Weak signal detection for scanning near-field optical microscopy

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Weak Signal Detection for Scanning Near-Field Optical Microscopy

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

2010

*To my parents, my siblings and my fiancée
for their encouragement and love.*

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Symbols and Acronyms

Acronyms

AFM	Atomic Force Microscopy
FWHM	Full Width at Half Maximum
LO	Local Oscillator
NA	Numerical Aperture
NEP	Noise Equivalent Power
OPD	Optical Path Difference
PLL	Phase Lock Loop
PMT	Photomultiplier Tube
Q-Factor	Quality Factor
SEM	Scanning Electron Microscopy
SNOM	Scanning Near-field Optical Microscopy
SNR	Signal-Noise Ratio
SPM	Scanning Probe Microscopy
VCO	Voltage Controlled Oscillator

Symbols

λ	Wavelength
$\mathfrak{R}$	Responsivity of Photo Diode
B	Bandwidth of the System
q	Electric Charge Constant
γ	Damping Ratio
k_B	Boltzmann Constant

Summary

This thesis covers the development of enabling technologies for the Scanning Near-field Optical Microscopy (SNOM). Two key technologies form the foundation of the SNOM system: (i) the weak electrical signal detection for probe-sample distance regulation and (ii) the weak optical signal detection for the near-field region of the sample.

In the SNOM system, the probe-sample distance regulation ensures that the fiber probe collects optical signals in the near-field region. The main concern is the ability to detect the weak electrical signal from the force sensing. The weak electrical signal detection for separation control can be divided into several key challenges and each of these challenges are considered and optimized. The first challenge is to obtain a sensor capable of sensing the atomic or frictional force. A high sensitivity sensing requires a sensor with Q-factor higher than 3000. The sensor used consists of a quartz tuning fork with a mounted optical probe. The Q-factor will deteriorate from tens of thousands in vacuum to a value less than 10 depending on the mounting and attachment on the fork. Based on the model of the tuning fork probe, the Q-factor improvement is achieved by balancing the tuning fork probe. The second challenge is the detection of the -30 dB signal change from the tuning fork probe. The detection of this small change is done by using a quadrature lock-in detection technique. The transient speed of the lock-in detection is usually slow. The feedback speed is another challenge for the tip-sample control. The design of a fast lock-in detection method improves the speed of detection by five times or more, thus the overall speed of the controller is improved. Based on the key technologies developed and the integration

of these technologies into a separation control system, the nanoscale displacement control between the tuning fork probe and the sample is established.

The weak optical signal detection system can be divided into three subsystems. The main challenge is the detectability of the weak optical signal in the near-field region. The optical signal of interest is usually in the picoWatt range, while the sensitivity depends on the output signal-to-noise ratio of the optical detection system. Thus, the three subsystems must be designed to address sensitivity enhancement in both the optical and electrical domains. The first subsystem is the use of coherent detection in a fiber interferometer setup to enhance the sensitivity of the near-field signal through shot noise limited detection. Next, in the electrical domain, the noise at the receiver end should be considered. Thus, wavelength modulation techniques with lock-in detection is applied to improve the sensitivity of the signal. Combining both the optical and electrical domain detection methods, a sensitivity improvement of 110 dB is achieved. To further enhance the sensitivity of the SNOM system, a multi-wavelength averaging method is implemented to compensate for noise interference on the detected signal. This method is then integrated into the interferometry SNOM to achieve a better sensitivity improvement.

With the integration of the two building blocks, a full SNOM system is developed. The combination of the above mentioned innovations of key SNOM components contributed to the construction of a versatile SNOM system. This system can be easily changed into different configuration for different applications. Note however that proper calibration of the SNOM is necessary to obtain reliable results. The usefulness of our proposed SNOM system is demonstrated on three requested applications from other research groups. The system produces good and repeatable results for these applications.

Chapter 1

Introduction

1.1 Motivations

The optical signal is the most important information for human to understand his/her surrounding and the world. Statistically, 70 to 90 percent of our daily information comes through the optical means from our eyes [1]. In fact, most of us, minus the small minority of unfortunate ones, are used to the comfort of “what we can do depends on what we see”. On the other hand, the optical properties of substances have helped us discover many interesting natural phenomena. Historically, the optical emission spectrum of the hydrogen atom has helped to reveal the band structure in atoms. These discoveries laid the foundation for modern physics. Nowadays, optical information like fluorescence is helping us discover how basic life units like cells and DNA are formed in the biological domain. In industry, various optical techniques have been employed as non-invasive tools to measure the dimensions of specimen, to locate failures in electronics, to store information in media, and so on and so forth. Due to the importance of optical information, optical instruments have been invented to extend human’s vision capability either to look outwards to see objects

at far distance like remote stars or to look inwards to see tiny structures within a substance. For example, the earth observatory telescopes, such as Hubble, Chandra and the current Overwhelmingly large(OWL) telescopes have provided means for deep space exploration. The curiosity to explore far away objects beyond the observatory pushes engineers to develop the James Webb space telescope [2]. The same curiosity also drives the invention of optical microscopes which can be used to observe micro- and nano- structures like cells.

Whether it is the telescopes or the optical microscopes, there is always a demand for better magnification and higher resolution. This demand has become more and more critical with the rapid advancement of science and technology today. Firstly, the feature from which we are interested to acquire the important optical information has shrunk in size. Indeed, in this current technological era, nano-technology has become a prominent focus of many research fields. From viewing bacteria to virus to DNA, material domain walls to individual molecules to atoms, the size and the profile of the objects being observed have become smaller and smaller. We are venturing into the nano-world! For example, in the characterization of solar cells, the region of interest of the individual structure is of 100 nm or less. Moore has predicted that the number of transistors in a wafer doubles every 12 months [3], and the next technological challenge in semiconductor is the ability to manufacture 32 nm devices which will require higher optical resolution during failure analysis. In forensics, the optical spectrum information on DNA strain requires a resolution of 2 nm! Secondly, the current optical microscopes have been built based on linear optics design which is limited in the lateral resolution. According to Abbe and Rayleigh, the highest possible lateral optical resolution using linear optics is about half the wavelength of light [4]. The best possible resolution of light detection in the diffraction limit can be expressed explicitly as $0.61\lambda/NA$, where λ is the wavelength and NA is the numerical aperture of the lens.

Over the past decades, many technologies have been developed to obtain higher spatial resolution. As an overview of the various advancements, we summarized the technologies into five categories depending on their principles. The basic principle governing the technologies in the first category is the alteration of the parameters in the diffraction limit equation, either by using shorter wavelengths of illumination or by using a higher numerical aperture (NA) of the collection optics. For example, ultra-violet light is used in confocal microscopy to achieve nano-meter resolution (Carl Zeiss confocal). However, light-matter interactions of materials are wavelength dependent and hence spectroscopic detection is usually used to acquire the required optical information. A successful example of using lenses of high NA to increase lateral resolution is the solid immersion lens. These lenses have very wide angle detection, thus they enhance the NA of the objective lens. The state-of-the-art optical lens has a NA of 3.2 [5] which allows one to push the detection resolution down to 140 nm. These lenses are usually in contact with the sample surface and may ultimately destroy or alter the properties of sample of interest. As improvement in the resolution by these two approaches is rather limited, this technique has not attracted much attention.

The technologies of the second category are based on the prior knowledge of light-matter interaction. The most successful ones are those fluorescence microscopes [6]. They are based on the idea of controlling the photo-switching properties of the dye molecules to obtain sub-wavelength images. The emission of the photo-fluorescence can be controlled by using reversible saturation techniques such as stimulation emission depletion (STED) microscopy [7] or structured illumination microscopy (SSIM) [8]. Other fluorescence optical microscopy such as stochastic optical reconstruction microscopy (STORM) [9] and photo-activatable localization microscopy (PALM) [10] are based on localization techniques, which can only show the relative positions of the molecules. The key limitation of all the above techniques is that they can only be used for bio-sample and the current dyes used will damage the living cells. Moreover,

there must be prior-knowledge about the sample. In the real situation of measurements, the sample is usually an unknown factor which any detection system tries to detect.

So far, all the methods in the first two categories only attempt to circumvent the physical limits, but not overcome them. The diffraction limit is still a boundary for further improvement of the lateral resolution. In order to overcome this limit, researchers are re-examining the assumption of the diffraction limit which is derived theoretically based on linear optics. As a result, nonlinear optics have been employed in the development of microscopes with higher resolution. This effort gives rise to the technologies in the third category. For example, two-photon excitation microscopy [11] and point-spread function engineering in a $4\text{-}\pi$ microscopy have achieved higher resolution by using non-linear optical interaction [12] [13]. Currently, with non-linear optics, it is only possible to have the resolution down to $\frac{\lambda}{4}$. Note however that these techniques are still in the infancy state.

The fourth category of technologies uses superlens [14] and hyperlens [15], which also overcomes the diffraction limits by obtaining high spatial resolution optical signal in the near-field region. These lenses act as an all pass filter for high frequency components in the near-field to propagate into the far-field region for collection. Usually, the sample is in direct contact with the lens. This leads to two limitations of superlens. First, the sample must be flat or the lens must follow the topography of the sample. Next, the method is destructive because direct contact will alter or destroy the sample surface. Since this is a relatively new method, there are still many implementation considerations that may improve the performance of this method.

The use of near-field optics to overcome the diffraction limit characterizes the fifth category of technologies that are used to achieve higher resolution. This category of technologies is usually termed as Scanning Near-field Optical Microscopy (SNOM).

Compared to the superlens technologies and the nonlinear optics technologies, SNOM is more established [18]. It obtains the "true" sub-wavelength optical resolution by harnessing the high spatial frequency components that are only available within the near-field region. However, in the near-field region, the optical power decays exponentially with respect to the displacement from the optical source. In order to obtain these high spatial frequencies, E. H. Synge suggested that a collector or a scatterer in sub-wavelength size be used in the near-field region [16]. Only under this condition, the high spatial resolution components can be scattered or collected and coupled into the far-field for detection. The possibilities for near-field microscopy emerge after the invention of the Scanning Probe Microscopy (SPM). The world's first SNOM was built by Pohl in 1984, where a sub-wavelength aperture is used to collect high spatial frequency components in the near-field region, and it opened the door for achieving sub-wavelength resolution detection of down to $\frac{\lambda}{20}$ [17]. SNOM is a non-invasive method which does not impose any surface conditions on the specimen. Thus, SNOM is regarded as the best operable tool for obtaining sub-wavelength optical images.

Although SNOM is a good choice for sub-wavelength imaging, its performance depends heavily on the detection of two types of weak signals. One of these weak signals is of the electrical form, which refers to the one used to represent the nano-separation between the sub-wavelength aperture and the sample. The other is of the optical form. It refers to the light signal going through the sub-wavelength aperture. The importance of detecting these signals can be understood from the principle of SNOM. First of all, the evanescent field is the key concern of SNOM as it contains the high spatial frequency of the optical properties of the sample under measurement, but this field decays exponentially in the direction away from the optical source. Typically, the evanescent field signal at a distance of more than half a wavelength from the sample surface is too weak to be detected. Thus, the implementation of a SNOM requires a sub-wavelength aperture to be placed into the near-field region which is a few

nanometers above the sample surface, and the aperture-sample separation should be well controlled to be within the near-field region in order to remove the artifacts due to topographic changes on the sample surface. To this end, a sub-wavelength aperture is made on the tip of a tapered fiber probe, and a resonant element like a tuning fork is used in a SNOM to hold the probe and sense the probe-sample separation. The tuning fork probe is made to oscillate at its resonant frequency, meanwhile it is driven by a Z-piezo (Z-PZT) to move towards the sample surface. When it is within close proximity to the sample surface, the probe encounters an atomic force which affects the resonant status. In turn, the degree of deterioration represents the probe-sample separation. It is detected as an electric current going through the tuning fork prongs. This electrical signal is fed back into a PID controller of the Z-PZT to maintain the separation. Once the probe-sample separation is regulated, the probe scans over the surface with an x-y piezo stage to obtain the topographic and optical images. Since the atomic force representing the separation is basically weak, in addition to various ambient noises, very high sensitivity is required for the detection of the weak electrical signal in order to ensure that the sub-wavelength aperture can collect the evanescent field under the same near-field condition.

Once the probe is placed in the near-field, optical detection becomes a key task and the SNOM system has to detect the light going through the sub-wavelength aperture of the SNOM probe. The challenge here is the weak nature of the optical signal. The signal is weak mainly due to two reasons. First, because of the small aperture size, which is usually in range of 50 nm to 100 nm in aperture diameter, and the light throughput is extremely low (inversely proportional to a^{-4} where a denotes the aperture diameter) [18]. For example, the throughput of a 100 nm aperture probe is typically -50 dB. The attempt to use a strong light illumination is not feasible because the small size of a SNOM tip will suffer from a thermal break-down if the illumination source is more than 10 mW. This limits the illumination light power.

Due to the limited illumination light power and the limited throughput, the optical signal to be detected from a SNOM is in the range of a few nW or even down to pW. Therefore, a very sensitive detection system to detect the weak optical signal is required. It is the requirement of achieving a high sensitive detection of these two signals for the SNOM system that motivates the research of this thesis.

1.2 Literature Review of SNOM

This section reviews the state-of-the-art of the SNOM technology. In what follows, a general overview of the principle, the types, and applications of SNOM is first presented to provide a better understanding of the importance of weak signal detection. Then, the state-of-the-art of the SNOM technology is elaborated from the weak signal detection perspective.

1.2.1 Principle, Types, and Applications of SNOM

In general, SNOM is known as a technology that can overcome the diffraction limit by exploiting the near-field optical signal to obtain high spatial resolution. The idea of near-field microscopy (NOM) was proposed by E.H. Synge in 1928. However, the successful demonstration of this principle was attributed to the recent capability of fabricating a sub-wavelength aperture probe and controlling the near-field conditions with an atomic force microscope.

The basic principle of SNOM can be explained by using Figure 1.1. Figure 1.1(a) illustrates far-field detection, and the sub-wavelength object of width ΔX is detected with the illumination source at wavelength λ . Under this condition, the spatial frequency k_x greater than $2\pi n/\lambda$ results in a complex k_z . Hence, there are no propagating

field in the z -direction and no image is detected at the image plane at $z = Z$ when $Z \gg \lambda$. In figure 1.1(b), a sub-wavelength aperture is placed between the object and the image plane at a distance $\epsilon \ll \lambda$ from the object. The sub-wavelength aperture causes the evanescent field to diffract through the aperture and propagate into the image plane at $z = Z$. Thus, with the help of the sub-wavelength aperture, spatial frequencies greater than $2\pi n\lambda$ can be imaged on the far-field image plane.

Figure 1.1: Principle of near-field imaging using SNOM

This idea was only a dream at the time when it was proposed due to the stringent requirement of placing the sub-wavelength aperture in the near-field region. This major hindrance is only overcome with the introduction of the SPM concept where the tip-sample separation is regulated by observing the oscillation frequency of the SPM probe. The sub-wavelength aperture is then fabricated on the tip of a SPM probe, and the SPM probe-sample separation mechanism is borrowed to implement the near-field separation between the sub-wavelength aperture and the sample surface. The actual implementation of the SNOM system was realized in 1984 by Pohl and co-workers [17]. Due to this development background, the SPM probe with an aperture used in a SNOM system is called a SNOM probe, and the probe-sample separation is referred to as the separation between the sub-wavelength aperture and the sample surface. In

practice, the near-field condition is specified by the probe-sample separation of 10 to 20 nm.

A SNOM system basically consists of two subsystems. One subsystem is responsible for regulating the nano-scale probe-sample separation, and the second subsystem is for optical detection of the near-field optical signal. Since the atomic force between the SNOM probe and the sample surface is used to detect the probe-sample separation, the first subsystem is actually an atomic force microscope (AFM). There are basically two types of sensing modes for the probe-sample separation: the normal force mode and the shear force mode. The probes used in the normal force mode of SNOM include the bent fiber probes [22], the aperture cantilevers [23] and the tip-enhanced cantilevers [24]. For the shear force mode of SNOM, which is commonly used in practice, straight tapered fiber probes are used [26]-[30]. This kind of probes is usually mounted on a tuning fork using Cyanoacrylate glue or epoxy. For convenience of illustration, this type of probes will be called tuning fork probes in this thesis.

Despite the various types of SNOM probes, the operation principles of these probes are similar. The probe is made to vibrate at its resonance to achieve the highest possible Q-factor. This is to ensure that the SNOM probe has the highest sensitivity to sense the change in the atomic force due to a small change in the probe-sample separation. Meanwhile, while the probe is still resonating, a piezo actuator moves the probe to approach the sample surface. The vibration amplitude of the probe will drop when it's moved into the vicinity of the sample's atomic force region. Upon sensing this drop, the controller of the piezo actuator reacts in accordance with the reference set-point displacement of the probe-sample separation, and in turn, the separation is controlled. Once the separation control is established, the probe scans over the sample in near-field conditions. It is clear from this principle that the performance of probe-sample separation sensing and regulation depends heavily on the sensitivity of

the resonant mechanism and the associated detection of the changes in the resonant status. The speed of sensing is also very crucial in any scanning system, especially for detecting transient changes in the sample. With a separation controller of nanometer resolution and millisecond response time, the near-field optical signal is ready to be detected.

After the SNOM probe is placed in the near-field region, the probe acts as a collector or a scatterer for the near-field optical signal. The diameter of the probe tip or the sub-wavelength aperture on the probe tip ranges from 10 nm to 100 nm, and this small area of interaction between the optical signal and the sample yields very weak optical signal changes. This optical power is usually in the range of picoWatt. Furthermore, the throughput of the aperture probe depends heavily on the aperture size. A typical 100 nm aperture probe only have a throughput of 10^{-5} . On the other hand, the size of the aperture determines the resolution of the optical signal. Thus, there has to be a trade-off between throughput and resolution. The decay rate of the evanescent optical signal is related to the feature size of interest. A higher sub-wavelength resolution corresponds to a larger k_z , which is proportional to the decay rate of the evanescent field [31]. Thus, the optical signal is even weaker. All in all, the very weak signal is embedded in a strong background noise which makes it extremely challenging for detection.

Using the above mentioned principle of SNOM, various configurations of SNOM systems have been proposed for different applications. Basically, the system configurations of SNOM can be classified into four main categories, usually denoted by the illumination methods then the detection methods. Figure 1.2 gives a summary of all the possible SNOM configurations. The setups are :

1. The far-field far-field mode. This mode is usually referred to as the apertureless SNOM (ASNOM) [32] or the scattering SNOM (S-SNOM) [33]. In this mode,

Illumination	Far-field	Far-field	Near-field	Near-field
Collection	Far-field	Near-field	Far-field	Near-field
SNOM configurations				

Figure 1.2: Configuration of SNOM setup

- the probe used is a metallic tip which acts as a scattering tip. The collection and illumination optics are usually the same because of the simplicity of the setup and the reduction of strong background light. The first type of SNOM configuration has become very popular recently due to its high resolution [34].
2. The far-field near-field mode. This consists of the reflection-collection mode [35], transmission-collection mode [36] and photon tunnelling (Dark field) mode [37] respectively, as shown in Figure 1.2. In this mode, the probe is used as the receiver and through this process, a lot of background radiation can be removed. This is the first implementation of SNOM where a fiber probe was introduced for collection.
 3. The near-field far-field mode. This is where the probe is usually used as the illuminator while collection is done using far-field optics. In Figure 1.2, we have the illumination-reflection [38] and illumination-transmission set-ups. In a unique illumination-transmission setup which is known as the Tunnelling Near-field setup, the transmitted light is collected in all angles [39]. The earliest SNOM built is based on the near-field illumination. Since the collection uses far-field optics, the background noise will contribute significantly to the optical

signal detected.

4. The near-field near-field mode. This is usually known as the illumination-collection mode [40]. One can also classify the collection of the optical signal of electroluminescence or photoluminescence feature under this mode, as the illumination source can be considered as a near-field source. However, this type of mode usually gives the lowest signal strength due to the very small area of illumination.

SNOM has wide applications, and not constrained to just the optical measurements domain. It has useful applications in the area of data storage. Basically, SNOM is the principal tool for nanophotonic and nanometric optical measurements. SNOM is the tool for local plasmonics excitation and detection. For instance, the use of plasmonic probe enhances the Raman optical signal by more than 3 order of magnitude, which renders the possibility of nano Raman imaging. Here, SNOM is also used to observe the plasmonics effects of nanophotonic samples [82]. In the semiconductor industries, the Scanning Near-field Photon Emission Microscopy (SNPEM) has been a useful tool for semiconductor localization and fault characterization [43]. The photon emission from the slightly damaged integrated circuits (IC) provide useful information about symptoms of possible failures. This helps the IC designers and process engineers on the prognosis of their final products. The usefulness of SNOM has also helped to extended its reach into the uncharted domains of biological researches. The detection of optical signal from DNA [22], excitation of single fluorescence protein molecule [49], and detection of polarization effects on the chemical composition and interaction in the biological cells [44] are some examples of such SNOM applications. On a different application front, SNOM can be used as a fabrication tool, especially in optical data storage [41].

Overall, the flourishing nano-technology industries have pushed the demand for nanopho-

tonics tools and sub-wavelength optical measurements tools into higher levels. SNOM is one of the very important tools to meet this demand. However, as governed by the principles of SNOM, the performance of a SNOM system depends critically on the sensitivity of detection of the two types of weak signals. Indeed, the instrumentation of SNOM in the past decades has revolved around the resolution of these two types of detection.

1.2.2 State-of-the-art Weak Signal Detection for Probe-sample Separation and Regulation in SNOM

This section overviews the evolution of weak electrical signal detection for the probe-sample separation in SNOM. As mentioned earlier, the implementing of SNOM is only possible after the invention of the Topografiner in 1972 by Russell Young, where it becomes possible to bring the probe into the near-field region of the sample. Later in the 1980, it was demonstrated that the Scanning Tunnelling Microscopy (STM) has atomic resolution [21], which started the series of Scanning Probe Microscopy (SPM). A group of researchers, notably Gred Binnig, Calvin Quate and Christoph Gerber; then developed the Atomic Force Microscopy (AFM) which marked the beginning of SNOM development. Today, most of the SNOM systems are built based on the AFM configurations. The principle of SNOM indicates that a good SNOM result requires a good probe-sample distance regulation in order to avoid the artifacts arising from topographic changes. The research on probe-sample separation for SNOM system can be clustered into four areas.

In the first area, the key concern is with the high Q-factor resonant mechanism of sensing the atomic force for probe-sample separation. As required by the principle of SNOM, the change in the resonant status is used to sense the atomic force and in turn the separation between the SNOM probe and the sample surface. The sensitivity

of detection is primarily determined by the quality factor (in short, Q-factor) of the sensing mechanism which consists of a resonant element with the probe [18]. From the practical perspective, it is of interest to understand the resonant element with an attached fiber probe [26] or other optical elements [27]. The quartz tuning fork is a cost effective resonant element and is widely used in probe-sample distance sensing, particularly for SNOM. It is advantageous over the cantilever because it does not require an extra light beam which causes interference to the desired optical signal [26]. Furthermore, tuning fork probe provides a more compact and neat instrumentation. However, in practice, the Q-factor of a tuning fork is significantly reduced after it is attached with a SNOM probe. Thus, over the past years, many efforts have been channelled into improving the Q-factor of the tuning fork probe. These efforts include the attachment orientation and position of the probe [45][46][52], the types of mounting technique [47][48][53], the operation of the tuning fork probe [25][26][54], the tuning fork designs [55][56], and the excitation sources of the tuning fork [30][57]. Till today, the design of a high Q-factor sensor probe is still a challenging problem.

The second research area focuses on the dynamic model of the tuning fork probe with which the performance of the probe-sample separation detection and control can be analyzed and optimized. The single beam oscillation model has been widely used as an approximation for the tuning fork probe. This simple model has effectively demonstrated the dynamics of the tuning fork probe, from which the signal-to-noise ratio and the sensitivity of the force detection were investigated [28][59]. Similarly, this single beam model can also be expressed in electrical representation where the electrical and mechanical excitations are well modelled [60]. However, the simplified model is not adequate to explain the dynamic phenomenon when a probe is attached to the tuning fork, particularly the shift in resonance frequency and the drop in Q-factor. To overcome this limitation, a dynamic two-coupled oscillator model was presented [57]. Although the model is successful in explaining the phenomenon after

the attachment of the probe, significant discrepancies still exist between the model and the actual experimental data. One of the obvious discrepancies is that there is an appearance of a second peak which is never notice in experimental results [61]. Hence, the dynamic model of the tuning fork needs further exploration.

In the third area, research is focused on improving the signal to noise ratio (SNR) of the detection of the weak electric signal representing the resonant status. Lock-in detection has been the state-of-the-art technology for high sensitivity detection [62]. By modulating and demodulating the signal to be detected, lock-in detection pushes the noise effect to within a very narrow bandwidth so that the total power of the noise coming into the detection is greatly reduced and a high SNR is achieved. Due to this merits, lock-in detection has been a ubiquitous method used in the SNOM probe-sample separation sensing and regulation systems [25][28]. Although different demodulation methods have been used such as rms detector [66] and the modified rms detection [67][68], these detection methods are lower in sensitivity as compared to the lock-in method [62]. The current research focus of lock-in detection is mainly concentrated on further improvement of the SNR and the lock-in time.

