*, 2000 38, 445-456.
- [76]. Li Zhigang, (2004). Investigation of Diode-pumped solid-state laser with power
amplifier. Ph.D thesis, Huazhong university of science & technology.
- [77]. The practical application of light, *Melles Griot*, (1999).
- [78]. Akhmanov, S. A., (1997). Physical optics. *Clarendon Press*.

- [79]. Condenser Aperture Diaphragm Control Of Specimen Contrasi.
<http://micro.magnet.fsu.edu/primer/java/kohler/contrast/index.html>.
- [80]. Substage Condenser Numerical Aperture.
<http://micro.magnet.fsu.edu/primer/java/kohler/condenseraperture/index.html>.
- [81]. Yariv, Amnon (c1985). Optical electronics, *Holt, Rinehart, and Winston*.
- [82]. Photocathode special response, *<http://www.electron-tubes.co.uk/pmts/OnLinepmtdataforETL.html>.*
- [83]. Module 4 photodetector characteristics,
<http://cord.org/cm/leot/Module4/module4.htm>.
- [84]. A Solid-state Alternative to the Vacuum Photomultiplier Tube,
<http://wwiu.advancedphotonix.com/techbriefart.htm>.
- [85]. A Solid-state Alternative to the Vacuum Photomultiplier Tube,
<http://www.nasatech.com/Briefs/July99/PTB07991.html>.
- [86]. D.A. Krohn, (c1992). Fiber Optic Sensors: Fandamentals and Applications. *Third Edition, Instrument Society of America*.
- [87]. Production menu, *NSG America, Inc. (1999)*
- [88]. A. T. J. Hayward, (1977) Repeatability and accuracy. *Mechanical engineering publications LTD, London and New York.*
- [89]. Alan S. Morris (1988). Principles of measurement and instrumentation, *Preiztice Hall International (UK) Ltd*.
- [90]. L Finkelstein, K T V Grattan (1994). Concise Encyclopedia of Measuremect & Instrumentation. *Pergamon Press, Oxford.New York.Seoul.Tokyo*.
- [91]. Graham Dunn (1989). Design and Analysis of Reliability Studies. The statistical evaluation of measurement errors. *Oxford University Press, New York*.

- [92]. Chx Li, A. K. Asundi, ZhP Fang (2001). Multi-channel 3D profilometry, *Advanced Photonic Sensors and Applications II, ISPA*, Vol.4596, p.175-181.
- [93]. T. R. Corle, C.-H. Chou, and G. S. Kino (1986). Depth response of confocal optical mirosopes, *Optical Letters*, Vol.11.No.12.
- [94]. Gordon S. Kino (1987). Acoustic Waves: Devices, Imaging, and Analog Signal Processing. *Englewood Cliffs, New Jersey 07632*, No 16/15 Aug.
- [95]. Joseph W. Goodman (1968). Introduction to Fourier Optics. *San Francisco, McGraw-Hill*.
- [96]. Tony Wilson (1985). Colin Sheppard, Theory and Practice of Scanning Optical Microscopy. *Academic Press INC. (London) Ltd*.
- [97]. Melvin J. Maron (1982). Numerical Analysis: A Practical Approach. *Macmillan Publishing Co., Inc., New York, Collier Macmillan Publishers, London*.
- [98]. Mitsuhiro Ishihara, Aichi-ken, (1998), Three-dimensional shape measuring apparatus, *United States Patent*, 5737084.
- [99]. Jerry C. Whitaker (c2000). Signal measurement, analysis, and testing, *CRC Press*.
- [100]. Johnny R. Johnson (1989). Introduction to digital signal processing, *Prentice-Hall International*.
- [101]. Lonnie C. Ludeman (1986). Fundamentals of digital signal processing, *Harper & Row, Publishers, Inc*.
- [102]. Richard S. Figliola (1995). Donald E. Beasley, Theory and design for mechanical measurements, *John Wiley & Sons, Inc*.
- [103]. H. Joseph Weaver (1989). Theory of discrete and continuous Fourier analysis, *John Wiley & Sons, inc*.
- [104]. K.E. Petersen (1982). Silicon as a mechanical material, *Proc. IEEE*, 70,420.

- [105]. K.J. Gabriel (1995). Engineering Microscope Machines, *Scientific American*, September, 118.
- [106]. Jurgen H. Daniel (1999). Micromachining Silicon for MEMS; *MTP; D.F. Moore Trinity Hall, Cambridge CB2 1TJ, U.K.*
- [107]. Long-Sun Huang, etc (1998). MEMS Packaging for Micro Mirror Switches, *IEEE, Electronic Components and Technology Conference*.
- [108]. Alan R. Mickelson, Nagesh R. B., Yung-Cheng Lee, (1997). Optoelectronic Packaging, John Wiley & Sons INC.
- [109]. S. Kaneko, etc (2000). Novel Fiber Alignment Method Using a Partially Metal-Coated Fiber in a Silicon V-Groove, *IEEE, Photonics Technology Letters*, Vol. 12, No. 6, June.

Appendix

1 Basic Fourier analysis

Fourier techniques, such as Fourier series (FS), Fourier transform (FT), discrete-time Fourier transform (DTFT), discrete-time Fourier series (DTFS), and fast Fourier transform (FFT), have matured dramatically in signal processing. Fourier analysis is widely used in many practical applications. FS is a useful tool to analyze continuous and periodic signal in time domain. The FFT is a general title applied to many algorithms for efficient machine computation of discrete Fourier transforms (DFTs). FT and FFT are the powerful tools to analyze signals in frequency domain. In reality, the signals obtained from experiments cannot always be easily described by analytical formula. Here FFT is an easy way to determine the frequency content of a signal. The FFT is used as a “black box” to produce Fourier transforms *and* Fourier series for analysis of complex signals.

Considering a continuous and periodic signal in time domain, $f(t)$, with arbitrary periods, ω , the expression for the FS can be written as

$$f(t) = A_0 + \sum_{n=1}^{\infty} [A_n \cos(n\omega t) + B_n \sin(n\omega t)] \quad (\text{A.1})$$

and its coefficients

$$A_0 = \frac{1}{T} \int_{-T/2}^{T/2} f(t) dt \quad (\text{A.2})$$

$$A_n = \frac{2}{T} \int_{-T/2}^{T/2} f(t) \cos(n\omega t) dt \quad (\text{A.3})$$

$$B_n = \frac{2}{T} \int_{-T/2}^{T/2} f(t) \sin(n\omega t) dt \quad (\text{A.4})$$

where T is the time period.

From the properties of periodic signal, we have

$$f(t + nT) = f\left(t + \frac{2\pi n}{\omega}\right) = f(t)$$

(A.5)

The FS can be written with only sine terms as

$$f(t) = A_0 + \sum_{n=1}^{\infty} C_n \sin(n\omega t + \theta) \quad (A.6)$$

$$C_n = \sqrt{A_n^2 + B_n^2} \quad (A.7)$$

where ω is the fundamental frequency, $C_1 \sin(\omega t + \theta)$ is fundamental wave, and C_1 , its amplitude; $C_n \sin(n\omega t + \theta), n = 2, 3, \dots, \infty$ is harmonic wave with C_n as its amplitude.