Lastly, in the forth research area, the speed of high sensitivity detection is the key concerned. The high Q-factor may result in slow system response, since the overall bandwidth of the detection circuit determines the scanning speed. Thus, there must be a trade-off between sensitivity and speed in order to have a reasonable scanning speed with good probe-sample separation control. In order to tune this trade-off for suitable application, the Q-control tuning fork system has been proposed [69][70]. However, the bandwidth is limited due to the use of the amplitude feedback detection method, which is also known as the "slope detection" method. In order to achieve a high bandwidth at high Q-factor, a frequency modulation (FM) detection method, where detection is based on frequency shift while maintaining the detection amplitude,

has been proposed [71]. A very high resonance FM detection has also been discussed [72]. This kind of method is usually not preferred in shear force mode tuning forks as the frequency shift is highly materials dependent. Furthermore, the non-linearity in the vertical motion of the probe may produce inaccurate optical signals. It has also been argued by some research groups that based on their detection circuits, the Q-factor may not be the fundamental limitation on the operating speed [51].

1.2.3 State-of-the-art Weak Optical Detection for SNOM

Although SNOM is a good way to obtain sub-wavelength resolution, the near-field signal is usually difficult to sense due to the weak optical light from the small area of interest, especially when coupling the field into a nano-aperture probe. The throughput of the aperture probe is characterized by the “Bethe/Bouwkamp” model [74]. The transmission coefficient of a sub-wavelength aperture scales as a^4 , where a denotes the aperture diameter. The transmission coefficient of a 10 nm probe is about 4×10^{-9} , while a 100 nm probe is about 4×10^{-5} [19]. The throughput of other aperture sizes can be interpolated by using the “Bethe/Bouwkamp” model. On the other hand, when the probe is used as an illuminator, the maximum temperature with which the probe can withstand before thermal breakdown is 470°C or equivalently 0.5-1 mW of delivered power [75]. At this power, the signal output of the probe is only in the range of nanoWatts. Thus, the sensitivity of detection is a primary concern of SNOM systems. Since the introduction of SNOM, there are many suggestions and experimentally proven ideas to improve the sensitivity of signal detection. These suggestions can be grouped into four categories, which are characterized respectively by the SNOM probe design, the optical detection methods, the demodulation techniques, and the detection instrumentation issues.

The most fundamental sub-component that many research groups focused on for

signal enhancement is the design of the SNOM probe. The probe has three main functions. It is used as a collection optics, an illumination source and a scattering probe. The illumination and collection probes are related and will be discussed together. The illumination probe is the pioneering idea in the development of SNOM [17][76]. Later on, the probe is used as the illuminator after the development of fiber probe [36], which has become the most popular material for SNOM probe. Regardless of the types of mode used, the main problem with aperture probe is the throughput. To improve the throughput of the SNOM aperture probe, many researchers have suggested new probe profile. The design is always a trade-off between throughput and resolution, which is directly related to the taper angle of the probe [77]. With this concern, a wide angle probe is introduced and fabricated [78]. Later, to improve the collection efficiency and resolution, a triple-tapered structure probe [79] has been proposed and it shows a 1000 times increase in throughput. Similarly, cantilever probes that are Si based can be shaped using FIB micromachining to obtain a wide taper angle aperture with a high throughput [80]. Recently, an optimized profile of the SNOM probe was proposed and theoretically shown to provide enhancement of the collected field [81]. From other perspectives, many groups also suggested to enhance the optical field through plasmonics via the attachment of nano-particle. This method was first suggested by coating the aperture probe with a 20 nm thick layer of metallic material [82]. However, after the first experimental demonstration of a plasmonic probe, there is not much discussion until recently. The fully coated plasmonic probe using fiber probe demonstrates good optical field enhancement [83][84], and later a new technique based on placing an elliptical Au nano island in the center of the aperture is preferred [85]. Frey et al proposed an aperture probe with a sharp metal tip and it has good signal enhancement and high resolution [86]. Other designs of plasmonic probes are nanoshells [87] and Bow-Tie antenna [88]. The detection of the optical signal by enhancing the throughput for illumination and collection probes

have been extensively discussed.

As for the third function of the SNOM probe, the scattering probe is usually an AFM probe and it does not have any collection ability. Thus, the far-field far-field mode is used. ASNOM uses a scattering probe to localize the tip-sample interaction point, where the interaction area of the probe is very small (~ 20 nm in diameter) [89], thus the SNOM signal is usually a small fraction of the total signal detected. The bulk of the detected signal is the reflected or scattered background light from the sample [73]. In order to enhance this very weak but useful signal, tip-enhanced probe has been introduced [89][90]. Similar to the aperture probe, the whole scattering probe is coated with gold [91]. Later, the scattering probe is fabricated by attaching gold nano particle to the AFM tip, which is also called the plasmonic probe [44]. This is very critical for ASNOM application because the enhancement enabled the detection of weak signal. The various types of SNOM probes are summarized and illustrated in Figure 1.3. To this end, the probe only serves as the signal enhancing mechanism.

There are other optical detection methods proposed by many research groups. These optical detection methods can be classified into two main methods (See Figure 1.4): the direct detection and the coherent detection methods [93]. In the direct optical detection method, the light from the sample is channelled directly into the photodetector and the optical power is measured. There is no optical signal enhancement or processing between the sample and the detection. This is the most primitive method used in SNOM [17]. Although the setup is easy, it does not provide a good signal-to-noise ratio (SNR) because of the presence of noise sources such as thermal noise, dark current noise, background noise and $1/f$ noise [93].

Coherent detection is an important detection method used in many optical systems to enhance the SNR. The principle of coherent detection is to amplify the total intensity of the detected signal until the noise in the detection process is dominated by shot

Figure 1.3: Types of SNOM probes. Aperture probes: Normal probe, wide angle probe, triple-tapered probe, sharp metal tip probe, cantilever probe, elliptical Au island probe, Nanoshell probe and Bow tie probe. Scattering probes: dielectric nano particle probe, gold coated tip enhanced probe and tip enhanced cantilever probe.

noise. This is also called the shot noise limit detection. In order to achieve this, a local oscillator (LO) is introduced in between the sample and the detector. The LO acts as the amplifying source for the weak near-field signal [93]-[101]. Coherent detection can be divided into homodyne and heterodyne detections with the former having twice the SNR as of the latter [94]. However, homodyne detection is usually not preferred because of low frequency drift which can easily affect the detection. Furthermore, homodyne detection gives only the combined amplitude and phase information. Since heterodyne detection has a slight shift in the optical frequency, the optical power detected is usually a sinusoidal wave. Thus, with this modulated signal, it is possible to detect the signal from the low frequency drift. Heterodyne detection is a more versatile method as the amplitude and the phase can be detected independently. Because of this ability for amplitude and phase detection with high SNR, heterodyne coherent detection has been introduced into the SNOM system since one and a half

decade ago [102]. It is only recently that the method is extensively used for detecting optical amplitude and phase [103]-[111]. In ASNOM, coherent detection is inevitable because the weak near-field signal and the strong background noise will be collected together and interference to the signal is unavoidable [105]. In order to differentiate the background and the signal, heterodyne detection is deployed [105]-[108].

Figure 1.4: Optical detection methods

Apart from the optical methods, the near-field signal can also be enhanced in the electrical domain by using demodulation techniques, where the most commonly used instrument for high sensitivity detection is the lock-in amplifier [102]-[111]. Based on the lock-in techniques, there are a number of possible modulation and demodulation techniques. The most straightforward method is to modulate the source amplitude and demodulate the signal. This method is often used in the near-field far-field mode because the signal can be differentiated from the background [102]. In ASNOM, demodulation is normally based on the dithering frequency of the scattering probe. This is because the near-field signal of interest is at the point where the tip-sample interacts [73]. By combining tip demodulation techniques and heterodyne ASNOM, and the selection of proper bandpass filters, the background signal of the scattered light can be removed [105]. These significantly enhanced the signal of interest. Some groups have found that the detection of different harmonics of the near-field signal gives a better

imaging contrast [106]. In some set-ups, a balanced detector is also used to remove the common mode noise [110]. To this end, we know that optical coherent detection has to be integrated with the demodulation and signal processing techniques in order to obtain the best SNR. In addition to intensity, these demodulation techniques can also be applied to the optical amplitude, optical phase [106], scattering tip modulation [109], polarization state [112], gate pulse acquisition [38] and second harmonics generation [32] detection. These types of detection give a higher contrast because of the different properties. On the other hand, some researchers have proposed the use of laser injection detection principle for SNOM measurements [113]. It seems to be an emerging technology due to its compactness in implementation.

The detection instrumentation also plays an important role in signal collection. The collection optics of SNOM is most critical, but can be ignored in fiber based collection SNOM. In order to collect most of the signal, high NA objective is usually preferred. However, the working distance is related to the NA of the objective lens [34]. Certain modes of operation require a longer working distance, and hence different types of objectives lens. Inserting filters within the collection optics can remove the background signal especially for the fluorescence detection [91]. Integrating spheres have also been suggested to increase the collection efficiency of the SNOM signal [92]. The detector also plays a critical role in the weak signal detection. The SNOM signal is usually very weak because the optical signal of the aperture SNOM is attenuated by 5 orders of magnitude, and the ASNOM usually detects the scattered light. Thus, a high sensitivity low dark current detector with thermoelectric cooling is preferred. Usually, the type of photodetector used is either the photomultiplier tube (PMT) or the Avalanche photodiode (APD).

1.3 Objectives

The overall objective of this thesis is to develop a high sensitivity SNOM system via the development of new devices and methods to improve the sensitivity of weak signal detection. The targeted improvements will center around two critical aspects of SNOM technology: the weak electrical signal detection for probe-sample separation and the weak optical detection of near-field signals. The following subsections define the key objectives and the associated technical approaches embodied in this thesis to overcome the key challenges of weak signal detection for SNOM.

1.3.1 High Sensitivity Weak Electrical Signal Detection

The high sensitive weak electrical signal detection will be approached from 3 perspectives: (i) improving the Q-factor of tuning fork probe by examining the dynamics model of tuning fork probe, (ii) improving the sensitivity of detection of the tuning fork responses by exploiting the phase information of the signal, and (iii) improving the SNR and time responses of lock-in detection technique by looking into the lock-in system design. These improvements are to be integrated into a probe-sample separation sensing sub-system for SNOM. These improvements are detailed below.

- (i) *Improvement on the Q-factor of the tuning fork probe.* The objective of this part of research is to obtain a dynamic model of the tuning fork probe such that the Q-factor drop due to probe attachment can be accurately characterized and in turn the Q-factor can be improved. Further, the improved performance can be evaluated qualitatively via the model.
- (ii) *Improvement on the sensitivity of detection of the tuning fork responses.* In the detection of the electric current going through the tuning fork prongs, which

represents the resonant status of the tuning fork probe, quadrature signals are available by using the lock-in technique. The objective of this part of research is to improve the sensitivity of detecting the electric current by making use of the phase information of the quadrature detection.

- (iii) *Improvement on SNR and time responses of lock-in detection technique.* In phase lock-in detection, the phase difference between the signal and the reference is used as the feedback to a lock-in controller to minimize the phase difference. The feedback controller is usually a linear system. The objective of this part of research is to design a nonlinear controller to improve the lock-in SNR and the lock-in time.

1.3.2 High Sensitivity Weak Optical Signal Detection

The sensitivity of the optical signal detection is improved by exploring a coherent detection method. The objective is to obtain an optical counterpart of the lock-in technique to reduce the noise in the optical domain before they are converted to electrical forms. Here, a multi-wavelength modulation method is to be applied to the coherent detection method with an electric lock-in demodulation at the receiver end. This part of the work also serves other objectives which include the use of the Fizeau interferometer implementation of the multi-wavelength modulation method to estimate the probe-sample separation, and the realization of phase measurement capability of SNOM to enlarge the application scopes of the SNOM technology.

1.3.3 System Integration

The third objective of this thesis is to integrate the above improvements into a SNOM system and to demonstrate the improved sensitivity not only by calibration samples

but also in real applications such as imaging biological samples, waveguides characterization, and photonics crystals characterization.

1.4 Major Contributions

The main contribution of this thesis is the development of a high sensitivity SNOM system which is versatile for real applications. This is achieved through sensitivity improvements of the SNOM system via the invention of new devices and novel methods. These sensitivity improvements are based on several major contributions towards weak electrical signal detection for the probe-sample separation and weak optical near-field signal detection. These contributions are especially innovated to tackle the challenges of weak signal detection in SNOM, and they are briefly described below:

- A high Q-factor tuning fork probe sensor is achieved with complete theoretical analysis. The Q-factor drops drastically after a SNOM probe is being attached to the prong of the tuning fork, resulting in the sensitivity drop. This is a very important problem for all tuning fork mounted probes. It is found that the Q-factor of the tuning fork probe can be enhanced by balancing the tuning fork through the addition of mass at the other prong. Based on the dynamic model, a theoretical analysis of the Q-factor improvement is first introduced. The Q-factor is experimentally shown to improve by up to 15 times. This improvement enables a nanometric displacement sensing for the SNOM system. Furthermore, this balancing technique can be used for all tuning fork based sensors in other types of SPM.
- An accurate dynamic model of the tuning fork probe with probe attachment is obtained. Single prong models are not able to describe the unbalanced effects of the tuning fork prong. Although the two-coupled oscillator is able to show the

unbalanced effects, the result still has some discrepancies. By using a frequency domain system identification method, we proposed a new two-coupled oscillator tuning fork model. This model can characterize accurately the tuning fork probe. The model is also able to characterize the noise and the sensitivity of the tuning fork probe. This model can also be used in other analyses like quantifying tribology measurements.

- An active quadrature detection method for high sensitivity tuning fork response is innovated. Due to the inconsistency of the phase response of the tuning fork, the resonant condition of the tuning fork response may change. Thus, the sensitivity of the sensor may be lower. The proposed active phase compensation technique by using the quadrature lock-in signals greatly improves the sensitivity of detecting the tuning fork response. The improvement has enabled the SNOM system to scan certain topography that it previously could not scan.
- A high SNR with high speed lock-in detection method is introduced. Lock-in techniques are designed based on a loop filter in which there is a trade-off between the SNR and the speed of detection. For a higher SNR, the bandwidth becomes narrower, so the speed of the lock-in decreases. A non-linear lock-in detection method based on a feed-forward control signal is used to improve the speed of the lock-in detection with the SNR determined by the loop filter. The new lock-in technique has yielded an improved response that is less than half the response time of the conventional lock-in techniques. Furthermore, the lock-in transient responses can be altered by fixing the gain of the feed forward signal.
- An interferometry fiber based SNOM is built with improved SNR. The noises from the optical source, the photo detector and the detection circuit are a potent threat to all optical detection methods, particularly the low frequency noise. In order to improve the SNR of coherent detection, modulation techniques are

used to enhance the SNR in the optical domain before the photo detection process. The modulated signal is then demodulated using lock-in detection to further reduce the electrical noise. Based the coherent detection technique, the SNR achieved can be 50 dB more than the direct detection method. With the lock-in detection, the SNR is further improved by 30 dB, giving a total of 80 dB of improvement. This makes it possible for the SNOM system to detect a signal with power of less than 1 fW. Furthermore, multi-harmonics signal processing technique is applied to the detected signal to achieve better results. This technique can also be used on other sensors to improve the SNR.

- For the first time, the SNOM is used as a displacement sensor. Conventional displacement sensors have diffraction limited spot size, and sub-wavelength features are indiscernible. Thus, a SNOM set-up based on Mach-Zehnder interferometer is introduced. The optical path difference between the sample arm and the reference arm must be obtained first. This optical phase data can be converted into the displacement information through calibration. Currently, the system is able to achieve at least 5 nm of displacement separation. In future, it will be possible to use this technique for the distance regulation of the SNOM probe. Another significant contribution to the SNOM system is that the optical phase information gives a better contrast than the optical amplitude information for certain samples.
- A versatile SNOM system is realized for real application in imaging. Calibration samples for SNOM can be easily demonstrated, but in real life applications these samples are unknown. Thus, the samples have different optical contrast when using certain modes. In order to see a better optical contrast of different samples, different modes of SNOM configuration have been implemented. The different modes of SNOM imaging have yielded good contrast results in samples

such as calibration gratings, photonics devices and biological samples.

1.5 Organization of the Thesis

The thesis is organized into six chapters. Chapter 1 describes the motivations of the research, the basic principle of SNOM, the state-of-the-art SNOM technology, the objectives of the thesis, and the major contributions of the thesis. The major contributions of this thesis are elaborated in Chapters 2 to 5.

Chapter 2 presents the innovations on the tuning sensor. It consists of a new dynamic model of tuning fork probe, the Q-factor improvement by balancing the tuning fork probe, and the results of quantitative analysis of the sensitivity and the noise performance.

Chapter 3 describes improvement in the detection of weak signal from the tuning fork sensor. The development and the performance of the proposed active quadrature detection approach for enhancing the sensitivity of detection is discussed. It also illustrates the improvement in the transient performance of the proposed lock-in technique with nonlinear feedback control.

Chapter 4 presents the sensitivity improvement by using multi-wavelength interferometry detection methods with lock-in detection in SNOM. In this chapter, the optical displacement sensing using SNOM is also demonstrated. Multi-harmonics averaging techniques are used to remove the noise of the displacement sensor.

Chapter 5 presents the integration of the various innovations into the final SNOM system. The capabilities of the SNOM system are demonstrated through applications on several real samples requested from various research groups.

Finally, the thesis is concluded in chapter 6 and some future research directions are

also suggested in this chapter.

Chapter 2

Dynamic Modelling and Q-factor Improvement of Tuning Fork Probe

2.1 Introduction

Tuning fork probes are commonly used in SPM [56], particularly in SNOM [28]. This is because tuning fork probe is easy to implement and does not have optical disturbance. Other uses of the tuning fork probe include quantitative measurements of mechanical properties of materials, such as tribology characterization in nano-scale resolution [50]. These quantitative measurements require an accurate dynamic model of the tuning fork probe. An accurate model is useful for tuning fork probe characterization especially in the optimization of the tuning fork probe design [55]. The characterization works involve mainly the assessment of signal-to-noise ratio (SNR) and the sensitivity of force measurements.

In this chapter, a two-coupled oscillators model to describe the dynamics of a tuning fork with an attached probe is presented. The two-coupled oscillators are unbalanced only in their effective masses and the damping ratios. By applying a frequency-domain

system identification approach in our experimental investigation of the various cases of probe attachments, a good accuracy of the model is demonstrated. When compared to existing models, the proposed model can more accurately characterize the dynamics of a tuning fork probe. The effectiveness of the model is further demonstrated via quantitative analyses of the noise performance and the sensitivity of force sensing with a tuning fork probe. Then based on this model, an approach for improving the Q-factor of the tuning fork probe is presented. The improvement is achieved by balancing the fork prongs with an extra mass attachment, and the idea of balancing the effective mass of the tuning fork probe is adopted [57]. In this chapter, an analytical model is proposed to characterize the Q-factor of the tuning fork probe with respect to the attachment of extra mass on the tuning fork prongs. Based on the model, the Q-factors of the unbalanced and balanced tuning fork probes are derived and compared. Experimental results showed that the model fits well with the experimental data (having an RMSE value of at less than 0.2) and the approach can improve the Q-factor by more than a factor of three or more. The effectiveness of the approach is further demonstrated by applying the balanced probe on an atomic force microscope to obtain improved topographic images.

2.2 An Improved Model of a Tuning Fork Probe

Since the simplified 2nd order model does not completely describe the full dynamics of the tuning fork probe, we shall begin with a more general model of two 2nd order-coupled oscillators [115] that is given by

$$m_1\ddot{x}_1 + k_1x_1 + \alpha_1(x_1 + x_2) + \frac{1}{2}\beta_1(m_1\dot{x}_1 + m_2\dot{x}_2) + m_1\gamma_1\dot{x}_1 = F_1(t) \quad (2.1)$$

$$m_2\ddot{x}_2 + k_2x_2 + \alpha_2(x_1 + x_2) + \frac{1}{2}\beta_2(m_1\dot{x}_1 + m_2\dot{x}_2) + m_2\gamma_2\dot{x}_2 = F_2(t) \quad (2.2)$$

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where x_1 and x_2 denote the displacements; m_1 and m_2 the effective masses; γ_1 and γ_2 the damping coefficients; k_1 and k_2 the stiffness coefficients; α_1 and α_2 the coupled stiffness coefficients; β_1 and β_2 the coupled damping coefficients; and F_1 and F_2 the excitation sources of the individual prongs, respectively.

The response of a tuning fork probe can be either the voltage measured across the electrodes of the tuning fork or the current signal from the tuning fork. It is related to the displacement of the prongs, due to the piezo-electric effect. In general, the response can be expressed as

$$y = c_1 x_1 + c_2 x_2 \quad (2.3)$$

where c_1 and c_2 characterize the gains from the displacements into the voltage/current signal.

Equations (2.1), (2.2), and (2.3) give the general model characterizing the dynamics of a tuning fork probe system. Next, a frequency-domain system identification approach is applied to estimate the parameters and identify the major characteristics of the model. To this end, the frequency-domain transfer function of the system (2.1), (2.2), and (2.3) is given by

$$\begin{aligned} Y(jw) = & [F(c_1(-m_2 w^2 + jw m_2(\gamma_2 + \frac{1}{2}(\beta_1 + \beta_2))) + k_2 + \alpha_1 + \alpha_2) \\ & + c_2(-m_1 w^2 + jw m_1(\gamma_1 + \frac{1}{2}(\beta_1 + \beta_2))) + k_1 + \alpha_1 + \alpha_2)] / \\ & [(-m_1 w^2 + jw(\gamma_1 + \frac{1}{2}\beta_1)m_1 + k_1 + \alpha_1)(-m_2 w^2 + jw(\gamma_2 + \\ & \frac{1}{2}\beta_2)m_2 + k_2 + \alpha_2) - (\alpha_2 + jw\frac{1}{2}\beta_2 m_1)(\alpha_1 + jw\frac{1}{2}\beta_1 m_2)] \end{aligned} \quad (2.4)$$

where electrical excitation of the tuning fork is considered. Due to the electrode design of the quartz tuning fork[28], electrical excitation will produce an anti-phase driving force to vibrate each of the prongs. This causes the prongs to oscillate in the opposite direction. Thus, the excitation sources can be considered as $F_1 = -F$ and

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$F_2 = F$, with F being the force caused by the electrical excitation signal.

Figure 2.1: Experimental set-up for frequency response data

The frequency response data is obtained experimentally by the set-up shown in Figure 2.1. This set-up is used in SPM to pre-amplify the tuning fork signal [28]. The input excitation source for the tuning fork is sinusoidal with an amplitude of 1 mV. This source is generated by a signal generator which is coupled into a center tapped transformer (C&D Technologies 78615/1C [137]). The center of the transformer is grounded to produce anti-phase signals at the two outputs. One of the output drives the tuning fork, while the other signal is fed into the tunable capacitor. The tunable capacitor is used to compensate for both the parasitic capacitance of the tuning fork and the input capacitance of the amplifier through current summation. The final signal is then amplified by using a transimpedance amplifier circuit. The operational amplifier used is LF353 from National Semiconductor [138]. The details of the implementation are discussed in the later section. The frequency of the excitation source is swept across the resonance frequency with a step of 0.1 Hz, while the output signal of the amplification circuit is fed into a Signal Recovery 7265 lock-in amplifier [139]. The time constant of the lock-in amplifier is set at 100 ms. The frequency response of the tuning fork is obtained at the output of the lock-in amplifier.

In the experiment, the frequency response of a bare tuning fork is first measured, followed by the frequency response of the tuning fork with a probe attached. In order

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to simulate different attachment scenarios, extra masses are added to the fork prong together with the probe and the corresponding frequency responses are measured. Using the model (2.4) and applying the frequency-domain system identification method on the obtained frequency responses, the system parameters are obtained for each scenario and the corresponding parameters are summarized in Table 2.1. The root mean square errors(RMSEs) of the fitting are also included in the Table. The fitted graphs and experimental data are shown in Figure 2.2.

Table 2.1: Parameters of the tuning fork through system identification

Parameters	Unmounted TF	TF with Probe	Extra Mass 1	Extra Mass 2	Extra Mass 3	Extra Mass 4
$m_1(\mu g)$	278.053	278.058	278.060	278.060	278.056	278.059
$m_2(\mu g)$	278.060	286.883	291.332	298.220	308.906	315.606
$\alpha_1(kN/m)$	8.89181	8.89051	8.88870	8.89097	8.89167	8.89061
$\alpha_2(kN/m)$	8.89037	8.89159	8.89080	8.89091	8.88967	8.89091
$k_1(kN/m)$	11.7783	11.7787	11.7781	11.7773	11.7781	11.7786
$k_2(kN/m)$	11.7781	11.7767	11.7776	11.7783	11.7780	11.7775
$\beta_1(Ns/gm)$	8.50784	8.50983	8.50729	8.50696	8.51081	8.50830
$\beta_2(Ns/gm)$	8.50681	8.50713	8.50780	8.50701	8.50861	8.50996
$F(nN)$	3.49661	3.49854	3.49854	3.49670	3.49721	3.49863
$\gamma_1(Ns/Kgm)$	19.681	19.955	19.955	19.912	19.625	19.692
$\gamma_2(Ns/Kgm)$	19.912	22.913	29.256	49.256	55.609	167.103
$R_{TF}(K\Omega)$	312.50	384.61	476.19	689.66	833.33	2222.22
$RMSE$	0.19	0.12	0.14	0.13	0.15	0.11

The identification results show several important characteristics of the dynamic model. First, $c_1 = 0$ and $c_2 = 1$, which means only the symmetric mode of the vibration is measured. Second, the attachment of the probe only affects the effective mass and the damping ratio of the attached prong, while all the other coupling coefficients remain constant. This concludes that a good model that is capable of characterizing

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the dynamics of a tuning fork probe is given by

$$m_1\ddot{x}_1 + kx_1 + \alpha(x_1 + x_2) + \frac{1}{2}\beta(m_1\dot{x}_1 + m_2\dot{x}_2) + m_1\gamma_1\dot{x}_1 = F_1(t) \quad (2.5)$$

$$m_2\ddot{x}_2 + kx_2 + \alpha(x_1 + x_2) + \frac{1}{2}\beta(m_1\dot{x}_1 + m_2\dot{x}_2) + m_2\gamma_2\dot{x}_2 = F_2(t) \quad (2.6)$$

$$y = x_2 \quad (2.7)$$

This is a two-coupled oscillators model that describes the dynamics of the tuning fork probe. In this model, only the effective masses and the damping ratios are unbalanced.

Figure 2.2: Experimental frequency response of the tuning fork (Dotted lines: Experimental data; Solid line: Calculation results)

To further verify the model, other types of tuning forks are also tested. Based on the model, the experimental data of another tuning fork is obtained by using a 10 mV excitation voltage. Similarly, the model (2.4) is used to obtain a new set of the system parameters for the tuning fork. The parameters are obtained with RMSE of less than 0.19. Based on the parameters, the frequency responses are plotted together with the experimental data in Figure 2.3.

Figure 2.3: Experimental frequency response of the tuning fork using a 10 mV excitation source(Dotted lines: Experimental data; Solid line: Calculation results)

A new tuning fork is used to perform the test of varying the excitation amplitude. Using the same set-up as in Figure 2.1, four different excitation voltages are applied and the experimental results are collected. The excitation voltages are 10 mV, 1 mV, 0.5 mV and 0.1 mV, respectively. This excitation can be mapped proportionally to the F_1 and F_2 terms in (2.5) and (2.6), as the transfer function gain remains a constant. Similarly, we can denote $F_1 = F$ and $F_2 = -F$ to simplify the fitting. Based on (2.5)-(2.7), the tuning fork output is generated and plotted in Figure 2.4. The model fits well with the experimental results having an RMSE of less than 0.2. The insert in Figure 2.4 shows the zoom-in view of the lower excitations. It can be seen that the center frequency of the experimental data shifted slightly to the right when a lower excitation is used. This may be due to the slight changes in the effective masses, m_1 and m_2 as the oscillation amplitude decreases. It is also found that the peak voltage of different tuning forks varies, but the model still fits well.

Figure 2.4: Varying the excitation amplitude of the tuning fork probe. Solid line: Calculated frequency response. Square: 10 mV excitation. Cross: 1 mV excitation. Circle: 0.5 mV excitation. Triangle: 0.1 mV excitation. Insert: Zoom-in view of the lower excitations.

2.3 Noise Analysis of the Tuning Fork

The obtained model is further examined by using it to calculate the noise response of the tuning fork probe system as in Figure 2.1. The noise response is obtained by removing the signal generator and grounding the two ends of the transformer [30]. The noise response consists of three parts: the noise from the tuning fork probe, the noise from the transimpedance amplifier resistor R , and the internal noise from the operational amplifier. Since the tuning fork is excited at high frequency (typically at 30 KHz), the noise is mainly contributed by the Johnson noise of its equivalent internal resistance, denoted as R_{TF} which can be obtained by $R_{TF} = R/|Y(j\omega_0)|$, where $|Y(j\omega_0)|$ is the amplitude of the transfer function at the resonance frequency ω_0 . If a junction gate field-effect transistor (JFET) operational amplifier is used, only

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the voltage noise has significant contribution [114]. Thus, the total noise response can be expressed as

$$Noise_{TF} = \sqrt{4k_B T R + 4k_B T \frac{R^2}{R_{TF}} \left| \frac{Y(j\omega)}{Y(j\omega_0)} \right|^2 + V_n^2 \left(\frac{R}{R_{TF}} + 1 \right)^2} \quad (2.8)$$

where k_B is the Boltzmann constant, T is the room temperature, $Y(j\omega)$ is the transfer function in (2.4), and V_n^2 is the input voltage noise of the op-amp used.

Figure 2.5: The noise spectrum of the tuning fork probe (Dotted line: Experimental data; Solid line: Calculation results)

Taking the parameters of the tuning fork probe from the first column of Table 2.1, its noise response is first calculated by using (2.8). Then, the noise response is measured experimentally by grounding the two ends of the transformer and sweeping the lock-in frequency in the set-up of Figure 2.1. The calculated and the recorded responses are plotted in Figure 2.5 which demonstrated a good fit for the proposed model.

2.4 Separation Detection Sensitivity of Tuning Fork Probe

Next, the model is used to examine the separation detection sensitivity of the tuning fork probe for two signal detection schemes which respectively detect the frequency shift, ω , and the absolute amplitude change, A . Here, we are only interested in the shear force detection for our intended application. To date, there is still no physical model to explain the phenomenon of shear force interaction. In practice, the shear force interaction affects both amplitude and frequency changes, but here we only considered the shear force as a linear model which means that the shear force is basically assumed to be related to the damping ratio, and the corresponding sensitivities obtained by using frequency shift and amplitude change are respectively defined as $\frac{(\Delta\omega/\omega)}{(\Delta\gamma_2/\gamma_2)}$ and $\frac{(\Delta A/A)}{(\Delta\gamma_2/\gamma_2)}$, where normalization has been used for fair comparison.

Using the proposed model given by (2.5), (2.6), and (2.7), the sensitivities of the tuning fork probe can be calculated against different attachment scenarios which can be characterized by the unbalanced effective mass and damping ratio due to the probe attachment. Denote the unbalanced effective mass by $q = (m_2 - m_1)/m_1$ and the unbalanced damping coefficient by $p = (\gamma_2 - \gamma_1)/\gamma_1$. The sensitivities against different attachment scenarios are calculated and visualized in 3-D plots given in Figure 2.6. In general, the attachment of the probe to the tuning fork prong leads to a decrease in the sensitivity of the tuning fork probe. Comparing Figures 2.6(a) and 2.6(b), the amplitude based detection scheme outperforms its counterpart using the frequency shift scheme when the two tuning fork prongs are slightly unbalanced because of the attached probe. The change in frequency in the shear force mode is almost insignificant.

Figure 2.6: Sensitivity of tuning fork probe in shear force detection as a function of the relative change in mass, q and the relative change in damping, p .

2.5 Theoretical Model of Q-factor Improvement

Based on the model obtained previously, we can derived the Q-factor of the tuning fork probe. Here, the tuning fork probe is described by the two-coupled oscillators given in (2.5) and (2.6). The two oscillators model was used in [57] and other references as well, but here, the attachment of the probe or the extra mass on prongs of the tuning fork is considered to cause the imbalance in both the effective masses and damping ratios, rather than only the unbalanced effective masses. We will show subsequently that this modification together with (2.16) yields provides an improved model that is capable of characterizing accurately the Q-factor of a tuning fork probe with respect to the attachment of extra mass on the tuning fork prongs.

Since the experiment is electrically excited, the excitation force applied to the tuning fork prongs should be in opposite directions, thus we let $F_2(t) = -F_1(t) = F(t)$. Hence, the displacement of each individual prong can be expressed in the frequency

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domain as,

$$x_1(w) = F \frac{(-m_2 w^2 + jw(\gamma_2 + \beta)m_2 + k + 2\alpha)}{H(w)} \quad (2.9)$$

$$x_2(w) = F \frac{(-m_1 w^2 + jw(\gamma_1 + \beta)m_1 + k + 2\alpha)}{H(w)} \quad (2.10)$$

where

$$\begin{aligned} H(w) = & (-m_1 w^2 + jw(\gamma_1 + \frac{1}{2}\beta)m_1 + k + \alpha)(-m_2 w^2 + jw\gamma_2 + \frac{1}{2}\beta)m_2 + k + \alpha \\ & - (\alpha + jw\frac{1}{2}\beta m_1)(\alpha + jw\frac{1}{2}\beta m_2) \end{aligned} \quad (2.11)$$

with w being the frequency of excitation. The output signal detected can be expressed as $y = cx_2$ where c is a constant gain. These coefficients of the oscillators can be obtained by fitting the system's frequency responses.

We shall now derive the expression of the Q-factor of the tuning fork probe. As in [57], we take advantage of the asymmetrical and the symmetric modes which are defined as $z_1 = x_1 - x_2$ and $z_2 = x_1 + x_2$, respectively. The above equations can be solved by substituting $z_1(t) = z_{11} \exp(-j\omega t)$ and $z_2(t) = z_{21} \exp(-j\omega t)$ where z_{11} and z_{21} denote the complex amplitudes. The ratio of the complex amplitudes of the two modes is given by

$$\begin{aligned} \left| \frac{z_{11}}{z_{21}} \right|^2 &= \left| \frac{-(m_1 - m_2)w^2 + \{(\gamma_1 m_1 - \gamma_2 m_2) + \beta(m_1 - m_2)\}jw}{-(m_1 + m_2)w^2 + 2k + 4\alpha + \{(\gamma_1 m_1 + \gamma_2 m_2) + \beta(m_1 + m_2)\}jw} \right|^2 \\ &= \frac{q^2 w^4}{\left(\frac{k+2\alpha}{m_1} - (1+q)w^2 \right)^2 + \left(\frac{\gamma_1}{2} \{1 + (2p+1)(2q+1)\} + \beta(q+1) \right)^2 w^2} \end{aligned} \quad (2.12)$$

where

$$p = \frac{\gamma_2 - \gamma_1}{2\gamma_1} \quad \text{and} \quad q = \frac{m_2 - m_1}{2m_1} \quad (2.13)$$

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At resonance condition, (2.12) can be approximated as

$$\begin{aligned} \left| \frac{z_{11}}{z_{21}} \right| &\approx \frac{qw^2}{\frac{k+2\alpha}{m_1} - (1+q)w^2} \\ &= \frac{2q(1+2q - \frac{k}{2\alpha}q^2)}{\left(\frac{k}{\alpha}q^2 + 8\frac{\alpha}{k}q + 4\frac{\alpha}{k}\right)(1+q)}, \end{aligned} \quad (2.14)$$

at resonance frequency

$$\begin{aligned} w_{11}^2 &= \frac{(k+\alpha)(1+q)}{m_1(2q+1)} - \frac{\alpha(q+1)}{m_1(2q+1)} \sqrt{1 + \frac{(2k\alpha + k^2)q^2}{\alpha^2(q+1)^2}} \\ &\approx \frac{k(\alpha + 2\alpha q - kq^2/2)}{m_1\alpha(1+2q)(1+q)}. \end{aligned} \quad (2.15)$$

To proceed, we introduce an approximation of the ratio of these modes with respect to the Q-factor, Q , as follows:

$$\begin{aligned} \left| \frac{z_{11}}{z_{21}} \right| &= f(p, q)Q \\ \frac{1}{Q} \left| \frac{z_{11}}{z_{21}} \right| &= \frac{(c_3q^3 + c_2q^2 + c_1q + c_0)(c_4p + 1)}{1 + c_5pq} \\ &\approx \frac{q(c_3q^2 + c_2q + c_1)(c_4p + 1)}{1 + c_5pq} \end{aligned} \quad (2.16)$$

where c_0, c_1, c_2, c_3, c_4 , and c_5 are constants. It is found from experiments that these constants depend on the tuning fork probe configuration, and once the tuning fork probe is made, they remain the same when an extra mass is added to the prongs. We can also neglect c_0 because it is insignificantly small as compared to the other coefficients. These parameters can be obtained from any set of experimental data at the resonance frequency w_{11} .

Using the model given in (2.5), (2.6), and (2.16), the quality factor for unbalanced

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tuning fork probe, denoted as $Q_{unbalanced}$, can be approximated by

$$Q_{unbalanced} = \frac{4c_1(1 + 2q - \frac{k}{2\alpha}q^2)(1 + c_5pq)}{((\frac{k}{\alpha})q^2 + 8q + 4)(c_3q^2 + c_2q + c_1)(c_4p + 1)(1 + q)}Q_0 \quad (2.17)$$

where Q_0 denotes the Q-factor of a bare tuning fork without the attached probe. It is given by $Q_0 = \frac{1}{\gamma} \sqrt{\frac{k}{3m}}$ [26] where m denotes the effective mass of a prong of a bare tuning fork.

Next, we derive the Q-factor of the balanced tuning fork probe obtained by adding appropriate extra mass on the free prong of the probe. If we denote the initial unbalanced status by p and q , the effective masses after balancing are given by $m_1 = m_2 = m(1 + 2q)$ and the damping ratios satisfy $\gamma_1 = \gamma_2$. The increase in the effective mass for the tuning fork is based on the increase in q . For the balanced oscillators, the asymmetry mode z_{11} disappears, and only the symmetry mode remains. The symmetry mode is governed by the equation,

$$\ddot{z}_2 + \gamma\dot{z}_2 + w_{22}^2 z_2 = F_m e^{-j\omega t} \quad (2.18)$$

where $w_{22}^2 = \frac{k+2\alpha}{m(1+2q)}$, and $F_m = \frac{F}{m(1+2q)}$.

Solving the equation by substituting $z_2 = z_{21} \exp(-j\omega t)$, we obtain

$$z_{21} = \frac{F_m}{w_{22}^2 - \omega^2 - j\gamma\omega} \quad (2.19)$$

$$|z_{21}|^2 = \frac{F_m^2}{(w_{22}^2 - \omega^2)^2 + (\gamma\omega)^2} \quad (2.20)$$

Thus, the resonance frequency is given by w_{22} . After several algebraic manipulations, the FWHM of z_{21} , denoted as Δw_{22} , can be obtained as $\Delta w_{22} = \gamma\sqrt{3}$.

Thus, by definition, the Q-factor after balancing is obtained as

$$Q_{balanced} \triangleq \frac{w_{22}}{\Delta w_{22}} = \frac{1}{\gamma \sqrt{(1+2q)}} \sqrt{\frac{k}{m}} = \frac{1}{\sqrt{(1+2q)}} Q_0. \quad (2.21)$$

Compared to (2.17), the improvement in the Q-factor can be expressed by

$$\frac{Q_{balanced}}{Q_{unbalanced}} = \frac{(\frac{k}{\alpha} q^2 + 8q + 4)(c_3 q^2 + c_2 q + c_1)(c_4 p + 1)(q + 1)}{4c_1(1 + 2q - \frac{k}{2\alpha} q^2)(1 + c_5 p q) \sqrt{(1 + 2q)}} \quad (2.22)$$

It can be seen that the Q-factor of the balanced probe is improved. Take a typical tuning fork as an example. Before attaching the probe, the tuning fork has a Q-factor of 11000, and after attaching a probe, the Q-factor of the tuning fork probe drops to 5170. By fitting the frequency curves, it is found that the attachment of the probe creates a 4% difference in effective masses and 50% in damping ratios, *i.e.*, $q = 0.04$ and $p = 0.5$. The coefficients in (2.16) take values of $k = 11.78$ kN/m, $\alpha = 8.9$ kN/m, $c_1 = 0.9009 \times 10^{-4}$, $c_2 = 2.01 \times 10^{-5}$, $c_3 = 0.0606$, $c_4 = 0.93$, and $c_5 = 7.98$, respectively. With these values, the Q-factor of the tuning fork can be improved by a factor of two after balancing, according to (2.22). The measured Q-factor for the balanced tuning fork probe is 10781.

2.6 Experiments for Q-factor Modelling

Using other tuning forks, various experiments are conducted to verify the theoretical model and the improvement in the Q-factor. The set-up for measuring the responses and the Q-factor of a tuning fork probe is shown in Figure 2.1 where the tuning fork is excited electrically and the packaging capacitance of the tuning fork is compensated by inverting the current of a tunable capacitor as suggested in [50]. In this series of experiments, the input excitation source for the tuning fork is 10 mV, the resistor

used in the current to voltage amplification circuit is chosen as $3.3\text{ M}\Omega$, and the step size of frequency sweeping is 0.1 Hz .

2.7 Validation of the Q-factor Model

We first take a bare tuning fork and measure its frequency response and this is shown in Figure 2.7. Then we calculate the system parameters in (2.5) and (2.6) by using a least-squares approach to fit the frequency response. Then, we attach the probe on the tuning fork. We measure the frequency responses and calculate the system parameters again. We also measure the Q-factor and calculate the asymmetric and symmetric modes. Using (2.16), we determine the constants c_i (for $i = 1, 2, 3, 4, 5$) as $c_1 = 1.1092 \times 10^{-4}$, $c_2 = 1.458 \times 10^{-4}$, $c_3 = 0.1317$, $c_4 = 0.931$ and $c_5 = 5.981$. We repeat the measurement and calculation by adding an extra mass to the same prong with the attached probe. The measured and fitted frequency responses are shown in Figure 2.7. The curves show that the proposed models (2.5) and (2.6) fit the measurement data.

Figure 2.7: Frequency responses of the tuning fork probe under different unbalancing scenarios. (Dotted lines: Experimental data; Solid lines: Calculated from model)

Figure 2.8 depicts the 3-D plot of the Q-factors measured each time when an extra

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mass is added. These Q-factors are highlighted in a projection of the 3D distribution on the $p = 0$ plane. As a comparison, the figure also includes a 3-D plot of Q-factors with respect to p and q which characterize different unbalancing scenarios. In order to validate the model, the theoretical Q-factors are calculated from model (2.17) with the coefficients taking the values obtained above. The calculated Q-factors are plotted into a mesh plot to fit the measured ones. The fitting obtains an RMSE of 285. This big RMSE value is due to the large values in the Q-factors. Thus, the fitting result is considered as good fitting results. This validates that the model given by (2.5), (2.6), and (2.16) can provide good characterization of the Q-factor of tuning fork probe.

Figure 2.8: Experiment data and calculation results of the Q factors under different unbalanced scenarios.

Another point worthy of mentioning is that the measured Q-factors do not fall on any cross-sectional plane along any fixed p values of the 3-D plot in Fig 2.8. This means that by adding an extra mass on the prong of the tuning fork, it influences not only the effective masses but also the damping ratios of the coupled oscillators. This

explains the discrepancy of the model in [57] where only q is considered.

2.8 Q-factor Improvement by Balancing the Tuning Fork Probe

To illustrate Q-factor improvement through balancing the prongs of the tuning fork probe, we continue the above experiment by gradually adding extra masses to the free prong of the tuning fork probe. The method of adding the extra mass is discussed in section 2.10.4. Similarly, we measure the Q-factors and calculate the corresponding values of p and q by fitting the frequency response each time an extra mass is added. The obtained values are depicted in Figure 2.9. The Q-factors calculated from the model is also plotted in the figure as a reference. They are calculated by using (2.17) with all the same constants c_i (for $i = 1, 2, 3, 4, 5$) given in section 2.7. But Q_0 is now replaced by $Q_{balanced}$ with q taking the value of the added mass in the last experiment in section 2.7.

These values demonstrate improvement in the Q values after the balancing was done by adding an extra mass on the prong. The Q-factor of the tuning fork before balancing was 1336, and it is 4189 after balancing, giving an improvement by a factor of 3! Continuing the balancing process, the improvement in the Q-factor can go up by more than three times.

The balancing process is done over a series of tuning forks and the results are summarized in Table 2.2. For each tuning fork, a SNOM probe is first mounted on one prong of the tuning fork. Then, the constants c_i are determined through frequency response fitting. Based on the constants obtained, the maximum achievable Q-factor is calculated. Next, a drop of glue is added to the free prong of the tuning fork. An

Figure 2.9: Improved the Q-factors by balancing the free prong of the tuning fork probe.

improvement of the Q-factor is seen in all the probes and the improvement can be more than 10 times.

Table 2.2: Improvement of Q-factor for different tuning forks after a drop of glue is added to the free prong

Tuning Fork	1	2	3	4	5	6
Q-factor after mounting probe	329	108	2148	1266	530	455
Q-factor after balancing	2183	1487	3727	4452	3403	7391
Theoretical Maximum Q-factor	8695	7655	10285	9148	9310	8643

2.9 AFM Topography Imaging with the Balanced Tuning Fork Probe

The effectiveness of the improved tuning fork probe is further demonstrated in AFM imaging. A traditional tuning fork probe and its balanced version are respectively used in a home-made AFM system to image a calibration sample TDG01/Au from NT-MDT [141]. The sample is a smooth periodic gratings of 298 nm pitch as shown by its SEM image in Figure 2.10. Figure 2.10 also presents the AFM images obtained respectively by the traditional probe and its balanced version, and the line scans of the AFM images are shown in Figure 2.11. Comparing the line scan curves, the balanced tuning fork probe has demonstrated a much smoother and more consistent topography.

Figure 2.10: Comparing the AFM images using unbalanced and balanced tuning forks

Figure 2.11: Line scan of the AFM images

2.10 Implementation Issues of the Tuning Fork SPM System

The implementation of high sensitivity SPM system using the tuning fork probe has several problems. These problems are discussed in the following sub-sections.

2.10.1 Transimpedance Amplifier for Tuning Fork Probe

The choice of the operation amplifier (Opamp) is crucial in the sensing circuit as it determines the minimum noise level of the tuning fork feedback signal. The noise of the Opamp consists of the input noise current, i_n , and the input noise voltage, v_n [114]. The noise parameters vary for different types of transistors. In general, Opamps are classified into 2 main categories: the field-effect transistor (FET) and the Bipolar Junction Transistor (BJT). The former has a higher input voltage noise compared to the latter. However, FET has a lower input noise current.

In our set-up, LF353 (FET Opamp) and OPA27 (BJT Opamp) [140] are considered.

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The input noise of the Opamps are $i_n = 0.01 \text{ pA}/\sqrt{\text{Hz}}$, $v_n = 25 \text{ nV}/\sqrt{\text{Hz}}$ and $i_n = 1.7 \text{ pA}/\sqrt{\text{Hz}}$, $v_n = 3.2 \text{ nV}/\sqrt{\text{Hz}}$, respectively. Based on the input noise, the total output noise power of the transimpedance amplifier is calculated and compared. The output noise powers are $10.1 \text{ fV}/\sqrt{\text{Hz}}$ and $2.89 \text{ pV}/\sqrt{\text{Hz}}$ respectively. Thus, the SNR of the FET amplifier will be 24 dB more than the BJT amplifier in the transimpedance circuit.

For the transimpedance amplifier design, we can conclude that the lower input noise current Opamps has significantly lower total output noise. Thus, FET Opamp is a better choice for the transimpedance pre-amplifier circuit.

Also, the stability of the op-amp can be an issue for the amplifier. From the specifications of the operational amplifier, the open loop gain has a 20 dB/dec slope response which corresponds to an internally compensated amplifier. The amplifier has an internal pole very far from the 3 dB roll off. The compensation will ensure the stability of the amplifier by fixing the phase margin at about 60° . This stability will ensure the feedback pole is more than 10 times greater than the open-loop roll-off frequency. Thus, the resistor used in the transimpedance amplification circuit is chosen as $R = 1 \text{ M}\Omega$.

2.10.2 PID Controller for Separation Control

The PID controller is implemented for the separation control. The controller consists of a series of operational amplifiers, resistor arrays, IC switches and capacitors. The major problem of the PID controller hardware is the saturation voltage of a practical integrator due to the unbalanced offset voltages at the input end of the integrator. Once the control loop is closed, the saturated output voltage of the integrator creates a surge of 120V at the input of the Z piezo. This results in two unfavorable situations. The lifespan of the piezo will be shortened due to the sudden switching effects and

the probe will crash into the sample.

Hence, a 'soft start' algorithm is developed to control the piezo input voltage to be near 0V before closing the control loop. This can be done by altering the input voltage of the integrator. The input voltage of the integrator is basically the input error of the PID controller, which is the difference between the set point signal and the tuning fork feedback signal. Since the control loop is not closed, the signal from the tuning fork feedback is always constant. Thus, in order to control the polarity and magnitude of the input voltage of the integrator, the soft start algorithm will adjust the set point signal. Once the output signal of the PID controller reaches ± 0.01 V, the algorithm closes the control loop which will prevent a surge in the Z-piezo input voltage. Once the loop is closed, the algorithm automatically switches into the approaching mode and the tuning fork probe will approach the sample surface.

2.10.3 Noise Shielding and Grounding

Noise coupling can occur at various points of the detection system, especially the capacitive coupling of noise into flying cables connecting the system to the circuit. This type of noise coupling is very pronounced in high input impedance circuits. The most significant noise source is the tuning fork probe sensing current, since the pre-amplifier uses a high impedance circuit. Thus, in order to minimize the noise coupling effects, a shielded cable is used. The shielding is grounded at the input end only to prevent ground loops. Furthermore, an electrical isolator ADUM1100 is used in the circuit to remove the ground loops in the system. The grounding of the devices are carefully laid to prevent any possible ground loops. Metal enclosures are also used for EMI shielding.

2.10.4 Probe Mounting and Balancing Techniques

The mounting of the probe on the tuning fork is quite a tedious process. In order for the tuning fork probe to be sensitive, the fiber probe must maintain its rigidity. The protruding length must be less than $300\text{ }\mu\text{m}$ as measured from the tuning fork end face [28]. Thus, the placement of the probe is usually done under a 10X microscope. Furthermore, a jig is made to hold the fiber probe for the adjustment. Once the fiber probe is in place, glue is applied. The type and the amount of glue used for bonding also plays a very important role. Usually, the apparatus used for transferring the glue is a piece of wire-wrapping wire. In this case, the cyanoacrylate glue is preferred as the glue is liquid based with low viscosity. The low viscosity enables the glue to slip into the interfacing gaps between the tuning fork prong and the probe through surface tension. This minimizes the amount of glue needed and maximizes its bonding area.

Throughout the whole chapter, the addition of masses to the tuning fork prong is frequently mentioned. Here, the experimental issues of adding the extra masses are discussed. The addition of extra masses is simulated based on the amount of cyanoacrylate glue used. Every drop of glue is transferred to the tuning fork prong by using a wire with a curl head. This curl head is fabricated by rolling the wire over the compass needle. This curl head is purposely made so that the head acts as a mini spoon. The glue will flow to the prong once the curl head touches it. This is considered as one droplet of glue. After each droplet is added, the glue will be left to cure. The curing process takes about one hour and should be maintained. Then, the Q-factor is tested. Since the additional glue volume is difficult to control, the mass added will not be equal. This process should be done under a 10X microscope.

From Table 2.2, the Q-factor shown is based on the placing of one drop of glue on the other prong. It is observed that the theoretical Q-factor after balancing is much higher. Thus, it is possible to add more droplets of glue on the other prong. However,

practically, balancing the tuning fork by using droplets of glue is very inconsistent as there is no control over the volume of glue used. An over balanced situation will cause the Q-factor to drop again. In order to prevent this, the balancing process usually stops once the Q-factor reaches half of the maximum theoretical Q.

2.11 Conclusion

In conclusion, we have established that the dynamics of a tuning fork probe can be well approximated by the proposed two-coupled oscillators with unbalanced effective masses and damping ratios, while all the other coupling coefficients of the coupled oscillator remain constant. The model parameters can be easily estimated by a simple frequency-domain system identification approach. The model, together with the approach used to obtain the model, is not only able to quantify the effect of probe attachment, it can also quantify practically the noise performance and the sensitivity of a tuning fork probe sensing system. In addition, the model is used to formulate a theoretical Q-factor model to characterize the Q-factors during the process of balancing the tuning fork prongs with extra masses added to the probe. Experimental results have validated the proposed model and demonstrated the effectiveness of the proposed approach. Since the proposed approach only exploits the balancing of the two prongs of the tuning fork, it can also be incorporated into all existing tuning fork SPM systems that use only a single prong of the tuning fork to further improve the Q-factors of these systems. Thus, we are able to attain sensitivity improvement of at least seven times for SPMs. The balanced tuning fork has been implemented on the system and the effectiveness of balancing is demonstrated. Finally, several implementation issues of the SPM system are discussed. By addressing all these issues, a highly sensitive tip-sample separation SPM system has been demonstrated.

Chapter 3

Improved Phase Lock-in Detection for SNOM

In the previous chapter, a new tuning fork probe is devised and it is more sensitive to the probe-sample interaction. It encodes the probe-sample separation into the electric signal. However, the electric signal is still weak as compared to the various ambient noises. In this chapter, the focus is turned to addressing signal detection methods that can be used to extract the weak electric signal. First, an improved detection method based on phase lock-in detection is proposed to optimize the sensitivity of the output of the tuning fork probe. Then, a general design scheme of a highly sensitive and fast phase lock loop detection is presented.

3.1 Phase Compensation for Sensitivity Improvement of Tuning Fork Detection System

3.1.1 Introduction

Lock-in detection is an ubiquitous method used in most SPM systems due to its high sensitivity. Although there are many different demodulation methods, the detection sensitivity is lower when compared to the lock-in method [62]. Hence, the lock-in detection methods are always preferred for meeting high sensitivity requirements.

There are four types of signals from the lock-in demodulation. These signals are known as in-phase component (X), quadrature component (Y), magnitude and phase. The X and Y components are obtained by multiplying the tuning fork signal with a reference and a 90° phase shifted reference, respectively. The magnitude is the square root of the sum of squares of X and Y , while the phase is the arc tangent of the quotient of Y over X . These demodulated components can be permuted in terms of their sums or product for optimal sensitivity in specific applications. In the separation control of the SPM, the two commonly used signals are the X signal [30] [63] and the magnitude signal [129] [131]. Although the X signal is easier to implement, the response of the tuning fork may suffer from the inconsistency of phase change, which will lead to poorer sensitivity. This unknown phase shifting is due to the mounting of the tuning fork probe. This effect also occurs on the Y signal. On the other hand, the magnitude signal is independent of the phase inconsistency of each tuning fork [64]. However, this detection method has some drawbacks in regards to the SNR when the summation process of the X and Y signals are unbalanced [130]. This is a very common problem in lock-in detection. Thus, post-detection methods to optimize the sensitivity using signal combination are have been proposed [127].

To this end, a phase compensation method based on gain altering of the combination of the X and Y signals is used. It is shown that the detection method improves the sensitivity of the tuning fork system. The effectiveness of the method is proven experimentally by performing a linescan over a step grating sample.

3.1.2 Sensitivity of the Tuning Fork Output

The sensitivity of the lock-in detection system of the tuning fork probe is presented in this section. The output signals of the lock-in amplifier can be denoted as

$$\begin{aligned} R(w) &= |H_{tf}(jw)|, & \theta(w) &= \arg(H_{tf}(jw)) \\ X(w) &= |H_{tf}(jw)| \cos(\arg(H_{tf}(jw))), & Y(w) &= |H_{tf}(jw)| \sin(\arg(H_{tf}(jw))) \end{aligned} \quad (3.1)$$

where $H_{tf}(jw)$ is the transfer function of the tuning fork, and R , θ , X and Y are the magnitude, phase, in-phase component and the quadrature component respectively. These parameters of the free running tuning fork can be estimated from experimental data. Here, we obtained a fourth order tuning fork transfer function experimentally and it is expressed as,

$$H_{tf}(jw) = \frac{-aw^2 + jbw + c}{w^4 - jd w^3 - ew^2 + jfw + g} \quad (3.2)$$

where $a = 1.021 \times 10^6$, $b = 1.279 \times 10^{10}$, $c = 1.010 \times 10^{17}$, $d = 1.272 \times 10^4$, $e = 1.391 \times 10^{11}$, $f = 5.348 \times 10^{14}$, $g = 4.051 \times 10^{21}$. Using these parameters, the magnitude, phase, X and Y signals are plotted in Figure 3.1.

In order to have a significant change in the amplitude during the interaction with the sample, the slope of the output graph is considered. Hence, the area of interest is set to be above the 3 dB point of the amplitude graph (Figure 3.1a). The corresponding frequency ranges from 32.406 KHz to 32.438 KHz.

Figure 3.1: Comparing the different types of output signals

During the separation control of the SPM, it is common to set a constant operating frequency, w_m . The index of the operation frequency is usually user defined at the free running (nominal) condition. In this section, we access the sensitivity based on a fixed operating frequency. The operating frequency defined here is based on the resonance of the Y-output graph, and is obtained by,

$$\frac{\partial Y}{\partial w} = 0. \quad (3.3)$$

The calculated nominal frequencies are denoted as w_{mx} and w_{my} respectively. The

slope of the frequency-domain graphs at the detector output denotes the sensitivity of the tuning fork sensor. Simply, the slope at each point is obtained by differentiating (3.1) with respect to w . The slopes are plotted in Figure 3.2 within the region of interest. It is found that either the X or Y component has a higher sensitivity as compared to the magnitude. Hence, it is sufficient to use either the X or Y output signal as a control feedback for the SPM separation control. Under nominal conditions, the sensitivity of the X signal at $w_{mx} = 32.4273$ KHz is higher than the sensitivity of the magnitude.

However, the above analysis is based on a free running tuning fork. When using the tuning fork probe to detect the force, the probe has to approach the sample surface. During the approach, the tuning fork response is perturbed, and the transfer function will be altered. Since the operating frequency of the tuning fork is fixed during the operation, the sensitivity of the sensor may defer when using the approach. Thus, the sensitivity may not be the optimal during the interaction and the scanning process. In order to solve this problem, we proposed a phase compensating detection method to estimate the unknown phase shift and to compensate for this uncertainty.

3.1.3 Phase Compensation Lock-in Detection of Unknown System

Here, we denote Z as the output of the tuning fork probe from the detection circuit. During the interaction with the sample surface, the Z output can be expressed as,

$$\hat{Z} = |\hat{H}_{tf}(jw)| \cos(\arg(\hat{H}_{tf}(jw))) \quad (3.4)$$

where $\hat{H}_{tf}(jw)$ is an unknown transfer function which depends on the interaction forces with the sample surface. The magnitude $|\hat{H}_{tf}(jw)|$ has no significant contribu-

Figure 3.2: Sensitivity plot of all outputs. Circle line: Magnitude. Star line: Phase. Triangle line: X component. Square line: Y component.

tion to the compensation effects as it only has the magnitude information. It can be normalized and interpreted as a gain factor. For simplicity, $\arg(\hat{H}_{tf}(jw))$ in (3.4) can be replaced with $\hat{\theta}$. In order to achieve the highest possible sensitivity, the phase is optimized. We insert the control parameter, α into (3.4). Thus, we can express the output signal as,

$$\hat{Z} = |\hat{H}_{tf}(jw)| \cos(\arg(\hat{H}_{tf}(jw)) + \theta_{compensate}) \quad (3.5)$$

$$\hat{R}(\sqrt{\alpha} \cos \hat{\theta} + \sqrt{1 - \alpha} \sin \hat{\theta}) \quad (3.6)$$

To optimize the Z output, the maximum value of the slope of (3.6) is obtained with

respect to α at a fixed operating frequency, w_m ,

$$\begin{aligned} \frac{\partial^2 \hat{Z}}{\partial w \partial \alpha} \Big|_{w_m} &= \frac{\partial \hat{R}}{\partial w} \Big|_{w_m} \left(\frac{1}{2\sqrt{\alpha}} \cos \hat{\theta} - \frac{1}{2\sqrt{1+\alpha}} \sin \hat{\theta} \right) \\ &\quad + \hat{R} \left(-\frac{1}{2\sqrt{\alpha}} \sin \hat{\theta} - \frac{1}{2\sqrt{1+\alpha}} \cos \hat{\theta} \right) \frac{\partial \hat{\theta}}{\partial w} \Big|_{w_m} \end{aligned} \quad (3.7)$$

In order to optimize the sensitivity based on α at the fixed wavelength, we equate (3.7) to zero. After some algebraic manipulations, the control parameter can be expressed as,

$$\alpha = \frac{(\cos \hat{\theta} \frac{\partial \hat{R}}{\partial w} \Big|_{w_m} - \hat{R} \sin \hat{\theta} \frac{\partial \hat{\theta}}{\partial w} \Big|_{w_m})^2}{(\cos \hat{\theta} \frac{\partial \hat{R}}{\partial w} \Big|_{w_m} - \hat{R} \sin \hat{\theta} \frac{\partial \hat{\theta}}{\partial w} \Big|_{w_m})^2 + (\sin \hat{\theta} \frac{\partial \hat{R}}{\partial w} \Big|_{w_m} - \hat{R} \cos \hat{\theta} \frac{\partial \hat{\theta}}{\partial w} \Big|_{w_m})^2} \quad (3.8)$$

Thus, the control signal can be used to compensate for the transfer function change.

3.1.4 Simulation and Experimental Results after Phase Compensation

Here we study the compensation circuit when the tuning fork probe is approaching the sample surface. We assume that the tuning fork model is slightly disturbed with a 0.05% change in the tuning fork spring constant and a 1% change in the damping ratio at any given operating point. This assumption is made because the tuning fork probe may experience forces in both the shear and normal directions due to imperfect mounting or at different separation displacement. The phase compensation is done by fixing the operating frequency at w_{mx} . Using equation (3.8), we can obtain $\alpha|_{w_{mx}} = 0.120$. From Figure 3.3, we can see that the simulation results show significant improvements in the slope of the output graph. Thus, by using the known free running tuning fork parameters, the same controlling feedback, $\alpha|_{w_{mx}}$ can be used to improve the sensitivity.

The feedback circuit can be implemented by using a feedback gain based on (3.8). The

experimental setup as shown in Figure 3.4 is used to demonstrate the effectiveness of compensation improvement. The variable resistor is used to tune the required $\alpha|_{w_{mx}}$ values. The experimental results and simulation calculations on the improvements of the free running tuning fork are shown in Figure 3.5. Evidently, the line scan shows a significant improvement when using the compensated circuitry.

Figure 3.3: Simulation results for estimated approach frequency response curves. Circle line: Before compensation. Solid line : After compensation

Figure 3.4: Experimental set-up for the detection method

Figure 3.5: Simulation and Experimental results of the detection circuit. (Before compensation - Dashed line: Simulated calculation; Cross line: Experimental data. After compensation - Solid line: Simulated calculation; Square line: Experimental data. Left Insert: Line Scan grating using uncompensated circuit. Right Insert: Line Scan grating using compensated circuit.)

3.2 Phase Locked-in Loop Design with Pre-specified Transient Performance

3.2.1 Introduction

Realizing that lock-in amplifier is the key enabling technology needed for the nano-scale tip-sample separation, we shall focus our attention on the lock-in techniques. In this section, a phase locked-in loops (PLL) scheme and the design of given specifications are presented. The proposed design suggests the imposition of an additional control signal on the normal input to the variable controlled oscillator (VCO) of the phase locked-in loop. Based on the design, the second method of Lyapunov is then used to construct the additional control signal and the loop filter parameters of the PLL. The proposed design scheme is better than the conventional PLL design results because of our phase locked-in loop is designed with pre-specified performance. The design scheme is based on nonlinear model of the PLL and it is applicable to the design of high order PLLs. Simulations results are given to demonstrate the effectiveness of the proposed scheme.

The basic building block of the lock-in detection is the phase locked loop structure, which consists of a phase detector, a loop filter, and a VCO unit. The PLL tracks the input signal precisely and so the signal containing the measurerant can be extracted quickly and accurately. Indeed, the lock-in capabilities is primarily limited by the speed performance of the PLL. Since SNOM is a scanning microscopy, the time required for acquisition is very critical for time-resolved observations. To this end, many studies on the performance of a PLL have been conducted since 1932 when PLL was invented [123], particularly the 2nd order linear [124] and non-linear PLLs [122].

Here, we shall present the studies of a PLL with pre-specified transient performance based on a non-linear model. The stability of the system was first shown based on the second method of Lyapunov [126][125]. Then, the PLL design can be studied using the Lyapunov function and a feedforward control signal from the loop filter output to the VCO is proposed. The numerical analysis shows a significant improvement in the transient performance in the PLL.

3.2.2 Nonlinear Model of the PLL

A basic PLL consists of three main components: a phase detector (PD), a loop filter (LF), and a voltage controller oscillator (VCO), as shown in Figure 3.6. The input signal of the PLL and the output signal of the VCO are respectively given by:

$$v_i = A_i \sin(\omega_i t + \theta(t)) \quad (3.9)$$

$$v_o = A_o \cos(\omega_o t + \phi(t)) \quad (3.10)$$

where A_i and A_o are amplitudes; ω_i and ω_o are the frequency to be tracked and the frequency output of the VCO, respectively; and $\theta(t)$ and $\phi(t)$ are the phase to be detected and the phase change generated by the VCO, respectively. The basic objective of a PLL is to control the VCO such that its output frequency and phase can follow those of the input signal. The input signal is usually expressed in terms of $\omega t + \theta$. However, the control signal induces a frequency change for the VCO, which is a property of the VCO, so the phase change is to be obtained by integrating the frequency change. The details of the PLL modeling can be found in [122].

The PD is usually a multiplier, and its output is

$$v_d = \frac{A_d}{2} [\sin(\omega_i t + \omega_o t + \theta(t) + \phi(t)) + \sin(\omega_i t - \omega_o t + \theta(t) - \phi(t))] \quad (3.11)$$

where $A_d = K_d A_i A_o$. This signal is fed into the loop filter which acts as a low pass filter to filter out the higher frequency component of $(\omega_i + \omega_o)$. The loop filter is generally an n th order linear system given by $\frac{B(s)}{A(s)}$ where $A(s) = s^n + a_1 s^{n-1} + \dots + a_{n-1} s + a_n$ and $B(s) = b_0 s^m + b_1 s^{m-1} + \dots + b_{m-1} s + b_m$. The output of the loop filter is used to control the VCO which can be modelled as an integrator with an assumed constant gain. This model can be further simplified under two practical cases characterized by

- (i) The higher frequency term is attenuated by the low pass filter.
- (ii) The frequency of the reference and the input signal are approximately equal.

Under these conditions, the output of the phase detector is expressed by

$$v_d = \frac{A_d}{2} \sin(\theta(t) - \phi(t)). \quad (3.12)$$

Therefore, the dynamic model of a basic PLL can be illustrated as in Figure 3.6. K_p and K_v are the proportional and integral gains respectively.

Figure 3.6: Schematic of a PLL

The design of a PLL can be described as one of constructing the control signal γ and choosing the parameters of the loop filter such that the output of the VCO can

follow the input signal so that the phase error vanishes. In the conventional design, the parameters of the loop filter are chosen by using a linearized PLL model. When a nonlinear model of the PLL is used, the control design would be difficult and the performance of the system can hardly be analyzed. To overcome this problem, we propose a new PLL design scheme in this section. The scheme introduces a dedicated signal γ in addition to the output of the loop filter to control the VCO so that we can make use of the second method of Lyapunov to design the loop filter to meet given performance specifications for the PLL.

3.2.3 Design of a PLL with a Low Order Loop Filter

For clarity of illustration, the derivation of the proposed design is illustrated with a second order PLL. First, we consider the case where the loop filter in the first order and does not have a zero. In this case, the loop filter is given by $\frac{1}{s+a_1}$. With this loop filter, the PLL becomes a second order system. The differential equations of a 2nd order PLL without zero can be evaluated as

$$\dot{x} = K_p \sin \psi - a_1 x \quad (3.13)$$

$$\dot{\psi} = -K_v(x + \gamma) \quad (3.14)$$

where $\psi = \theta - \phi$ and x is the state variable of the loop filter.

To analyse the stability of this nonlinear model, we apply the second method of Lyapunov. A suitable Lyapunov function is given by

$$V = \int_0^\psi \sin(\sigma) d\sigma + \frac{1}{2} p x^2 = 1 - \cos(\psi) + \frac{1}{2} p x^2, \quad p > 0. \quad (3.15)$$

With (3.13) and (3.14),

$$\begin{aligned}
 \dot{V} &= \sin(\psi)\dot{\psi} + px\dot{x} \\
 &= \sin(\psi)(-K_v x - K_v \gamma) + px(K_p \sin(\psi) - a_1 x) \\
 &= -a_1 p x^2 + \sin(\psi)x(pK_p - K_v) - K_v \gamma \sin(\psi).
 \end{aligned} \tag{3.16}$$

Next, we consider the case where the loop filter has a zero, *i.e.*, the loop filter is given by $\frac{s+b_1}{s+a_1}$. The differential equations of a 2nd order PLL with the filter loop is thus expressed by

$$\dot{x}_1 = -a_1 x_1 + K_p \sin \psi, \tag{3.17}$$

$$\dot{\psi} = K_v a_1 x - K_v K_p \sin \psi - K_v b_1 x - K_v \gamma. \tag{3.18}$$

Using again the Lyapunov function (3.15) and after further simplification, we arrive at the following equation:

$$\begin{aligned}
 \dot{V} &= \sin \psi (-K_v a_1 x - K_p K_v \sin \psi - K_v b_1 x - K_v \gamma) + px(K_p \sin \psi - a_1 x) \\
 &= -K_p K_v \sin^2 \psi - a_1 p x^2 + \sin \psi x (pK_p - a_1 K_v - K_v b_1) - K_v \gamma \sin \psi.
 \end{aligned} \tag{3.19}$$

Compared to (3.16), the first order derivative of the Lyapunov function has a similar form. To achieve the required transient performance of the PLL, it suffices to obtain

$$\dot{V} \leq -\alpha V \tag{3.20}$$

with which we can choose α properly so that the PLL achieves the required performance in addition to stability.

Motivated by this, the control signal γ is chosen to satisfy

$$\gamma = a_0 \tan \frac{\psi}{2}, \quad (3.21)$$

where $\psi \in (-\pi, \pi)$.

First, we establish the stability of the PLL. To this end, we choose the parameter p in the Lyapunov function as $p = \frac{K_v}{K_p}$. Using (3.16) and (3.21), i.e. for the case where the loop filter has no zero, we have

$$\begin{aligned} \dot{V} &= -[a_1 p x^2 + 2a_0 p K_p \sin^2 \frac{\psi}{2}] \\ &= -2a_1 [\frac{1}{2} p x^2 + K_v \frac{a_0}{a_1} \sin^2 \frac{\psi}{2}]. \end{aligned} \quad (3.22)$$

Then, we choose $2a_1 \leq a_0 K_v$, which results in

$$\begin{aligned} \dot{V} &\leq -2a_1 [\frac{1}{2} p x^2 + 2 \sin^2 \frac{\psi}{2}] \\ &\leq -2a_1 [\frac{1}{2} p x^2 + 1 - \cos \psi] \\ &\leq -2a_1 V. \end{aligned} \quad (3.23)$$

This expression assures that the transient of the system is bounded by the magnitude of a_1 because the solution to this differential equation can be as $V(t) \leq V(0)e^{-2a_1 t}$. Thus, the transients of the PLL can be controlled by properly choosing a_1 and a_0 to satisfy $2a_1 \leq a_0 K_v$ and the required damping rate of the transients.

We can perform similar procedures to obtain the control design for the case when the loop filter has a zero. Applying (3.19) and (3.21), and choosing the following

conditions,

$$a_0 K_v \geq 4a_1 \quad (3.24)$$

$$a_1 p > 0 \quad (3.25)$$

$$K_p K_v > 0 \quad (3.26)$$

$$pK_p - K_v(a_1 + b_1) = 0 \quad (3.27)$$

Then,

$$\dot{V} = -K_p K_v \sin^2 \psi - a_1 p x^2 - a_0 \sin^2 \frac{\psi}{2} \quad (3.28)$$

$$\begin{aligned} &\leq -[a_1 p x^2 + a_0 \sin^2 \frac{\psi}{2}] \\ &\leq -2a_1 [\frac{1}{2} p x^2 + 2 \sin^2 \frac{\psi}{2}] \\ &\leq -2a_1 V. \end{aligned} \quad (3.29)$$

The transient performance of the PLL with a given transient damping rate can be controlled by using (3.24)-(3.27) to choose a_1 , a_0 , and b_1 .

3.2.4 Design of a PLL with Higher Order Loop Filter

In this section, we extend the proposed PLL design scheme to the design of a PLL with higher order loop filter. Firstly, this is done by adding an additional 1st order transfer function in series with the existing one, the differential equation of the 3rd

order phase-locked loop with a zero can be easily derived as

$$\dot{x}_1 = -a_1x_1 + K_p \sin \psi \quad (3.30)$$

$$\dot{x}_2 = -a_2x_2 + K_p \sin \psi \quad (3.31)$$

$$\begin{aligned} \dot{\psi} &= -K_v(y + \gamma) \\ &= -K_v(b_1 - a_2)y - K_vK_p \sin \psi - K_v\gamma \end{aligned} \quad (3.32)$$

where x_1 and x_2 are the state variables of the loop filter. We choose a similar Lyapunov function:

$$V = 1 - \cos \psi + \frac{1}{2}p_1x_1^2 + \frac{1}{2}p_2x_2^2, \quad \text{where } p_1, p_2 > 0. \quad (3.33)$$

Using the above equations (3.30)-(3.33), $\dot{V}$ can be simplified as follows:

$$\begin{aligned} \dot{V} &= -p_1a_1x_1^2 - p_2a_2x_2^2 - K_pK_v \sin^2 \psi + p_1x_1K_p \sin \psi \\ &\quad + x_2 \sin \psi [p_2K_p - K_v(b_1 - a_2)] - K_v\gamma \sin \psi. \end{aligned} \quad (3.34)$$

To achieve stability of the PLL design with $\gamma = a_0 \tan \frac{\psi}{2}$, the following conditions shall apply:

$$p_2K_p = K_v(b_1 - a_2) \quad (3.35)$$

$$K_v - \frac{p_1}{2} > 0 \quad (3.36)$$

$$a_1 - 1 \geq 0 \quad (3.37)$$

$$a_1 \geq a_2 \quad (3.38)$$

$$a_0K_v \geq 2a_2 \quad (3.39)$$

Then,

$$\begin{aligned}\dot{V} &= -p_1 a_1 x_1^2 - p_2 a_2 x_2^2 - K_p K_v \sin^2 \psi - a_0 K_v \sin^2 \frac{\psi}{2} \\ &\leq -2a_2 V.\end{aligned}\quad (3.40)$$

From this expression, we can see that the transients of the PLL system is directly determined by a_2 . The other parameters can be chosen according to the conditions in (3.35)-(3.39).

Now, we consider a higher order loop filter given by $\frac{B(s)}{A(s)}$. The loop filter can be implemented in state space, with output y , as follows:

$$\dot{X} = \mathbf{A}X + \mathbf{B}u \quad (3.41)$$

$$y = \mathbf{C}X \quad (3.42)$$

where $X = [x_1 \ x_2 \ \dots \ x_n]^T$, $\mathbf{B} = [1 \ 1 \ \dots \ 1]^T$, $\mathbf{A} = \begin{pmatrix} -a_1 & 0 & \dots & 0 \\ (b_1 - a_1) & -a_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ (b_{n-1} - a_{n-1}) & 0 & \dots & -a_n \end{pmatrix}$,

and $u = K_p \sin \psi$.

Then, the output of the VCO is given by

$$\dot{\psi} = -K_v \mathbf{C}X - K_v u - K_v \gamma \quad (3.43)$$

where $\mathbf{C} = [b_1 - a_1 \ b_2 - a_2 \ \dots \ b_n - a_n]$.

For this general case, we consider the Lyapunov function,

$$V = 1 - \cos \psi + \frac{1}{2} X^T \mathbf{P} X \quad (3.44)$$

Following similar procedures, a PLL with given transient requirements can be designed by choosing $\gamma = a_0 \tan \frac{\psi}{2}$ and the loop filter with parameters satisfying

$$b_1 < a_1, b_2 < a_2, \dots, b_n < a_n \quad (3.45)$$

$$2X^T \mathbf{P} \mathbf{B} K_p - K_v \mathbf{C} X = 0 \quad (3.46)$$

For this system, the transients of the PLL can be characterized by $\dot{V} \leq V(0)e^{-a_n t}$.

3.2.5 Numerical Analysis

In this section, we present the numerical results to demonstrate the performance of the proposed PLL design. The numerical analysis are done by using MATLAB-Simulink. The model for the numerical analysis can be found in Appendix III. In the numerical simulations, we consider 2nd order and 3rd order PLLs. The performance of PLLs with the proposed design is compared with those with the conventional design method.

Test 1

Here, we use a 1st order loop filter without zero and setting $a_1 = 1$ while assuming different values of $a_0 = 2, 4, 8$ and 16 for all $t \geq 0$. The initial conditions $\psi(0)$ and $x(0)$ are set to zero. The simulation result is shown in Figure 3.7. It is observed that the improved system (solid line) has a faster locking response than the standard PLL (dashed line). It also shows that the locking time increases with higher values of a_0 .

Next, the transient response of PLL is simulated by fixing $a_0 = 2$ and varying a_1 subject to the condition $2a_1 \leq a_0 K_v$ being satisfied. The simulation result is shown in Figure 3.8. It is observed that the locking time improves with higher value of a_1 .

Figure 3.7: Comparison of transient response of 1st order loop filter with different values of a_0 . Cross line: $a_0 = 2$; Circle line: $a_0 = 4$; Square line: $a_0 = 8$; Diamond line: $a_0 = 16$.

Test 2

Now, we use a 1st order loop filter with a zero, and setting $a_1 = 1$, $b_1 = 2$ and $a_0 = 4$ for all $t \geq 0$. The simulation result is shown in Figure 3.9. It is observed that the improved system (solid line) has a faster locking response than the standard PLL (dashed line).

Test 3

In this case, we use a 2nd order loop filter with a zero, and setting $a_1 = 1.5$, $a_2 = 1$, $b_1 = 2$, and $a_0 = 4$ for all $t \geq 0$. The simulation result is shown in Figure 3.10. It is observed that the improved system (solid line) has a faster locking response than the standard PLL (dashed line).

Figure 3.8: Comparison of transient response of 1st order loop filter with different values of a_1 . Triangle line: $a_1 = 1$; Square line: $a_1 = 2$; Circle line: $a_1 = 5$.

Test 4

Here, we examine a 2nd order loop filter with two zeros, and setting $a_1 = 1.5$, $a_2 = 1$, $b_1 = 2$, $b_2 = 1.2$, and $a_0 = 4$ for all $t \geq 0$. The simulation result is shown in Figure 3.11. Again, it is observed that the improved system (solid line) has a faster locking response than the standard PLL (dashed line).

Finally, using a 2nd order loop filter with two zeros and with the above parameters, we examine the performance under different initial phase values. The different initial phase values are 0.5 rad (Triangle line), 1 rad (Square line) and 1.5 rad (Circle line). The results are shown in Figure 3.12.

Test 5

In this case, a 1st order loop filter is used with a gain saturation block in the feed forward path. The filter parameter is $a_1 = 10$ and the other parameters are $K_p =$

Figure 3.9: Transient response of 1st order loop filter with a zero. Solid line: Improved PLL; Dotted line: standard PLL

10 and $K_v = 20$. We let $a_0 = 4, 10$ and 100 to see the effects of the saturation of the gain. The saturation values are set to ± 1 . The results are shown in Figure 3.13. From the graphs, the unsaturated PLL performance for $a_0 = 100$ is shown in the triangle line, which can the performance can be increase arbitrarily. However, due to the gain saturation, the speed of the PLL is capped at the saturation line.

Test 6

In this test, we consider a 2nd order loop filter of a standard PLL are used for fast response. Typically, this filter loop has wider bandwidth. By considering the 2nd order loop filter parameters as $a_1 = 5K$, $a_2 = 1K$ and $b_1 = 2K$; and calculate the other parameters $K_p = 5K$, $K_v = 5K$ and $a_0 = 4$ to satisfy the conditions in the analysis. A 5 times improvement in transient response of the improved PLL is observed and the results are shown in Figure 3.14.

Figure 3.10: Transient response of 2nd order loop filter with a zero. Solid line: Improved PLL; Dotted line: standard PLL

3.3 Conclusion

We have presented a novel yet simple detection method of using phase compensation for optimizing the X output of the lock-in amplifier. The sensitivity is assessed at a fixed nominal operating frequency. Similarly, the Y output can also be compensated, but it will be redundant. The detection method has been experimentally verified and the detection system does give a better Q-factor, thus improving the sensitivity. This detection method has been demonstrated on a quartz tuning fork probe and can be extended into other types of SPM.

We have also addressed the speed performance of the PLL based on an additional control signal on top of the loop filter output to control the VCO of the PLL. With this design scheme, the second method of Lyapunov can be readily used to construct the parameters of the loop filter. Furthermore, it can improve the transient response of any existing loop filter designed by at least five times thus making them suitable for high speed applications. Compared to the conventional results, the proposed

Figure 3.11: Transient response of 2nd order loop filter with two zeros. Solid line: Improved PLL; Dotted line: standard PLL

design scheme enabled us to design PLLs with specified transient performance. The design scheme is developed directly on the nonlinear model of PLL and it can be easily extended to the design of high order PLLs. In summary, we have successfully developed a highly sensitive and fast phase lock loop detector.

Figure 3.12: Transient response of 2nd order loop filter with two zeros with different initial phase. Circle line: $\theta = 0.5$ rad; Square line: $\theta = 1$ rad; Triangle line: $\theta = 1.5$ rad

Figure 3.13: Transient response of 1st order loop filter with saturated gain feed forward path. Cross line: $a_0 = 4$; Square line: $a_0 = 10$; Circle line: $a_0 = 100$. Triangle line: $a_0 = 100$ without saturation limit; .

Figure 3.14: Transient response of fast 2nd order loop filter. Solid line: Improved PLL; Dotted line: standard PLL

Chapter 4

Multi-wavelength Modulation Based Optical Detection for SNOM

In the previous chapters, we have addressed the weak electric signal detection which ensured accurate positioning of the nano-aperture probe of SNOM in the near-field. The next concern is the detection of weak evanescent optical signal going through the nano-aperture of SNOM. Following the same idea as that for phase lock-in detection used in electric signal detection, it is expected that the weak optical signal detection has be done within a bandwidth that is as narrow as possible in the optical domain before the optical signal is converted to the electric domain by the photo-detector.

In this chapter, an optical detection approach using multi-wavelength modulation technique is presented. This approach can improve the sensitivity of weak optical signal detection, and it will also provide a direct means to measure the probe-sample separation. We will present the approach in three sections which respectively address the principle of the multi-wavelength modulation based optical detection, the direct measurement of probe-sample separation, and a multiple harmonic averaging technique for improving the performance of the multi-wavelength modulation based

optical detection.

4.1 Introduction

The optical detection for SNOM faces several key challenges. The first challenge comes from the low signal-to-noise ratio (SNR) because the measurement has to compete with various noises when in the nano-scale regime. The second challenge is due to the low throughput of the optical system used to enhance the lateral-resolution. The intensity of the optical signal under detection decreases significantly especially with the optical system like the SNOM that is designed to overcome the diffraction limit. For example, the nominal optical power is only of a few hundreds of pico-Watt in the optical detection using SNOM systems. The third challenge concerns the implementation issues like thermal drift, light source instability, acoustic vibration, etc [118][119]. These challenges must be addressed in an effort to achieve a high sensitivity optical detection system.

Coherent detection has been introduced for weak signal detection and has contributed significantly to the improvement in the sensitivity of the optical detection, typically by at least 30 dB [93]. The beauty of coherent detection is its ability to amplify the signal until it reaches the shot noise limit. At the shot noise limit, the shot noise is the only noise component present because all other noise sources are relatively small and can be ignored. Thus, the sensitivity of coherent detection is higher (a comparison of direct detection and coherent detection for SNOM application is shown in the Appendix). Coherent detection is classified into two categories [95]-[99]. The first category is known as homodyne detection, in which the optical frequencies of the reference and signal paths are the same. The other method is known as heterodyne detection where there is a slight difference in the mixing frequency between the two paths.

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Although homodyne detection has twice the sensitivity of heterodyne detection, it is more susceptible to low frequency noise. Thus, heterodyne detection is usually the preferred method in the optical detection arena. Heterodyne detection is very commonly used in apertureless SNOM [106]. Another benefit of heterodyne SNOM is its ability to obtain the optical field amplitude and phase information simultaneously [37]. However, in aperture SNOM, not many groups use coherent detection techniques to enhance the optical signals. The common applications of heterodyne in SNOM is the study of evanescent waves in dark-field SNOM [37] or the waveguide tailing effects [104].

In this chapter, we proposed a multi-wavelength modulation based detection for SNOM. The fiber-optic interferometer based on the multi-wavelength modulation principle is also known as the fiber-optic frequency modulated continuous wave interferometer [120]. It has an advantage over other interferometers because of its versatility of having more measurand carriers: amplitude, frequency and phase. The optical properties to be measured are encoded by a signature carrier formed by multi-wavelengths. They are detected by measuring the amplitude changes and the phase changes of the signature at different wavelengths. This detection method combines the strengths of heterodyne and homodyne detections. It is easily implemented by using a laser diode rather than an expensive laser to generate the optical carrier. Using this method, the SNOM probe can be treated as a Fizeau interferometer which enables us to measure directly the probe-sample separation. Again, as more modulation variables are available, we have more freedom to improve the detection performance, and this is demonstrated by the proposed multi-harmonic averaging technique.

4.2 Weak Signal Detection using Wavelength Modulation Interferometry

Optical coherent detection is basically implemented by optical interferometers. In order to illustrate the multi-wavelength modulation based optical detection for SNOM, one of its implementations in the form of a fiber based Mach-Zehnder interferometer is considered and it is illustrated in Figure 4.1. The optical set-up of the SNOM consists of three main parts; the source, the interferometer and the detection circuit. First, a 658 nm pigtail laser diode from Mitsubishi is used as the illumination light source. A laser diode driver (Thorlab ITC110) is used to provide current modulation of up to 200 KHz for the laser diode. The waveform output of the laser driver is controlled by a programmable function generator (Tabor 8023) which is also linked to the lock-in amplifier (Signal Recovery 7265) for synchronous detection.

Figure 4.1: Experimental set-up of the wavelength modulation SNOM

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Second, two home-made couplers are used to build the Mach-Zehnder interferometry. The laser source is first split into a 99:1 ratio in the splitter which is used as a reference for the divider circuit. Then the source is again split into 2 channels in directional coupler 1. One serves as the reference channel or reference LO, the other channel is the signal channel to illuminate the sample. The coupling ratio of coupler 1 is 90:10, where most of the light is used to illuminate the sample. The illumination channel fiber is terminated at a microscope objective so that the light source is focused on the sample surface. A SNOM probe is used to collect the optical signal in the near-field region. The probe-sample regulation is controlled by using the previous tuning fork sensing system. The tuning fork probe is mounted on a 2 axis PI P-733.2CD PZT stage for the X-Y scanning and a PI P-753 Z PZT for the separation control. The collected optical signal is guided through the fiber into coupler 2. The coupling ratio of coupler 2 must be considered carefully. Since the SNOM signal is extremely weak, a 95:5 coupler is used to conserve the SNOM signal.

Third, the output signal from coupler 2 is detected using a Hamamatsu H5784-20 PMT. This output signal is then divided by the reference PMT to remove the amplitude variations. Then, the detected signal is demodulated using a Signal recovery 7265 lock-in amplifier for high sensitive detection.

Now, let's examine the detected optical SNOM signal. The optical signals involved in the interferometry are the inputs of coupler 2 shown in Figure 4.1. The expressions for the two interference signals within a modulation period are expressed respectively as

$$E_{SNOM}(t) = k_{SNOM}A(t) \cos(\theta_T(t)) \quad (4.1)$$

$$E_{LO}(t) = A(t - \tau) \cos(\theta_T(t - \tau)) \quad (4.2)$$

where $\theta_T(t)$ is the phase function caused by the wavelength modulation, $A(t)$ is the

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E-field amplitude, k_{SNOM} is the attenuation factor of the probe channel and τ is the optical path time delay. Let's set the modulation of the injection current of the laser diode to be a ramp function and the wavelength change is given as,

$$w(t) = \omega_o + \alpha t \quad (4.3)$$

where ω_o is the center frequency and α is the angular frequency modulation rate given by,

$$\alpha = \frac{\Delta\omega}{T_m} \quad (4.4)$$

with $\Delta\omega$ being the modulation depth and T_m the modulation period. Then, the phase function is expressed as the integration of the frequency change,

$$\begin{aligned} \theta_T(t) &= \int (\omega_o + \alpha t) dt \\ &= \omega_o t + \frac{1}{2} \alpha t^2 \end{aligned} \quad (4.5)$$

The expressions for the two signals (4.1)-(4.2) with ramp modulation that are used for interference are given as,

$$E_{SNOM}(t) = \sqrt{k_{SNOM}(A + Bt)} \cos(\omega_o t + \frac{1}{2} \alpha t^2) \quad (4.6)$$

$$E_{LO}(t) = \sqrt{A + B(t - \tau)} \cos(\omega_o(t - \tau) + \frac{1}{2} \alpha(t - \tau)^2) \quad (4.7)$$

At the receiver end, the interference signal for a single period is expressed as,

$$\begin{aligned} i(t) &= \langle |E_{SNOM} + E_{LO}|^2 \rangle \\ &= \frac{1}{2} k_{SNOM} (A + Bt) + \frac{1}{2} (A + B(t - \tau)) \\ &\quad + 2k_{SNOM} \sqrt{(A + B(t - \tau))(A + Bt)} \cos(\alpha\tau t + \omega_o\tau - \frac{1}{2} \alpha\tau^2) \end{aligned} \quad (4.8)$$

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The first two terms of (4.8) depict a ramp function, while the third term is the immediate frequency(IF) term which contains the optical phase delay. Considering that τ is very small, typically about 10^{-9} s for a 1 m long optical path difference(OPD), the term $\frac{1}{2}\alpha\tau^2$ is neglected as $\frac{1}{2}\alpha\tau^2 \ll \omega_0\tau$. Further simplification can be made by dividing (4.8) by its ramp function, so that

$$i_s(t) = \frac{1}{2}(A + Bt)(k_{SNOM} + 1 + k_{SNOM} \cos(\alpha\tau t + \omega_0\tau - \frac{1}{2}\alpha\tau^2)) \quad (4.9)$$

Thus, the time series detected signal at the photodetector can be expressed as,

$$\begin{aligned} S(t) = & \sum_{k=-\infty}^{\infty} k_{SNOM} (e^{j\omega_0\tau} \left\{ \frac{\sin\{(\alpha\tau - \omega_m k) \frac{T_m}{2}\}}{(\alpha\tau - \omega_m k)} \right\} \\ & + e^{-j\omega_0\tau} \left\{ \frac{\sin\{(\alpha\tau + \omega_m k) \frac{T_m}{2}\}}{(\alpha\tau + \omega_m k)} \right\}) e^{jk\omega_m t} + n_k(t) \end{aligned} \quad (4.10)$$

where $n_k(t)$ is the white Gaussian noise. At this point, we will choose the highest amplitude signal to maximum the signal strength. This is done by choosing the nearest $\omega_m k \approx \alpha\tau$, and this k value is denoted as k_{max} . The final filtered signal is expressed as

$$\begin{aligned} S(t) = & 2k_{SNOM} \left(\frac{\sin\{(\alpha\tau - \omega_m k_{max}) \frac{T_m}{2}\}}{(\alpha\tau - \omega_m k_{max})} \cos(k_{max}\omega_m t + \omega_0\tau) \right. \\ & \left. + \frac{\sin\{(\alpha\tau + \omega_m k_{max}) \frac{T_m}{2}\}}{(\alpha\tau + \omega_m k_{max})} \cos(k_{max}\omega_m t - \omega_0\tau) \right) + n_{k_{max}}(t) \end{aligned} \quad (4.11)$$

The latter signal term is usually ignored because its amplitude is insignificant as compared to noise.

To demonstrate the principle, a SNOM set-up is built as in Figure 4.1. The image is formed by scanning in the constant separation mode. It was applied to two photonic crystal samples made from PMMA material. The samples are fabricated through

(a) Topography

(b) Optical

Figure 4.2: SNOM imaging of PMMA opal sample of 300 nm using normal set-up the cooling of a PMMA mixture. The opal should have a diameter of 200-300 nm. The measurement requirements include the optical phase profile of each crystal and defects incurred under different fabrication conditions. Figure 4.2 shows the AFM topography and the optical intensity profile of the opal sample. The lines in the AFM images may be due to drifts in the tuning fork resonance frequency, acoustic disturbance or air-flow, which cause a temporary lost of control of the probe-sample separation.

The results of using multi-wavelength modulation SNOM are shown in Figure 4.3 and 4.4 and they show that the multi-wavelength modulation SNOM displays higher sensitivity images as compared with Figure 4.2, which uses the normal SNOM set-up. Both figures showed clearly the phase information of the optical signal. Here, the optical phase information denotes the optical path difference between the signal arm and the reference arm. In figure 4.3, the lines in the SNOM image is due to poor phase unwrapping algorithm due to the noise effects around the phase wrapping boundary. The small connecting junctions and the boundaries of the opals can be

Figure 4.3: Imaging of PMMA opal sample of 300 nm using multi-wavelength modulation SNOM

seen very clearly. The lighter spots and lines represent the smaller optical path, i.e. the sample is thinner, and vice verse.

The sample is an opal structure and the center is thicker than the sides which coincide with both the topography and optical images. Figure 4.4 shows the image of an uneven opal sample of size 300 nm. The SNOM image follows closely the AFM images at two very distinct regions of different heights. At each height, the individual structure of the opal can also be resolved. This is due to the lattice imperfection of the opal during the manufacturing process. Figure 4.3(a) shows a flat topography of the opal. However, Figure 4.3(b) shows a very uneven optical phase image. Comparing both Figures 4.4 and 4.3, we can conclude that some subsurface features are observed. This phenomenon is contributed by some subsurface layers cracks or dislocations in this opal sample. This is because within the cracks or dislocations, the missing spheres created distinctive difference in the optical path detected.

Figure 4.4: Imaging of PMMA opal sample of 300 nm having an uneven surface using multi-wavelength modulation SNOM

4.3 Optical Measurement of SNOM Probe-sample Separation

As govern by its principle, SNOM measures the evanescent optical field which decays exponentially in the direction normal to the sample surface. Thus, the probe-sample separation affects the optical contrast if the probe-separation is not maintained at a constant. In the previous chapters, we have addressed the probe-sample separation sensing for improving the Q-factor of the tuning fork probe and the sensitivity of the weak electric signal detection. However, the probe-sample separation sensing is done through an indirect way by measuring the atomic force between the probe and the sample. The relation between the separation and the force can be complicated and dependent upon many other factors like the materials properties. Thus, it is desirable to have a more direct measurement approach.

By introducing the multi-wavelength optical detection, we demonstrate for the first

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Figure 4.5: Calibration of SNOM displacement sensor. Cross line: Measured displacement; Solid line: Calculated displacement

time that the SNOM probe functions as a Fizeau interferometer, hence the optical detection method can also help to measure the change in probe-sample separation.

Figure 4.6: Setup of Fizeau interferometer for SNOM

Here, the measurement of the probe-sample separation by using the SNOM probe with the proposed optical detection is illustrated in Figure 4.6 where a mirror driven by a Z-Piezo stage is used to calibrate the separation. First, the phase information detected by the multi-wavelength modulation SNOM must be understood. The detected signal

is a difference between the two optical paths. The optical path different (OPD) can be obtained by multiplying with the speed of light in a medium and the displacement under measurement is half of the OPD. The reference path and the signal path can be denoted as $n_r z_r$ and $n_s z_s$, respectively. Then, the phase information detected with respect to the sample coordinate is expressed as,

$$OPD(x, y) = n_s(x, y)z_s(x, y) - n_r(x, y)z_r(x, y) = \frac{\Delta\theta\lambda}{2\pi} \quad (4.12)$$

For calibration, the medium used has a constant refractive index, n_0 . Thus, the phase change corresponds to the optical path difference given by,

$$OPD = n_0\Delta z = \frac{\Delta\theta\lambda}{2\pi} \quad (4.13)$$

where $\Delta\theta$ is the phase change detected and $\Delta z = z_s - z_r$. The displacement can be calculated using (4.13) and the results are plotted in Figure 4.5(a). The gradient of the slope gives a calculated value of $0.691 \mu\text{m/V}$ which is very close to the gradient of the Z displacement moved. The displacement sensor results are plotted together with the piezo movement results in Figure 4.5(b). The discrepancy at the ends is due the non-linearity of an open loop voltage controlled piezo actuator. The resolution of our SNOM displacement sensor can also be calculated based on the phase error of each experiment. The phase error is defined as $\delta\theta = 1/\sqrt{SNR}$. The phase error defines the resolution limits of the displacement sensor.

The phase error in the displacement sensor is further investigated by scanning a mirror surface. The result of the displacement sensor is shown in Figure 4.7. In this experimental set-up, the SNR is approximately calculated as 60 dB. Thus, the phase error will be 0.36° . From the line scan of the optical phase, the phase error is about 0.5° which is quite close to the calculated results. Correspondingly, this gives

Figure 4.7: Imaging of a mirror surface using Fizeau interferometer SNOM
a resolution of 0.9 nm.

Figure 4.8: Imaging of a Rhombus surface using Fizeau interferometer SNOM in constant separation scanning

The performance of displacement sensor is further investigated by scanning the sensor over the mirror surface over a larger range of 10μm. The analysis of the performance is based on the assumption that there is no dust on the surface. The phase error variance is measured to be about 1.5° which corresponds to 2.7nm. This measurement shows that that the displacement sensor is capable of achieving a very high resolution displacement sensing.

Figure 4.9: Displacement sensing using a longer scanning range

Now, let's examine the separation measurement capabilities of the multi-wavelength modulation SNOM. In order to verify that the measurement quantity of the displacement sensor is correct, a known sample is used to demonstrate the measurement capabilities of the SNOM system. The sample used is a periodic rhombus sample made of Vanadium. The rhombus sample is a standard SNOM calibration sample SNG01 from NT-MDT. The rhombus thickness is 10-20nm and its surface has a reflectivity of more than 0.4. The perimeter of each rhombus has been oxidized, thus unevenness of the edges are observed.

First, the displacement sensor is used to detect the displacement changes when the probe is following the topography of the sample. Figure 4.8 shows the topography, the optical amplitude and the optical phase images, respectively. The optical phase image shows a flat surface which corresponds to the constant probe-sample separation. In order to further illustrate the capabilities, the SNOM displacement sensor is used to measure the separation between the probe and the sample by scanning the probe

Figure 4.10: Imaging of a Rhombus surface using Fizeau interferometer SNOM in constant height scanning

across the sample surface in the constant height mode. The topography image is also used to compare with the displacement obtained by the displacement sensor. This topography image is done independently because a constant height scanning does not have the height information. The images are shown in Figure 4.10. The linescans of both the calculated displacement from the optical phase and the topography are shown in Figure 4.11. The three flat surfaces are well mapped. From the observation, the height of the rhombus, about 15 nm, corresponds to the measured optical displacement. The only discrepancy is at the edge of the features. This is due to the geometry of the SNOM probe, in which the force interaction of the probe and the features will affect the topographical images. However, the optical displacement will not be affected as there is no interaction with the surface. This is the main advantage of optical displacement sensing.

Figure 4.11: Comparison of the line scans of the Z displacement as measured by AFM and the optical method. Solid line: AFM measured displacement; Dotted line: Optically measured displacement.

4.4 Multi-harmonics Averaging Technique

In the previous section, we have demonstrated the capabilities of the SNOM with multi-wavelength modulation based optical detection. However, from most of the line scans of the optical phase images, we can observe the instability of measured results because of noise and interference drift. The interference drift is caused by temperature change, vibration, and air flow dynamics. It is actually a serious problem with all kinds of interferometers. In this section, we proposed a multi-harmonics technique to minimize the drift effect on the measurements with optical interferometers. Since the phase carries the measurand, the technique is achieved by averaging the phases obtained from the various orders of heterodyne harmonics in the multi-wavelength modulation based optical detection. The basic idea behind the method is that the drift caused by the various ambient changes will affect the phases of different heterodyne harmonics differently. The development and the effectiveness of the proposed method are described by applying the method on a fiber-optics displacement sensor that is based on the multi-wavelength modulation principle.

To illustrate the principle of the proposed technique, we consider the modulation of the injection current of the laser diode as a ramp function. Then, the optical frequency of the laser diode will also change, accordingly. When the optical signals are split and recombined with one of the arms having an optical path difference, the interfered signal will contain harmonics of a beating frequency. This feature of the beating made heterodyne detection possible. The interference signal can be expressed as in (4.8). Dividing (4.8) by the ramp modulation signal, we can obtain the normalized interference signal. Since we are only interested in the heterodyne harmonics, the DC component of the normalized signal is filtered. Then, the time-domain signal that we

intend to detect can be expressed as,

$$S(t) = [A_0 \cos(\alpha\tau t + \omega_0\tau - \frac{1}{2}\alpha\tau^2) \cdot \prod(t, 0, T_m - \tau)] \otimes \sum_{n=-\infty}^{\infty} \delta(t - nT_m) m + n_k(t). \quad (4.14)$$

We can see from (4.14) that the displacement information is in both the frequency, $\alpha\tau$, and the phase, $\omega_0\tau$, of the signal. Since we are measuring small displacements, we are only interested in the phase which can be obtained by performing lock-in amplification on the heterodyne harmonics. In order to analyze further the signal, we express (4.14) as a Fourier series as follows:

$$\begin{aligned} S(t) = & \sum_{k=-\infty}^{\infty} A_0(e^{j\omega_0\tau} \left\{ \frac{\sin\{(\alpha\tau - \omega_m k) \frac{T_m}{2}\}}{2(\alpha\tau - \omega_m k)} \right\} \\ & - e^{-j\omega_0\tau} \left\{ \frac{\sin\{(\alpha\tau + \omega_m k) \frac{T_m}{2}\}}{2(\alpha\tau + \omega_m k)} \right\}) e^{jk\omega_m t} + n_k(t). \end{aligned} \quad (4.15)$$

Equation (4.15) shows that the detected signal contains higher heterodyne harmonics of the modulation frequencies. It is possible to recover the phase value in every harmonics if the amplitude of the coefficient is larger than the noise of the detection system. Figure 4.12 shows the spectrum of the multi-wavelength modulation. At each harmonics, there is a difference in the intensity value. If we look at the insert in Figure 4.12, we can conclude that the phase of the 7th harmonics cannot be retrieved as the signal strength is smaller than the noise. Hence, there is a limit to the usable harmonics for the proposed averaging. The highest amplitude harmonic is often used to demodulate the phase to ensure the highest sensitivity. However, it is not robust to drift. Thus, we proposed a multiple harmonics method to detect the phase. Instead of using a single harmonic, we use the mean value of the phases obtained from several heterodyne harmonics. The averaging is simply done by,

$$E(\theta) = \frac{1}{W_t} \Sigma W_n \theta_n, \quad (4.16)$$

where W_t is the summation of all the W_n . For a simple demonstration of the wavelength averaging method, we let all the W_n be 1 and the averaging equation is expressed as,

$$E(\theta) = \frac{1}{n}(\theta_1 + \theta_2 + \theta_3 + \dots + \theta_n), \quad (4.17)$$

Figure 4.12: The spectrum of multi-wavelength modulation.
Insert: Comparison of theoretical shot noise to the harmonics

4.4.1 Experimental Demonstration of Multi-harmonic Averaging in Probe-sample Separation Sensing

The proposed method is tested using a Fizeau interferometry set-up. The set-up is shown in Figure 4.6. In this experiment, a DFB laser diode of 1540 nm wavelength is used. The laser diode is mounted on the Thorlab ITC110 butterfly package driver. This laser diode is modulated with a 50 mV ramp signal using a Tabor 8023 function generator. The laser output is coupled into a fiber and split into two channels at

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coupler 1 at a 50/50 ratio. The laser output is detected at photodiode 1 connected at one channel of coupler 1. At the other channel, the optical light passes through coupler 2 with 3 dB loss and exits the fiber from the collimator. The transmitted light is partially reflected and reflected at the collimator surface and the mirror, respectively. The reflected light, E_1 , travels back into coupler 2. It is interfered by the light E_2 that is reflected back from the mirror. The interfered signal is detected at photodiode 2. It is normalized by dividing by the optical signal obtained at photodiode 1. Finally, the phase at different harmonics is obtained by using a lock-in amplifier.

In order to simulate the displacement change, the mirror is placed on the PZT. The displacements are simulated by increasing the voltages across the PZT. The mirror moves every 35 nm by increasing the voltage in steps of 2 volts. The corresponding phases are then recorded. By calculating the phase changes, the OPDs are obtained follow by the displacement.

Figure 4.13 shows a set of the phase values obtained from the above set-up. It lists the phase values of four different harmonics, including the fundamental harmonics. We observe that the phase changes measured from different harmonics have significant fluctuations. This phenomenon arises from the drift of the interference signals. In order to compensate for the undesired drift, multi-harmonic averaging in (4.17) is performed on the sets of phase data. First, we calculate the averaged displacement measurements in each step of PZT movement. Then, we plotted the obtained measurements in Figure 4.14. Compared the responses in Figure 4.13, the response in Figure 4.14 showed less deviation per step size. It is shown that the proposed method has significantly improved the robustness of the displacement measurements.

Next, we narrow down into a single step and analyze the effects on the step size after harmonic averaging. A set of 12 samples have been taken. The five consecutive steps are analyzed and the variance resulting from more harmonic averaging is found to

Table 4.1: Summary of the standard deviation on each 35 nm step at different harmonics

	First Step(nm)	Second Step(nm)	Third Step(nm)	Fourth Step(nm)	Fifth Step(nm)
1 st Harmonics	3.94	3.83	3.92	3.51	4.11
2 nd Harmonics	2.16	2.32	2.96	4.73	5.09
3 rd Harmonics	2.50	3.33	2.22	1.74	2.36
4 th Harmonics	4.09	2.86	1.36	7.47	7.82
Combining 1 st and 2 nd Harmonics components	2.31	2.86	2.04	2.17	2.09
Combining 1 st , 2 nd and 3 rd Harmonics components	2.06	1.71	1.34	1.97	1.90
Combining all 4 Harmonics components	1.26	1.55	1.16	1.22	1.44

be smaller than that resulting from a single harmonic. There is a 58% improvement in the variance when comparing the 2nd harmonic steps with the combination of 4 harmonic components. The results of the standard deviations are summarized in Table 4.1.

4.4.2 Experimental Demonstration of Multi-harmonic Averaging in SNOM Imaging

The use of the multi-harmonics averaging technique as applied to SNOM is now examined. Note however that, there are some constraints during the implementation as the SNOM system only allows 2 input channels. Only two different harmonics can be detected during each scan. Thus, the sensitivity improvement using the averaging does not show much improvement in regards to the scanned results. From table 4.1, it is shown that in certain cases the results of the using 2 harmonics for the averaging process does not produce better results than that of using just a single harmonic.

The experiment set-up is shown in Figure 4.1. The scanning results of the harmonics

Figure 4.13: Steps of 35 nm with detection at different harmonics

detection are shown in Figure 4.15. There are significant difference between the 2nd harmonics and 3rd harmonics images. The central region shows a very distinct difference in the phase information. From the topography, the height of the central region is rather similar, but in the 2nd harmonics image the difference is very clear. After the averaging, the optical phase information looks rather close to the topographic image. Here, the horizontal lines should not be included in the analysis as these lines maybe due to the phase unwrapping problem. The image can be further improved by using more harmonics to do the averaging in a modified SNOM system.

The optical phase in this set-up measures the phase lag and lead of the material. This phase information can be linked to the refractive index of the material. Since the set-up is a transmission-collection SNOM, the optical signal that passes through each sphere of the photonic crystal. Since the sphere has a bigger reflective index than

Figure 4.14: Steps of 35 nm after multi-harmonics averaging

air, the optical phase delay at the center of the sphere is more than the boundary. From Figure 4.15(b), the brighter portion denotes a bigger phase value recorded which means a larger phase lag. As for the boundary, the phase value is small thus the phase lag is smaller than the center of the sphere. This is similar to figure 4.15(a).

The experimental results showed that the multi-wavelength modulation based optical detection with a multi-harmonics averaging technique can indeed remove the interference drift effect in nano-scale measurements and in SNOM imaging.

Remark: Optical methods have always been favored for measurements and material analysis due to their potentials of high bandwidth, immunity to electric-magnetic interferences, and ease of nondestructive implementation. As a convenient light carrier, fiber optics is chosen to implement the optical measurement methods into devices and

Figure 4.15: Multi-harmonics SNOM with 2 harmonics averaging

sensors for a wide range of applications such as optical communications, displacement sensing, motion monitoring, sub-surface imaging, thermal imaging and spectroscopy [116, 117]. These sensors face many challenges as the demand for high precision applications increases. For instance, in the applications of sensing displacement, the prevalent downsizing trend in various manufacturing processes has demanded good nano-scale resolution on the displacement measurements.

4.5 Conclusion

In conclusion, an optical detection approach by using multi-wavelength modulation is presented. Based on this approach, the sensitivity of weak optical detection of the SNOM probe is improved by more than an order of five. The details of the sensitivity improvement are formulated in the Appendix. The improvements are verified experimentally via the area imaging of photonics crystals. Also, this approach provides the first direct measurement of the probe-sample separation optically. This will enable us to use non-contact distance regulation for probe-sample separation control. Further, using the multi-wavelength modulation method, we presented the multiple harmonics averaging technique for improving the optical displacement measured. This

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method is able to remove noise from the environment that is affecting a particular frequency. The multiple harmonics averaging method is also verified experimentally on the SNOM system based on the single point displacement sensing and the area imaging.

In this chapter, 3 different types of optical information are obtained. There are the optical intensity which is based on the reflectivity of the material; the optical phase difference which is related to the refractive index of the material; and the optical path length in air which gives the displacement information for the probe sample interaction. Based on the capabilities built up, the SNOM system can be further developed to detect other physical mechanism of the sample.

Chapter 5

SNOM System Integration and its Applications

In this chapter, we shall examine the various implementation considerations of the SNOM system and demonstrate its capabilities by using the system for nanoscale optical imaging in a variety of applications. The challenges in these applications are due to the minute difference in the optical properties across the sample. Thus, a very sensitive optical detection system is required to observe the difference. Furthermore, in the near-field region, the optical signal is very weak and this makes the detection process more challenging. In our implementation, the several basic configurations of SNOM are built and tested on calibration samples. Based on the basic configurations, some real applications are also tested and undesirable results are obtained. It was shown in the earlier chapter that the multi-wavelength modulation SNOM has high sensitivity, and based on the multi-wavelength modulation SNOM system better results are achieved as compared to the basic configuration SNOM. The three different types of real applications demonstrate the capability of the SNOM system. These applications include the characterization of photonics crystals, the waveguide

loss measurements and the characterization of biological samples.

5.1 Introduction

There are many important applications of SNOM such as in the characterization of fluorescence in biological samples, photo luminescence of materials and photon emission of semiconductors devices. Among these applications, many do require high sensitivity optical detection system with at least -90 dBm of optical power. This is due to the challenges of collecting of the optical signal in the near-field over a small area. The optical signal collected at the detector end is usually very weak, typically in picoWatts. Furthermore, the changes in the optical signal of adjacent features during the scanning process maybe a hundredth of this weak collected signal, which demands the need of developing a highly sensitive optical system.

Although the development of SNOM system has progressed over a few decades and commercially available SNOM system can be found easily, the sensitivity issue is still a challenge in many applications. One example is the detection of the change in the refractive index of 10^{-5} , which requires extremely high sensitivity detection methods.

We have shown that the use of the multi-wavelength modulation SNOM improved the sensitivity of the current optical detection methods by a factor of 5. This enables us to use the system in many applications. Through our research efforts, versatile SNOM is designed and built and it can be changed into the required configurations for different applications. In the following sections, the configurations of the SNOM systems and the corresponding scanning results using calibration samples are shown. Furthermore, the SNOM system is demonstrated on three applications. First, the multi-wavelength modulation SNOM system is used to detect the phase distribution of photonics crystals used in solar cells. Next, a transmission-collection SNOM is used

to measure the loss of photonic integrated waveguide that is used in the interconnects of photonic integrated circuit. Lastly, the system is tested on 2 types of biological proteins sample coated with silver and gold.

5.2 SNOM System Integration

This section illustrates the integration of the innovations presented in the previous chapters into a functional SNOM system.

5.2.1 Implementation of Various SNOM Configurations

In order for the SNOM system to be used in various applications, several basic configuration modes of the system are built. These configurations are illumination-collection (IC-SNOM), transmission-collection (TC-SNOM), illumination-transmission (IT-SNOM) and reflection-collection (RC-SNOM). The schematics of the various SNOM configuration modes are shown in Figure 5.1.

Furthermore, these SNOM modes are tested on standard calibration samples from NT-MDT [141]. The samples used are TDG01/Au and SNG01, and scanning result are shown in Figure 5.2 and Figure 5.3 respectively.

The TDG01 sample is a Au coated sinusoidal gratings with a pitch of 298 nm. The line scan of Figure 5.2(b) and Figure 5.2(d) are presented in Figure 5.4 to demonstrate the optical resolution of the SNOM system. The line scan shows that the RC-SNOM has a noisy signal than the IC-SNOM because of lower SNR. The back reflection signal and collected signal cause interference in the IC-SNOM which enables shot noise limited detection. The lateral resolution for optical signal is 60 nm based on the the Full-Width at Half Maximum of Figure 5.4.

Figure 5.1: Schematic of various SNOM configurations. Solid path: Collection; Dotted path: Illumination

The SNG01 is a sample that consists of rhombus pattern made of Vanadium of thickness 10 – 20 nm. The metal has a transmission coefficient of less than 20% and the pointed end of the rhombus is about 50 nm. Figure 5.5(a) shows a line scan of Figure 5.3(c). The measured Z-displacement is about 24.3 nm with a calculated uncertainty error of ± 2.8 nm. In Figure 5.5(b), the average maximum and minimum intensities are used to find the transmission coefficient which is about 15.8%, which is close to the sample specifications. The uneven intensity profile at the maximum is due to certain parts of the rhombus that is oxidized and no longer exhibit the specific transmission.

Although the calibration samples give reasonably good SNOM results, the optical sensitivity may not always give good results for some real applications. For instance, Figure 4.2 shows poor optical contrast on the PMMA opal sample when using IT-SNOM. The optical sensitivity of the current SNOM system is not high enough to

Figure 5.2: Image of Au gratings using RC-SNOM(a,b) and IC-SNOM (c,d)

Figure 5.3: Image of Vanadium rhombus using IT-SNOM (a,b) and TC-SNOM(c,d)

resolve the opal sample. Since the thickness difference between adjacent opals is about 10 nm, the difference in the transmission coefficient is too small to be detected. Thus, other optical detection techniques such as multi-wavelength modulation are required to improve the optical sensitivity of the SNOM system.

5.2.2 SNOM with Various Implementation of the Multi-wavelength Modulation based Optical Detection

In the Appendix, coherent detection is proven to be the method for high sensitivity optical detection of less than -150 dB of optical power. Here, the interferometry mod-

Figure 5.4: Line scan of optical images for computing the average resolution

Figure 5.5: Line scan of the Vanadium rhombus

ule is built and integrated into the basic configuration of SNOM modes. The multi-wavelength modulation SNOM is built on three types of fiber based interferometers: the Mach-Zehnder interferometer, the Fizeau interferometer and the Michelson interferometer. The IC-SNOM is based on Fizeau and Michelson interferometers while the rest are based on the Mach-Zehnder set-up. The schematics of the multi-wavelength modulation SNOMs are shown in Figure 5.6.

Up to this point, the optical set-up is implemented based on the condition of shot

Figure 5.6: Schematic of various multi-wavelength modulation SNOM configurations. Solid path: Collection; Dotted path: Illumination

noise limited detection. In order to achieve the shot noise limit condition, the LO power intensity, $P_{LO} = \langle A + Bt \rangle$, must create the photon shot noise to be equal to the summation of all the noise terms, $n_{k_{max}}(t)$. In heterodyne detection, the total noise terms include the thermal noise and the dark current shot noise. The optical power limit of the LO should be at least,

$$P_{LO} > \frac{2qI_D + \frac{4K_B T}{R_{PMT}}}{2q\mathcal{R}} \quad (5.1)$$

From the measured noise in the previous section, the minimum LO optical power required for shot noise limit detection is $0.998 \mu\text{W}$. Thus, one can set the LO channel at $1 \mu\text{W}$.

Now, the coupling ratio of the two couplers is fixed. Let's consider the coupling ratio

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of the SNOM set-up in the transmission-collection mode. The weak SNOM signal collected from the probe must have a very large proportion of the light collected at the PMT, so a 95:5 coupling ratio is used. Using the above calculated value of LO power, the LO arm of the coupler input should be at least $50 \mu\text{W}$ of the optical power. The coupling ratio for coupler 2 is fixed at 90:10 because the illumination arm needs more optical power to shine on the sample. Here, we can neglect the splitter power because it only takes about 1% of the total power. Thus, the optical power needed at the laser is about $600 \mu\text{W}$. This output power is achievable for most of the pigtail laser diodes that are commercially available.

5.2.3 Several Considerations of SNOM System Integration**5.2.3.1 Specifications of Laser Diode**

An important implementation consideration is to ensure that the optical path difference between the reference arm and the signal arm of the interferometer is within the coherent length. The coherent length is dependent on the linewidth of the laser diode, $\Delta\lambda$, which can be expressed as [121],

$$\ell_c = \frac{\lambda^2}{\Delta\lambda} \quad (5.2)$$

Here, a Mitsubishi ML120G21 laser diode in a pigtailed fixture is used as the source of the SNOM system. The spectral shift of the laser diode with respect to the current supplied is observed through the optical spectrum analyzer AQ6317B from ANDO and plotted in Figure 5.7(a). From Figure 5.7(a), the linewidth of the laser diode is obtained. With a linewidth of 0.03 nm and (5.2), the difference in the optical path for possible interference would be about 14.3 nm. The center wavelengths of the spectrum at different current values are recorded and shown in Figure 5.7(b).

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With this calibration, the change in wavelength of the laser diode with respect to the current is known. Hence, the wavelength change, $\Delta\omega$, can be obtained and α can be calculated by using (4.4).

Figure 5.7: Characteristic of Laser diode

5.2.3.2 Calibration of Scanning Stage

Figure 5.8: Calibration of scanning stage

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The scanning stage used for this SNOM system is a piezo stage P-733.2CD from Physik Instrumente. Voltage is supplied on the piezo stage and the displacement is measured every 200 nm using a Keytec LT8011 displacement sensor. The open loop movement of the stage is recorded in Figure 5.8(a). The corresponding displacement is then assigned to the controlled voltage. This calibration only gives us an estimate for the scanning area. For a precision stage, there are more issues that need to be addressed. For example, the hysteresis of the piezo stage has to be compensated with capacitive feedback. The calibration is done at a fixed scanning speed, and this scanning speed is fixed throughout all the AFM and SNOM experiments. This is because the calibrated data is greatly influenced by the response time of the scanning stage and the displacement for each step will be different at different speed. To test the calibration of the scanning stage, an AFM calibration sample, TGX01 from MikroMash, is used. The structure is a $1.1\ \mu\text{m}$ checkbox structure with $3\ \mu\text{m}$ pitch. The structure is shown in Figure 5.8(b).

5.2.3.3 Laboratory Conditions for the SNOM System

Since the set-up is fiber based, the environmental disturbances have very significant effects during the data collection process. Air flow, thermal fluctuation, acoustic disturbance are very common disturbance for fiber based implementation. Hence, the SNOM system is placed in black acrylic enclosure. This enclosure provides good insulation for the air flow and thermal fluctuation disturbances. Although this enclosure cannot remove the acoustic disturbance, it minimizes the disturbance to a certain extent. Furthermore, the system is placed on an anti-vibration table to isolate the vibration from the ground.

5.3 Applications of SNOM

The proposed SNOM system also demonstrated its capabilities in the characterization of samples for three different fields of applications. First, the multi-wavelength modulation SNOM system based on the transmission-collection mode is used to detect the phase distribution of photonics crystals used in dye-sensitized solar cells. The second application is the use of transmission-collection SNOM to measure the loss of photonic integrated waveguide that is used in the interconnects of photonic integrated circuit. Last but not least, the system is tested on 2 different types of biological proteins samples coated with silver and gold respectively.

5.3.1 Phase Detection of Photonic Crystal

Solar cells have been an important technology development for tapping renewable solar energy source. The development has progressed into the third generation of solar cells which focuses on low manufacturing cost, ease of production and high efficiency [135]. One example of this solar cell is the dye-sensitized solar cell. This new generation of solar cells is usually based on nano structures of materials. One of the important factors that affects the efficiency of solar cell is the absorbing rate which affects the charge-carriers generation. The efficiency of solar cells is positively correlated to the time-of-flight of the solar rays in the cell [136]. A slower light travel in the cells will give a higher efficiency. In this regards, the optical phase in the photonic crystal is an important property. One of the important characteristics of optical phase is the refractive index. By knowing the phase lag, one can characterize the speed of light that is propagating through the medium. This is extremely helpful in solar-cells development if we have the ability to characterize different nano structures of the cell substrates.

(a) Topography

(b) Optical phase

Figure 5.9: Phase imaging of photonic crystal

The multi-wavelength modulation SNOM is used to measure the optical phase of photonic crystals. The photonic crystals of size 200-300 nm in diameter are measured. This crystal is the place in the SNOM system with a transmission-collection mode. This sample should be place on a 3 axis stage from Melles Griot for navigation. The alignment of the objective lens and the fiber probe must be fixed throughout the whole scanning process. One must make sure that the probe is at the center of the focused light. This can be done by observing the maximum intensity at the PMT. The set-up of the experiment is similar to Figure 5.6(b). An optical fiber interferometer will be required. The total optical path length of the optical interferometry arms are measured and trimmed according to the coherent length of the laser diode, which is about 4 cm. The total optical path length includes the fiber, the objective distance and the free space areas. This is to ensure that the two signals can interfere within the coherent length. The laser diode is modulated using a Thorlab ITC101 driver with a 10KHz modulated saw-tooth wave provided by the Tabor 8023 function generator. The optical signal is collected at the PMT(Hamamatsu H5784-20) with gain set at 2×10^5 . Another reference optical signal which is used as the reference is detected

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using another PMT with gain set at 2×10^3 . The measured optical signal is divided by the reference optical signal in the AD584 divider circuit. The output of this circuit is then feed into the Signal Recovery 7265 lock-in amplifier to detect the phase. The lock-in amplifier parameters of the lock-in amplifier are set as: gain = 40 dB, TC = 5 ms, Filter = 18 dB.

Using wavelength modulation described above and lock-in amplification detection technique, the optical phase of the photonic crystal is measured. The topography and SNOM results of the scanning are shown in Figure 5.9. In order to analyze the obtained results, the line scans of the images are plotted in Figure 5.10. From Figure 5.10, one can compare the phase distribution of the photonic crystal with respect to the topography. These phase values are being unwrapped using the Matlab unwrapping algorithm. Here, the phase values are relative phase changes and they are offsetted to be between -360° to 360° . Various different samples of photonic crystals, with different size or height or materials, have been tried and they all achieved phase results with SNR of 30 dB higher than that obtained via direct measurements.

Furthermore, the refractive index may be retrieved but this possibility has neither been implemented nor studied yet. For instance, let's take a look at Figure 5.10, which presents the line scans at two different cross-sections of Figure 5.9. For line scan B, the topography follows the optical phase while line scan A does not. This might mean that the refractive index of line scan B is a constant while that of line scan A varies. However, the physical meaning and the usage of this phase information are not known and it could be an interesting information for material researchers to investigate. Thus, SNOM has demonstrated the possibility of its use in characterizing nano-scale photonic crystals.

Figure 5.10: Line scan of photonic crystal at two different cross-section in Figure 5.8(a)

5.3.2 Loss Measurements of Photonic Integrated Waveguide

Optical waveguide is an important component for the integration of photonics circuits and systems, as it serves as the interconnects for laser sources, optical amplifiers, couplers and other photonics devices. The loss of the waveguide is an important issue that should be characterized as it affects the selection of the input device and the detector. Here, the transmission-collection SNOM is used to characterize the loss of a trapezoid photonic waveguide structure (see Figure 5.12(a)). The waveguide is embedded in a piece of polymer slab with the input channel and the output channel

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facing opposite ends. This waveguide is then placed such that the waveguide input channel faces the collimated light source while the output faces the collection SNOM probe at the other end (see Figure 5.11).

Figure 5.11: Setup for loss measurement of waveguide

The SNOM probe scans over the waveguide structure and obtains the image that provides the intensity distribution of propagating field at the output end of the waveguide. The total output intensity of the waveguide is the summation of the total field distribution collected. This region is summed up and represented as the output intensity, P_{out} . After that, the waveguide is removed from the sample stage. The SNOM probe is then used to scan over the same area. The input light source is computed by obtaining the scan results over the input position of the waveguide at a constant height, follow by the summation of the field intensity. This intensity variation is rather flat, which coincided with the collimated source characteristics. The input power of the waveguide is denoted as P_{in} . The loss of the waveguide can be calculated by the given equation, $P_{loss} = \frac{P_{in} - P_{out}}{P_{in}}$. The AFM and SNOM images are shown in Figure 5.12(b). From a series of repeated experiments, the average measured loss is about 4.87 dB.

Similarly, the far-field loss measurement is done by using the pin hole method to

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collect the waveguide output power. The mean loss measured by using the far-field method is 6.19 dB, which is about 1.32 dB lower than that measured by the SNOM. This discrepancy maybe due to the irregular shape of the waveguide and the divergence angle at the output of the waveguide. The sides of the waveguide are blocked by the pin hole, thus the loss is larger. That is, the limitation of the far-field method of measuring the loss can be attributed to the geometric uncertainties of the pin hole. The loss of the waveguide can be approximated theoretically by dividing the total loss into 3 sub-sections. First, let us consider the Fresnel reflection loss. The Fresnel reflection coefficient is given by,

$$r = \frac{n_{air} - n_{core}}{n_{air} + n_{core}}, \quad (5.3)$$

where n_{air} and n_{core} are the refractive indices of air and core respectively. Therefore, due to reflection at the two end facets, the transmitted optical power ratio is $T = (1 - r^2)^2 = 0.9084$, which means that the Fresnel reflection loss is 0.42 dB.

Next, the coupling loss is considered. The coupling loss consists of the facet scattering loss and the mode mismatch loss. The typical value of the end facet scattering loss is about 2.7 dB [134]. The geometric optics approach has been used to calculate the source coupling efficiency [132]. However, this approach cannot provide accurate results when dealing with optical waveguides, whose dimensions are comparable to the wavelength. In this case, wave optics theory is used to calculate the source coupling efficiency, which is defined as [132],

$$\eta_{coupling} = \frac{\int \int_{output} (\vec{E}_{output} \times \vec{H}_{output}) \cdot \hat{a}_z dS}{\int \int_{incident} (\vec{E}_{incident} \times \vec{H}_{incident}) \cdot \hat{a}_z dS}. \quad (5.4)$$

Then, the finite difference time domain method is applied to calculate the coupling efficiency. Since the incident field is a uniform field, the calculated optical source

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coupling efficiency $\eta_{coupling}$ is about 71.9, which is 1.43 dB. Hence, the total coupling loss is 4.13 dB.

The third issue is the material absorption loss. The total material loss for typical polymer based waveguide is estimated as 0.04 dB. In addition, the roughness of the interface between the core and the cladding region will also affect the propagation loss. The roughness of the interface is measured by using the AFM (see Figure 5.12(b)). The standard deviation of roughness, σ is about 0.1 μm . The attenuation coefficient due to scattering can be estimated by $\alpha = \frac{\sigma}{k_0 d^4 n_1} g$ [133] where k_0 is free space wave number, d is the effective half-width, n_1 is the effective refractive index and $g = 0.48$ for exponential statistics. Therefore, the attenuation coefficient α is about $1.352 \times 10^{-3} \text{ cm}^{-1}$. In the experiment, the waveguide length is 0.4 cm. The transmission efficiency is $\eta_{propagation} = e^{-2\alpha L} = 0.9989$. Hence, the total material loss is 0.05 dB, and the total loss summed up to 4.60 dB. This shows that the theoretical analysis is close to the SNOM experimental results.

The detail experimental results of different waveguides are summarized in Table 5.1. It can be seen that the values obtained from the pin hole method deviated more from the theoretical results, while the loss measurements using SNOM are closer to the theoretical calculations. Furthermore, due to its higher resolution, future applications on high density photonic integrated waveguide can be characterized by using this method.

Table 5.1: Comparison chart of pin-hole method and SNOM method

	Waveguide 1	Waveguide 2	Waveguide 3	Waveguide 4	Waveguide 5
Pin hole	-6.19±0.2 dB	-7.32±0.2 dB	-5.95±0.3 dB	-6.93±0.1 dB	-6.29±0.1 dB
SNOM	-4.87±0.2 dB	-5.08±0.2 dB	-4.82±0.1 dB	-5.17±0.2 dB	-4.76±0.1 dB

Figure 5.12: Waveguide images at the output facet

5.3.3 Optical Interaction of Biological Samples

In many biological samples, the change in the refractive index is one of the most important parameters for clinical scientists to analyze the presence of certain molecules. The refractive index changes that need to be observed are claimed to be less than 10^{-5} . In this regard, optical phase measurement is one of the useful methods for the required refractive index detection. In addition, the feature size to be observed has gone far beyond the diffraction limits. Thus, an instrument of high spatial resolution with high sensitivity optical detection technique is required. The multi-wavelength modulation SNOM proposed earlier is a suitable option.

Optical images of biological samples have been obtained using the interferometric SNOM set-up which is shown in Figure 5.6(b). In this section, we shall demonstrate the use of SNOM for the phase detection of two types of biological dyes.

First, the use of optical phase information obtained via multi-wavelength modulation SNOM in a constant height sample has yielded very good results. This sample consists of an array of biological sample enclosed in a polymer cavity. This polymer cavity is coated with about 100 nm of gold. The coated gold surface gives a very flat topography which enabled us to achieve constant height detection, although the

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SNOM system is operating in the constant separation mode. The image is taken in the transmission-collection mode (Figure 5.13(b)). The laser diode used is same as the pigtail laser diode used in previously mentioned experiments. The laser diode has been modulated using a 50 mV saw-tooth signal. The gain of the optical signal PMT is set at 8×10^6 , while the gain of the reference signal PMT is set at 1×10^3 . After all the optical alignments are done, the SNOM probe approaches the sample surface to scan the optical image. The topographic and optical images are shown in Figure 5.13. From the phase information, we can observe the different contents in the polymer cavities. The bright spots are the areas with higher refractive index, which contains the sample. Due to the flat surface of the sample, these scanned results show the true optical phase change rather than the topographical artifacts. The scan lines during the imaging are due to some disturbances at one of the arms of the interferometry.

In this sample, the illumination-collection mode (Figure 5.13(c)) has also been applied, but the SNR is only about 10 dB. The experimental details remained the same as before. The reason for a poorer contrast is due to the -40 dB loss in the throughput of the probe. This is because the illumination-collection mode uses the probe as the illuminator and the collector, and so the optical signal is attenuated twice.

Figure 5.13: Biological sample imaging using multi-wavelength modulation SNOM

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Next, the optical image of another biological dye is also tested. The biological dye is known as crystal violet, which is used as florescence markers for biological samples. The sample is coated with about 50 nm layer of silver. The experimental set-up is based on the transmission-collection SNOM. The results are shown in Figure 5.14. A FE-SEM operating at 5 KV is used to characterize the structure of this sample. From the SEM image, spheres of sizes that range from 200-300 nm are observed and the structural layout is irregular and random. Similarly, this irregular layout is also shown in the AFM images. The optical phase of the sample is also detected. Here, some of the features can be correlated to the topography images. This shows that the optical phase imaging is capable of differentiating each dye. However, in the optical images, it is found that some unknown lines have appeared in the SNOM images. This could be due to the disturbance of noise from the environment which causes fluctuations at the phase wrapping region, thus the unwrapping of the phase is not done adequately.

Figure 5.14: Biological dye imaging using multi-wavelength modulation SNOM

5.4 Conclusion

In conclusion, we have successfully intergraded a versatile high sensitivity SNOM system. Due to the picoWatt signals from the SNOM probe, a very sensitive system of at least -90 dBm is required and this has been achieved through the research effort. The SNOM optical set-up based on multi-wavelength modulation has been implemented into the SNOM system to achieve a high sensitivity detection. Actual experimental results have shown significant improvement if we use the multi-wavelength modulation SNOM as compared to the basic SNOM system. With the proposed multi-wavelength modulation SNOM, a subwavelength displacement sensor can also be achieved. To ensure credible results, proper calibration of the displacement sensor is necessary. Finally, the application of the proposed SNOM on different samples are demonstrated and confirmed the capabilities of this SNOM set-up.

Chapter 6

Conclusions and further works

6.1 Conclusion

The thesis covers the development of a versatile high sensitivity SNOM system. The sensitivity improvement of the weak signal in SNOM system is achieved through the exploration of new devices and methods. These improvements are centered on two critical aspects of the SNOM technology: the weak electrical detection for the probe-sample separation and the weak optical detection of the near-field signals. The improvements of the weak electrical signal detection are integrated together to implement a very high sensitive probe-sample separation SPM. On the basis of this SPM, other innovations for weak optical detection are developed to obtain a high sensitivity SNOM system.

A high sensitivity weak electrical signal detection is implemented in three aspects. The first aspect is the enhancement of the Q-factor of the tuning fork sensor. A two-coupled oscillators model is proposed to represent the dynamics of a tuning fork with a probe attached. By applying a frequency-domain system identification approach in the experimental investigation of various cases of probe attachment, an

accurate model is demonstrated. The model is tested with quantitative analysis of the noise performance and the sensitivity of force sensing as compared to another tuning fork probe. Based on the dynamic model, the theoretical analysis of the Q-factor improvement based on prong balancing is presented. The balancing of probe can give a Q-factor improvement of 15 times. The effectiveness of the approach is demonstrated by comparing the unbalanced and the balanced probes on an atomic force microscope, and the balanced probe shows vastly improved topographic images. This method is not restricted to our SNOM system but can be readily extended to other SPM systems that use two beam oscillator as a sensing device.

The second aspect is the improvement of the detection sensitivity of the sensor response. An active quadrature detection method for high sensitivity tuning fork response is introduced. The quadrature lock-in signals, the X and Y components, are used in different gain combinations to improve the sensitivity of the tuning fork response. The gain is obtained by maximizing the gradient of the resonant response at a given operating frequency. Simulation and experimental results on the frequency response graph show an improvement in the Q-factor. The effectiveness of the phase compensation technique is demonstrated on the gratings samples.

The third aspect is the improvement on the SNR and time response of the lock-in detection. This is done by examining the lock-in system design. The design is done by considering an additional feedforward control signal and the loop filter parameters using the second method of Lyapunov. A non-linear lock-in detection design based on a feed-forward control signal is used to improve the speed of the lock-in detection with the SNR determined by the loop filter. Based on the simulation results, the design scheme that is based on the nonlinear model demonstrates a five times better transient performance.

Based on the integration of the above three innovations, a highly sensitive SPM is

built. Thus, the near-field optical signal can be harnessed. However, this near-field signal is very weak and a high sensitivity optical signal detection method is developed.

The introduction of coherent detection into interferometry SNOM has yield the desired improvement in the sensitivity of the weak optical signal detection. Using a combination of coherent detection and electrical lock-in, further improvement of the sensitivity is achieved. The coherent detection uses the concept of shot noise limit detection and it improves the SNR by 50 dB when compared to the direct detection method. The lock-in detection reduces the bandwidth of the noise by at least a factor of 3. The total SNR improvement of coherent detection with modulation techniques can be as much as 80 dB.

Based on the interferometry SNOM, the optical path difference between the sample arm and the reference arm is obtained. A displacement sensor is then achieved based on the calibration of the optical phase data. The displacement information of sub-wavelength features is obtained. The system is able to achieve a 5 nm change in displacement. This can be further improved by considering the implementation issues. Furthermore, multi-harmonics averaging is applied to the detected signal to achieve displacement resolution with 1.27nm standard deviation. The variance of the phase drops by half after applying this technique. The multi-harmonics averaging techniques can also be used on other sensors in improve the SNR.

We have also realized a versatile SNOM system for real application imaging. Various modes using fiber optics are built for different types of samples for a better optical contrast. The different modes of SNOM imaging show good contrast results in samples such as photonics crystal devices, waveguides structures and biological samples. In all this cases, the SNOM system built has shown high sensitivity detection in both electrical and optical domains, which meets the requirements of real applications in industry and research.

6.2 Recommendation of future research

Despite our significant successes, there are still many problems that need to be studied and explored as far as weak signal detection of SNOM is concerned. In future, the possible topics that are interesting for further explorations are listed below.

- To investigate the possibilities of using the tuning fork sensor for nano-tribology measurements, especially based on the improved model of the tuning fork. The tuning fork sensor is a non-destructive detection technique, which is favored in many applications. However, the tuning fork probe does not have a good model to characterize the shear force interaction. Thus, we will like to extend the use of the improved model to describe the shear force interaction or tribology.
- The high speed PLL has been demonstrated in the simulation studies. The critical implementation issues of a high speed PLL in the hardware must be considered as the non-linear controller may not be feasible. Due to the nature of the feedforward controller, which is a tangent function, the implementation of this controller is challenging.
- A high bandwidth with high Q-factor detection method is required for high sensitivity time resolved issues. A frequency modulation (FM) detection method can also be considered. The detection is based on frequency shift while maintaining a constant amplitude. This can be implemented using a feedback controller circuit to control the amplitude of the tuning fork probe response, at the same time, the frequency shift can be detected using a PLL.
- For an unknown sample, the optical phase information is not the true displacement. This is due to the unknown refractive index of the sample. There are two unknown physical quantities, the displacement and the refractive index. Hence,

more studies and explorations are required to extract the physical quantities from the optical phase information.

- To increase the number of harmonics for the multi-harmonics averaging in the SNOM system. Currently, the SNOM system can only detect up to 4 harmonics components. This is due to some practical limitations. For any standard lock-in amplifier circuit, there is a fixed number of output signals, typically two. Thus, we have to develop a more comprehensive lock-in amplifier capable of detecting more harmonics components.
- There is a certain relationship between the different harmonics in the multi-wavelength modulation technique. Further exploration and optimization of the weights relationship are required for better performance in the overall SNR. Since different harmonics gives different SNR values, we can find an optimal weights combination for a particular system.

Appendix I: Comparison of Direct Detection and Coherent Detection in our SNOM Setup

The noise equivalent power (NEP) of the output electrical signal is used to measure the sensitivity of the SNOM optical detection system. The NEP is obtained by letting $SNR = 1$. Here, the SNR expression is obtained first. The output photon current of the optical detection process can be expressed as,

$$i_s(t) = \Re P_s(t) \quad (6.1)$$

where $\Re = (G\eta q/hv)$ is the responsivity of the detector, with G being the gain of the PMT η the quantum efficiency, q the electronic charge, h the plank constant, and v the frequency of the optical signal. In our SNOM, a PMT module, H5784-20 from Hamamatsu, is used as the photodetector. Since the output of the PMT module is a voltage source, with a transimpedance gain of $R_{PMT} = 1 \text{ M}\Omega$ and $\Re = 15.6 \text{ K}$, the SNR is expressed in terms of the mean square voltage, $\langle v_s^2 \rangle = R_{PMT}^2 \Re^2 \langle P_s^2(t) \rangle$. The total noise source consists of a few uncorrelated noise voltage sources; the photon shot noise, the optical background, the dark current shot noise, the thermal noise and the $\frac{1}{f}$ noise. The noise mean square voltages are denoted respectively as $\langle n_{ps}^2 \rangle$,

$\langle n_b^2 \rangle$, $\langle n_{ds}^2 \rangle$, $\langle n_t^2 \rangle$ and $\langle n_f^2 \rangle$. The SNR of output mean square voltages of the optical system can then be expressed as,

$$SNR = \frac{\langle v_s^2 \rangle}{\langle n_{ps}^2 \rangle + \langle n_b^2 \rangle + \langle n_{ds}^2 \rangle + \langle n_t^2 \rangle + \langle n_f^2 \rangle} \quad (6.2)$$

In order to characterize the noise of the detection circuit, the average noise power of the PMT is measured using a lock-in amplifier in a dark environment. However, the total noise is subject to two environmental conditions. First, the configuration of the SNOM affects the optical background noise. The optical signal collected through the SNOM probe gives a lower background noise than those using the far-field collection. Second, the exposure time of PMT to ambient light over a period of time affects the amount of dark current. Thus, the SNOM system is usually enclosed in a black box for at least 15 mins before the scanning process to minimize the dark current shot noise and the background noise. Under this condition, and with the probe as the collector, the total noise at the output of the PMT is be measured using the lock-in amplifier and the average noise voltage density above 1 kHz is $4.53 \mu\text{V}/\sqrt{\text{Hz}}$. This total noise included the optical background, the dark current shot noise, the thermal noise. The $\frac{1}{f}$ noise will be insignificant in the case of modulation detection as the detection bandwidth is shifted into the KHz region. For simplification, (6.2) and the NEP can be expressed as,

$$SNR = \frac{\langle v_s^2 \rangle}{\langle n_{ps}^2 \rangle + \langle n_{Total}^2 \rangle} \quad (6.3)$$

$$NEP = \sqrt{\frac{\langle n_{ps}^2 \rangle + \langle n_{Total}^2 \rangle}{\Re^2 P_{PMT}^2}} \quad (6.4)$$

where $\langle n_{Total}^2 \rangle$ is the total noise. In the collection mode SNOM with modulation, $\langle n_{Total}^2 \rangle = \langle n_t^2 \rangle + \langle n_{ds}^2 \rangle$ because the other two components are negligible. Now, the

only unknown noise is the photon shot noise which can be expressed as,

$$\langle n_{ps}^2(t) \rangle = 2BqI_sR_PMT^2. \quad (6.5)$$

where B is the bandwidth of the detector, $I_s = \langle i_s t \rangle$ is the mean photon current, and q is the electrical charge constant.

Next, the NEP of the direct detection is calculated using (6.4). In the SNOM setup, the optical power is usually in the pico Watt range, thus the photon shot noise can be ignored because $\langle n_{Total}^2 \rangle \gg \langle n_{ps}^2 \rangle$, typically by an order of 3. Considering that the bandwidth of the detector is $B = 20$ KHz, the minimum detectable optical power is 41.06 fW.

In order to enhance the optical signal, shot noise limited detection is required. It is impossible to achieve this limit as the optical signal of SNOM is far too weak. Thus, only the coherent detection method can make shot noise limited detection possible. In coherent detection, a local oscillator (LO) light source is used to interfere with the SNOM signal. The LO is usually very large and the photon shot noise generated will be correspondingly large as well. Thus, the noise term is overwhelmed with the photon shot noise and the ideal shot noise limited detection is expressed as,

$$SNR = \frac{\langle v_s^2 \rangle}{\langle n_{ps}^2 \rangle} = \frac{\Re \langle P_s \rangle}{2Bq}. \quad (6.6)$$

Practically, a large LO may not be possible and we define the shot noise limit when the photon shot noise power is equal to the total circuit power, i.e. $\langle n_{Total}^2 \rangle = \langle n_{ps}^2 \rangle$. Thus, it is more meaningful to express the SNR as,

$$SNR_{SL} = \frac{\langle v_s^2 \rangle}{2\langle n_{ps}^2 \rangle} = \frac{\Re \langle P_s \rangle}{4Bq}. \quad (6.7)$$

From the (6.7), the NEP is 8.21×10^{-18} W. Clearly, the sensitivity of the coherent detection is 50.02 dB higher than the direct detection method in SNOM system.

Appendix II: Matlab Simulink

Codes and Simulation Parameter for PLL Analysis

The model of the Matlab simlink are shown in the figure below. The solver used in the simulation is ode45(Dormand-Prince) with a variable step options. The initial condition of the integrator are set to zero. The parameters for the gains and the loops filters are set according to the results described in chapter 3. The subsystem is the traditional PLL. The model is shown in the second figure below. The third model is used to simulate of the gain saturation. A saturation block is added after the multiplier in the feed forward loop.

Figure 6.1: Model used for the numerical analysis of the PLL

Figure 6.2: Subsystem of the above figure

Figure 6.3: Model used in saturation analysis of the feed forward gain

Author's Publications

1. B. P. Ng, Y. Zhang, and Y. C. Soh, "Phase locked-in loop design with pre-specified transient performance," *Proceedings of SPIE*, vol.5907, art. no.59070U, pp.1-8, 2005.
2. B. P. Ng, H. L. Seck, Y. Zhang, and Y. C. Soh "Optical Detection using Multi-wavelength Modulation," *Key Engineering Materials*, vol.381, pp.325-328, 2008.
3. B. P. Ng, Z. G. Dong, S. W. Kok, Y. Zhang, and Y. C. Soh, "Loss Measurement of Photonic Integrated Waveguides by Scanning Near-field Optical Microscopy," *Frontiers in Optics 2008/Laser Science (LS) XXIV conference*, JWA-58, 2008.
4. B. P. Ng, Y. Zhang, S. W. Kok, and Y. C. Soh, "Improve Performance of Scanning Probe Microscopy by Balancing Tuning Fork Prongs," *Ultramicroscopy*, vol.109, pp.291, 2009.
5. B. P. Ng, Y. Zhang, S. W. Kok, and Y. C. Soh, "An Improved Dynamic Model of Tuning Fork Probe for Scanning Probe Microscopy," *J. Microscopy*, vol. 234, pp.191, 2009.
6. B. P. Ng, Y. Zhang, S. W. Kok, and Y. C. Soh, "Sensitivity Improvement based on Phase Compensation on Tuning Fork Detection System," In preparation.
7. Y. Zhang, B. P. Ng, and S. W. Kok, A fiber optic displacement sensor, Oct., 2008, TD-P-08-018.

8. Y. Zhang, B. P. Ng, and S. W. Kok, Scanning probe microscopy with a balanced tuning fork probe and a balanced detector, Oct., 2008, TD-P-019.

Bibliography

- [1] D. Hyerle, "Visual tools for transforming information into knowledge," *Corwin Press*, Thousand Oaks, 2nd Ed, 2009.
- [2] <http://www.jwst.nasa.gov/about.html>
- [3] G. E. Moore, "Cramming more components onto integrated circuits," *Electronics Magazine*, vol.38, 1965.
- [4] E. Abbe, "Beiträge zur Theorie des Mikrockops und der mikroskopischen Wahrnehmung," *Archiv f. Miroskop. Anat.*, vol.9, pp.413, 1873.
- [5] S. B. Ippolito, B. B. Goldberg, and M. S. Ünlü, "High spatial resolution subsurface microscopy," *Appl. Phys. Lett.*, vol.78, pp.4071, 2001.
- [6] S. W. Hell, "Far-field Optical Nanoscopy," *Science*, vol.316, pp.1153, 2007.
- [7] S. W. Hell, and J. Wichmann, "Breaking the diffraction resolution limit by stimulated emission," *Opt. Lett.* vol.19, pp.780, 1994.
- [8] M. G. L. Gustafsson, "Non-linear structure-illumination microscopy: Wide-field fluorescence imaging with theoretically unlimited resolution," *Proc. Nat. Acad. Sci.*, vol.102, pp.13081, 2000.

- [9] M. J. Rust, M. Bates, and X. Zhuang, "Sub-diffraction-limit imaging by stochastic optical reconstruction microscopy (STORM)," *Nature Methods*, vol.3, pp.793, 2006.
- [10] E. Betzig, G. H. Patterson, R. Sougrat, O. W. Lindwasser, S. D. Olenych, J. S. Bonifacino, M. W. Davidson, J. C. Lippincott-Schwartz, and H. F. Hess, "Imaging intracellular fluorescent proteins at nanometer resolution," *Science*, vol.313, pp.1642, 2006.
- [11] W. Denk, J. H. Strickler, and W. W. Webb, "2-photon laser scanning fluorescence microscopy," *Science*, vol.248, pp.73, 1990.
- [12] M. R. Beversluis, L. Novotny, and S. J. Stranick, "Programmable vector point-spread function engineering," *Opt. Exp.*, vol.14, pp.2650, 2006.
- [13] M. Dyba and S. W. Hell, "Focal spots of size $\lambda/23$ open up far-field fluorescence microscopy at 33 nm axial resolution," *Phys. Rev. Lett.*, vol.88, pp.163901, 2002.
- [14] X. Zhang and Z. Liu, "Superlenses to overcome diffraction limits," *Nature materials*, vol.7, pp.435, 2008.
- [15] Z. Jacob, L. V. Alekseyev, and E. Narimanov, "Optical Hyperlens: Far-field imaging beyond the diffraction limit," *Opt. Exp.*, vol.14, pp.8247, 2006.
- [16] E. H. Synge, "A suggested model for extending microscopic resolution into the ultra-microscopic region," *Phil. Mag.*, vol.6, pp.356, 1928.
- [17] D.W. Pohl, W. Denk, and M. Lanz, "Optical stethoscopy: Image recording with resolution $\lambda/20$," *Appl. Phys. Lett.*, vol.44, pp.651, 1984.
- [18] L. Novotny and B. Hecht, "Principles of Nano-optics," *Cambridge University Press*, Cambridge, 2006.

- [19] B. Hecht, B. Sick, U.P. Wild, V. Deckert, R. Zenobi, O.J.F. Martin, and D.W. Pohl, "Scanning near-field optical microscopy with aperture probes: Fundamentals and applications," *J. of Chem. Phys.*, vol.12, pp.7761, 2000.
- [20] J. W. P Hsu, "Near-Field scanning optical microscopystudies of electronic and photonic material and devices," *Mat. Sci. and Eng.*, vol.33, pp.1, 2001.
- [21] G. Binning, H. Rohrer, C. Gerber, and E. Weibel, "Surface studies by scanning tunneling microscopy," *Phys. Rev. Lett.*, vol.49, pp.57, 1982.
- [22] H. Muramatsu ,K. Homma, N. Yamamoto, J. Wang, K. Sakata-Sogawa, and N. Shimamoto, "Imaging of DNA molecules by scanning near-field microscope," *Mat. Sci. and Eng. C* vol.12, pp.29, 2000.
- [23] A. Vollkopf, O. Rudow, T. Leinhos, C. Mihalcea, and E. Oesterschulze, "Modified fabrication process for aperture probes cantilevers," *J. Mircoscopy*, vol.194, pp.344, 1999.
- [24] Y. Inouye and S. Kawata, "Near-field scanning optical microscope with a metallic probe tip," *Opt. Lett.*, vol.19, pp.159, 1994.
- [25] D. P. Tsai and Y. Y. Lu, "Tapping-mode tuning fork force sensing for near-field scanning optical microscopy," *Appl. Phys. Lett.*, vol.73, pp.2724, 1998.
- [26] K. Karrai and R. D. Grober, "Piezoelectric tip-sample distance control for near-field optical microscopes," *Appl. Phys. Lett.*, vol.66, pp.1842, 1995.
- [27] M. Ono, H. Sone, and S. Hosaka, "Prototype of atomic force cantilevered SNOM based on Through-The-Lens-Type optical lever and polarized illumination and detection system," *Jap. J. Appl. Phys.*, vol.44, pp.5434, 2005.

- [28] K. Karrai, "Lecture notes on shear and friction force detection with quartz tuning forks," *Work presensted at the "Ecole Thématique du CNRS" on near-field optics*, March 2000.
- [29] R. M. Cramer, V. Ebinghaus, R. Heiderhoff, and L. J. Balk, "Near-field detection cathodoluminescence investigations," *J. Phys. D*, vol.31, pp.1918, 1998.
- [30] R. D. Grober, J. Acimovic, J. Schuck, D. Hessman, P. J. Kindlemann, J. Hespanha, A. Stephen Morse, K. Karrai, I. Tiemann, and S. Manus, "Fundamental limits to force detection using quartz tuning forks," *Rev. Sci. Instrum.*, vol.71, pp.2776, 2000.
- [31] J. M. Vigoureux and D. Courjon, "Detection of nonradiative fields in light of the Heisenberg uncertainty principle and the Rayleigh criterion," *Appl. Opt.*, vol.31, pp.3170, 1992.
- [32] A. V. Zayats and V. Sandoghdar, "Apertureless near-field optical microscopy via local second harmonic generation," *J. Microscopy*, vol.202, pp.94, 2001.
- [33] Y. Sasaki and H. Sasaki, "Heterodyne detection for the extraction of the probe-scattering signal in scattering-type scanning near-field optical microscope," *Jpn. J. Appl. Phys.*, vol.39, pp.321, 2000.
- [34] A. Bek, R. Vogelgesang, and K. Kern, "Apertureless scanning near field optical microscope with sub-10 nm resolution," *Rev. Sci. Instrum.*, vol.77, pp.043703, 2006.
- [35] P. K. Wei, J. H. Hsu, W. S. Fann, and K. T. Tsai, "Dual optical mode near-field scanning optical microscopy," *Appl. Opt.*, vol.35, no.34, pp.6727, 1996.
- [36] E. Betzig, M. Isaacson, and A. Lewis, "Collection mode near-field scanning optical microscopy," *Appl. Phys. Lett.*, vol.51, pp.2088, 1987.

- [37] A. Nesci, R. Dändliker, and H. P. Herzig, "Quantitative amplitude and phase measurement by use of a heterodyne scanning near-field optical microscope," *Opt. Lett.*, vol.26, no.4, pp.208, 2001.
- [38] K. Nakamoto, C. B. Mooney, and S. Kitamura, "AC mode feedback and gate pulse acquisition methods for scanning Near-Field Optical Microscope," *Jpn. J. Appl. Phys.*, vol.43, pp.2686, 2004.
- [39] B. Hecht, H. Bielefeldt, D. W. Pohl, L. Novotny, and H. Heinzelmann, "Influence of detection conditions on near-field optical imaging," *J. Appl. Phys.*, vol.84, pp.5873, 1998.
- [40] J. Park, M. R. Kim, and W. Jhe, "Resolution enhancement in reflection mode near-field optical microscope by second-harmonic modulation signals," *Opt. Lett.*, vol.25, pp.628, 2000.
- [41] E. Betzig, J. K. Trautman, R. Wolfe, E. M. Gyorgy, P. L. Finn, M. H. Kryder, and C. H. Chang, "Near-field magneto-optics and high density data storage," *Appl. Phys. Lett.*, vol.61, pp.142, 1992.
- [42] N. Hayazawa, M. Motohashi, Y. Saito, and S. Kawata, "Highly sensitive strain detection in strained silicon by surface-enhanced Raman spectroscopy," *Appl. Phys. Lett.*, vol.86, pp.1, 2005.
- [43] D. Isakov, T. Geinzer, A. Tio, J. C. H. Phang, Y. Zhang, and L.J. Balk, "Scanning near-field photon emission microscopy," *IEEE IRPS Proc.*, pp.575, 2008.
- [44] C. Höppener and L. Novotny, "Imaging of membrane proteins using antenna-based optical microscopy," *Nanotechnology*, vol.19, pp.384012, 2008.

- [45] A. P. Cherkun, D. V. Serebryakov, S. K. Sekatskii, I. V. Morozov, and V. S. Letokhov, "Double-resonance probe for near-field scanning optical microscopy," *Rev. Sci. Instrum.*, vol.77, pp.033703, 2006.
- [46] J. Morville, J. Liu, A. Callegari, and M. Chergui, "Q-factor optimization of a tuning-fork/fiber sensor for shear-force detection," *Appl. Phys. Lett.*, vol.86, pp.064103, 2005.
- [47] D. Mulim, C. Vannier, C. Bainier, D. Courjon, and M. Spajer, "Easy-to-use unglued tip replacement near-field optical microscope with piezoelectric shear force detection," *Rev. Sci. Instrum.*, vol.71, pp.3441, 2000.
- [48] P. Muhlschlegel, J. Toquant, D.W. Pohl, and B. Hecht, "Glue-free tuning fork shear-force microscope," *Rev. Sci Instrum.*, vol.77, pp.016105, 2006.
- [49] N. Hosaka and T. Saiki, "10nm spatial resolution fluorescence imaging of single molecules by near-field scanning optical microscopy using a tiny aperture probe," *Opt. Rev.*, vol.13, pp.262, 2006.
- [50] K. Karrai and I. Tiemann, "Interfactual shear force microscopy," *Phys. Rev. B*, vol.62, pp.13174, 2000.
- [51] D. V. Serebryakov, A. P. Cherkun, B. A. Loginov, and V. S. Letokhov, "Tuning-fork-based fast highly sensitive surface-contact for atomic force microscopy/near-field scanning optical microscopy", *Rev. Sci. Instrum.*, vol. 73, pp. 1795, 2002.
- [52] K. B. Shelimov, D. N. Davydov, and M. Moskovits, "Dynamics of a piezoelectric tuning fork/optical fiber assembly in a near field scanning optical microscope," *Rev. Sci. Instrum.*, vol.71, pp.437, 2000.

- [53] A. Crottini, J.L. Staehli, B. Deveaud, X.L. Wang, and M. Ogura, "Ultra stable tuning fork sensor for low-temperature near-field spectroscopy," *Ultramicroscopy*, vol.90, pp.97, 2002.
- [54] A. Naber, H. J. Maas and K. Razavi, and U. C. Fischer, "Dynamic force distance control suited to various probes for scanning near-field optical microscopy," *Rev. Sci. Instrum.*, vol.70, pp.3955, 1999.
- [55] M. Barbic, L. Eliason, and J. Ranshaw, "Femto-Newton force sensitive quartz tuning fork sensor," *sensor and Actuators*, vol.136, pp.564, 2007.
- [56] F.J. Giessibl, "Advances in atomic force microscopy," *Rev. Modern Phys.*, vol.75, pp.949, 2003
- [57] A. Naber, "Tuning fork as sensor for dynamic force distance control in scanning near-field optical microscopy," *J. Microscopy*, vol.194, pp.307, 1999.
- [58] C. L. Jahncke, O. Brandt, K. E. Fellows, and H. D. Hallen , "Choosing a preamplifier for tuning fork signal detection in scanning force microscopy," *Rev. Sci. Instrum.* ,vol.75 , pp.2759, 2004.
- [59] A. G. T. Ruiter, J. A. Veerman, K. O. van der Werf, and N. F. van Hulst, "Dynamic behaviour of tuning fork shear-fork feedback," *Appl. Phys. Lett.*, vol.71, pp.28, 1997.
- [60] M. Lee, J. Jahng, K. Kim, and W. Jhe, "Quantitative atomic force measurement with quartz tuning fork," *Appl. Phys. Lett.*, vol.91, pp.023117, 2007.
- [61] M. Labardi, "Dynamnics of probes attached to quartz tuning forks for the detection of surface forces," *Nanotechnology*, vol.18, pp.084019, 2007.
- [62] A. Mandelis, "Signal-to-noise in lock-in amplifier synchronous detection: A generalized communications systems approach with applications to frequency,

- time and hybrid(rate window) photothermal measurements”, *Rev. Sci. Instrum.*, vol.65, pp.3309, 1994.
- [63] W. A. Atia and C. C. Davis, “A phase-locked shear-force microscope for distance regulation in near-field optical microscopy”, *Appl. Phys. Lett.*, vol.70, pp.405, 1997.
- [64] M. L. Meade, “Lock-in amplifiers: principles and applications”, *IEE electrical measurement series 1*, Peter Peregrinus Ltd, 1983.
- [65] R. Alonso, F. Villuendas, J. Borja, L. A. Barragán, and I. Salinas, “Low-cost, digital lock-in module with external reference for coating glass transmission/reflection spectrophotometer,” *Meas. Sci. Technol.*, vol.14, pp.511, 2003.
- [66] I. Gunev, A. Varol, S. Karaman, and C. Basdogan, “Adaptive Q control for tapping-mode nanoscanning using a piezoactuated bimorph probe”, *Rev. Sci. Instrum.*, vol.78, pp.043707, 2007.
- [67] J. W. P. Hsu, A. A. McDaniel, and H. D. Hallen, “A shear force feedback control system for near-field scanning optical microscopes without lock-in detection”, *Rev. Sci. Instrum.*, vol.68, pp.3093, 1997.
- [68] A. Grant and L. McDonnell, “A non-contact mode scanning force microscope optimised to image biological samples in liquid”, *Ultramicroscopy*, vol.97, pp.177, 2003.
- [69] M. Lippitz, M. Schuttler, H. Giessen, M. Born, and W. W. Rühle, “Bandwidth enhancement of a shear-force-controlled distance regulation in near-field microscopy,” *J. Appl. Phys*, vol.86, pp.100, 1999.
- [70] J. Jahng, M. Lee, and H. Noh, Y. Seo, and W. Jhe, “Active Q control in tuning-fork-based atomic force microscopy,” *Appl. Phys. Lett.*, vol.91, pp.023103, 2007.

- [71] T. R. Albrecht, P. Grütter, D. Horne, and D. Rugar, "Frequency modulation detection using high-Q cantilevers for enhanced force microscopy sensitivity," *J. Appl. Phys.*, vol.69, pp.668, 1991.
- [72] D. Kobayashi, S. Kawai, and H. Kawakatsu, "New FM detection techniques for scanning probe microscopy," *Jap. J. Appl. Phys.*, Vol.43, pp.4566, 2004.
- [73] J. J. Greffet and R. Carminati, "Image formation in near-field optics," *Prog. Surface Sci.*, vol.56, pp.133, 1997.
- [74] C. Bouwkamp, "On Bethes theory of diffraction by small holes," *Philips Res. Rep.*, vol.5, pp.321, 19450.
- [75] M. Stähelin, M. A. Bopp, G. Tarrach, A. J. Meixner, and I. Z. Gränacher, "Temperature profile of fiber tips used in scanning near-field optical microscopy," *Appl. Phys. Lett.*, vol.68, pp.2603, 1996.
- [76] A. Lewis, M. Isaacson, A. Harootunian, and A. Muray, "Development of a 500 Å spatial resolution light microscope: I. light is efficiently transmitted through $\lambda/16$ diameter apertures," *Ultramicroscopy*, vol.13, pp.227, 1984.
- [77] L. Novotny, D. W. Pohl, and B. Hecht, "Scanning near-field optical probe with ultrasmall spot size," *Opt. Lett.*, vol.20, pp.970, 1995.
- [78] S. Patanè, E. Cefalì, A. Arena, P. G. Gucciardi, and M. Allegrini, "Wide angle near-field optical probes by reverse tube etching," *Ultramicroscopy*, vol.106, pp.475, 2005.
- [79] T. Yatsui, M. Kourogi, and M. Ohtsu, "Increasing throughput of a near-field optical fiber probe over 1000 times by the use of a triple-tapered structure," *Appl. Phys. Lett.*, vol.73, pp.2089, 1998.

- [80] J. Radojewski and P. Grabiec, "Combined SNOM/AFM microscopy with micro-machined nanoapertures," *Mat. Sci.*, vol.21, pp.320, 2003.
- [81] N. M. Arslanov, "The optimal form of the scanning near-field optical microscopy probe with subwavelength aperture," *J. Opt. A*, vol.8, pp.338, 2006.
- [82] U. C. Fischer and D. W. Pohl, "Observation on single-particle plasmons by near-field optical microscopy," *Phys. Rev. Lett.*, vol.62, pp.458, 1989.
- [83] L. Vaccaro, L. Aeschimann, U. Staufer, H. P. Herzig, and R. Dändliker, "Propagation of the electromagnetic field in fully coated near-field optical probes," *Appl. Phys. Lett.*, vol.83, pp.584, 2003.
- [84] N. A. Janunts, K. S. Baghdasaryan, K. V. Nerkararyan, and B. Hecht, "Excitation and superfocusing of surface plasmon polaritons on a silver-coated optical fiber tip," *Opt. Commun.*, vol.253, pp.118, 2005.
- [85] O. Sqalli, I. Utke, P. Hoffmann, and F. Marquis-Weible, "Gold elliptical nanoantennas as probes for near field optical microscopy," *J. Appl. Phys.*, vol.92, pp.1078, 2002.
- [86] H. G. Frey, F. Keilmann, A. Kriele, and R. Guckenberger, "Enhancing the resolution of scanning near-field optical microscopy by a metal tip grown on an aperture probe," *Appl. Phys. Lett.*, vol.81, pp.5030.
- [87] E. Prodan, C. Radloff, N. J. Halas, and P. Nordlander, "A hybridization model for the plasmon response of complex nanostructures," *Science*, vol.302, pp.419, 2003.
- [88] R.D. Grober, R.J. Schoelkopf, and D.E. Prober, "Optical antenna: Towards a unity efficiency near-field optical probe," *Appl. Phys. Lett.*, vol.70, pp.1354, 1997.

- [89] F. Keilmann and R. Hillenbrand, "Near-field microscopy by elastic light scattering from a tip," *Phil. Trans. Royal Soc. A*, vol.362, pp.787, 2004.
- [90] N. Anderson, A. Bouhelier, and L. Novotny, "Near-field photonics: tip-enhanced microscopy and spectroscopy on the nanoscale," *J. Opt. A*, vol.8, pp. S227, 2006.
- [91] E. J. Sánchez, L. Novotny, and X. S. Xie, "Near-field fluorescence microscopy based on two-photon excitation with metal tips," *Phys. Rev. Lett.*, vol.82, pp.4014, 1999.
- [92] M. Kiguchi and M. Kato, "Near-field optical microscopy using an integrating sphere," *Appl. Phys. B*, vol.73, pp.727, 2001.
- [93] G. R. Osche, "Optical Detection Theory for Laser Applications," *A John Wiley & Sons, Inc*, 2002.
- [94] S. B. Alexander, "Optical Communication Receiver Design," *SPIE Optical Engineering Press, The Institution of Electrical Engineers*, 1997.
- [95] H. P. Yuen and V. W. S. Chan, "Noise in homodyne and heterodyne," *Opt. Lett.*, vol.8, no.3, pp.177-179, 1983.
- [96] A. F. Elrefaie, D. A. Atlas, L. G. Kazovsky, and R. E. Wanger, "Intensity noise in ASK coherent Lightwave Receiver," *Electronic. Lett.*, vol.24, no.3, pp.158, 1988.
- [97] H. Uehara, I. Seto, T. Ohtsuki, I. Sasase, and S. Mori, "Impact of local oscillator intensity noise in coherent optical polsk heterodyne/homodyne receivers," *IEEE Pac Rim*, pp.757-760, 1993.
- [98] J. H. Shapiro, "Quantum noise and excess noise in optical homodyne and heterodyne receivers," *IEEE J. of Quan. Elect.*, vol.21, no.3, pp.237-250, 1985.

- [99] S. Machida and Y. Yamamoto, "Quantum-limited operation of balance mixer homodyne and heterodyne Receivers," *IEEE J. of Quan. Elect.*, vol.22, no.5, pp.617-624, 1986.
- [100] W. Grice and I. A. Walmsley, "Homodyne detection in a photon counting application," *J. of Modern Opt.*, vol.43, no.4, pp.795-805, 1996.
- [101] G. L. Abbas, V. W. S. Chan, and T.K. Yee, "A dual-detector optical heterodyne receiver for local oscillator Noise suppression," *J. of Lightwave Tech.*, vol.3, no.5, pp.1110-1122, 1985.
- [102] M. Vaez-Iravani and R. Toledo-Crow, "Phase contrast and amplitude pseudoheterodyne interference near field scanning optical microscopy," *Appl. Phys. Lett.*, vol.62, pp.1044, 1993.
- [103] R. Hillenbrand and F. Keilmann, "Complex optical constants on a subwavelength scale," *Phys. Rev. Lett.*, vol.85, pp.3029, 2000.
- [104] M. L. M. Balistreri, J. P. Korterik, L. Kuipers, and N. F. van Hulst. "Phase mapping of optical fields in integrated optical waveguide structures," *J. Lightwave Tech.*, vol.19, pp.1169, 2001.
- [105] L. Gomez, R. Bachelot, A. Bouhelier, G. P. Wiederrecht, S. Chang, S. K. Gray, F. Hua, S. Jeon, J. A. Rogers, M. E. Castro, S. Blaize, I. Stefanon, G. Lerondel, and P. Royer, "Apertureless scanning near-field optical microscopy a comparison between homodyne and heterodyne approaches," *J. Opt. Soc. Am. B*, Vol. 23, pp.823, 2003.
- [106] N. Ocelic, A. Huber, and R. Hillenbrand, "Pseudoheterodyne detection for background-free near-field spectroscopy," *Appl. Phys. Lett.*, vol. 89, pp.101124, 2006.

- [107] L. Stebounova, B. B. Akhremitchev, and G. C. Walker, "Enhancement of the weak scattered signal in apertureless near-field scanning infrared microscopy," *Rev. Sci. Instrum.*, vol.74, pp.3670, 2003.
- [108] T. Taubner, R. Hillenbrand, and F. Keilmann, "Performance of visible and mid-infrared scattering-type near-field optical microscopes," *J. Microscopy*, vol.210, pp.311, 2002.
- [109] C. Chuang and Y. Lo, "An analysis of heterodyne signals in apertureless scanning near-field optical microscopy," *Opt. Exp.*, vol.16, pp.17982.
- [110] M. Labardi, O. Tikhomirov, C. Ascoli, and M. Allegrini, "Balanced homodyning for apertureless near-field optical imaging," *Rev. Sci. Instrum.*, vol.79, pp.033709, 2008
- [111] R. Dändliker, I. Märki, M. Salt, and A. Nesci, "Measuring optical phase singularities at subwavelength resolution," *J. Opt. A*, vol.6, pp.S189, 2004.
- [112] T. Lacoste, T. Huser, R. Prioli, and H. Heinzelmann, "Contrast enhancement using polarization-modulation scanning near-field optical microscopy (PM-SNOM)," *Ultramicroscopy*, vol.71, pp.333, 1998.
- [113] C. Gorecki, S. Khalfallah, H. Kawakatsu, and Y. Arakawa, "New SNOM sensor using optical feedback in a VCSEL-based compound-cavity," *Sensors and Actuators*, vol.87, pp.113, 2001.
- [114] P. R. Gary and R. G. Mayer, "Analysis and Design of Analog Integrated Circuits," *John Wiley & Sons, Inc*, 3rd ed., New York, 1993.
- [115] L. Meirovitch, "Fundamentals of Vibrations," *McGraw- Hill, New York*, 2001.
- [116] K.T.V Grattan, "Optical Fiber Sensor Technology", *Kluwer Academic*, 2006.

- [117] D. Kersey and A. Dandridge, "Application of Fiber-Optic Sensors," *IEEE Trans. Com. Hybrids. Manu. Tech.*, vol.13, pp.137, 1990.
- [118] J. Zheng, "Multiplexed reflectometric fiber optic frequency- modulated continuous wave interferometric displacement sensor," *Optical Engineering*, vol.44, pp.084401, 2005.
- [119] Y. Zhou and X Qiang, "Dual Fizeau heterodyne interferometry for high-precision fibre-optic displacement sensor," *Sensors and Actuators*, vol.65, pp.1, 1998.
- [120] J. Zheng, "Optical Frequency Modulated Continuous-Wave (FMCW) Interferometry," *Springer*, 2005.
- [121] M. Born, E. Wolf, "Principle of Optics," *Cambridge University Press*, 1999.
- [122] J. L. Stensby, "Phase-locked loops : theory and applications," *CRC Press*, 1997.
- [123] G. C. Hsieh and J. C. Hung, "Phase-Locked Loop Techniques - A Survey," *IEEE Trans. Industrial Elec.*, Vol.43, pp.609, 1996.
- [124] V. F. Kroupa, "Phase lock loops and frequency synthesis," *John Wiley, New York*, 2003.
- [125] D. Y. Abramovitch, "Lyapunov Redesign of Analog Phase-Lock Loops," *IEEE Trans. Commun.*, vol.38, pp.2197, 1990.
- [126] D. Y. Abramovitch, "Analysis and design of third order phase-lock loop," *Proc. IEEE Military Commun. Conf.*, vol.2, pp.455, 1988.
- [127] J. K. Holmes, "Coherent spread spectrum systems", *John Wiley & Sons*, 1982.

- [128] A. D. L. Humphris, J. K. Hobbs, and M. J. Miles, "Ultrahigh-speed scanning near-field optical microscopy capable of over 100 frames per second," *Appl. Phys. Lett.*, vol. 83, pp. 6, 2003.
- [129] M. Labardi and M. Allegrini, "Noncontact friction force microscopy based on quartz tuning fork sensors," *Appl. Phys. Lett.*, vol.89, pp.174107, 2006.
- [130] A. Georgiadis, "Gain, phase imbalance and phase noise effects on error vector magnitude," *IEEE Trans. Vehicular Tech.*, vol.53, pp.443, 2004.
- [131] Mark Lee, E. B. McDaniel, and J. W. Hsu, "An impedance based non-contact feedback control system for scanning probe microscopes," *Rev. Sci. Instrum.*, vol.67, pp.1468, 1996.
- [132] A. W. Snyder and J. D. Love, "Optical waveguide theory," *Chapman & Hall, London*, 1983.
- [133] F. P. Payne and J. P. R. Lacey, "A theoretical analysis of scattering loss from planar optical waveguide," *Opt. Quantum Electron*, vol.26, pp.977, 1994.
- [134] H. M. Lee, M. C. Oh, H. Park, W. Y. Hwang, and J. J. Kim, "End face scattering loss in integrated-optical waveguides," *Appl. Optics*, vol.36, pp.9021, 1997.
- [135] B. Regan and M. Grätzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films," *Nature*, vol.353, pp.737, 1991.
- [136] A. Mihi, F. J. López-Alcaraz, and H. Míguez, "Full spectrum enhancement of the light harvesting efficiency of dye sensitized solar cells by including colloidal photonic crystal multilayers," *Appl. Phys. Lett.*, vol.88, pp.193110, 2006.
- [137] <http://www.datasheetdir.com/78615-1C+download>

BIBLIOGRAPHY

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- [138] <http://www.national.com/mpf/LF/LF353.html>
- [139] <http://www.signalrecovery.com/7265page.htm>
- [140] <http://focus.ti.com/lit/ds/symlink/opa27.pdf>
- [141] <http://www.ntmdt-tips.com/catalog/gratings/tdg/products/TDG01.html>