INTERFEROMETRIC DISTRIBUTED FIBER OPTIC SENSING

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
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Abstract

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This thesis studies single-arm frequency-shifted interferometry (SA-FSI), a simple, compact, practical and versatile fiber optic sensing technique which have many advantages over conventional techniques. I further developed the theory of SA-FSI, and successfully demonstrate that SA-FSI can achieve long distance and high sensitivity sensing multiplexing.

Two configurations of SA-FSI have been introduced in this thesis work. In one configuration, 5 weak reflectors were put in series along two fiber links. The frequency of the driving RF signal was swept from 2.5 to 3.5 GHz at steps of 1 MHz, which leads to a spatial resolution of 0.1 m and a measurement range of 50 m. In the other configuration, we located four weak reflectors in series along a single fiber link. By sweeping the amplitude modulator driving frequency in the range between 2.7 and 3.2 GHz at steps of 41.7 KHz, a spatial resolution of 0.2 m and a measurement range of about 1 km have been demonstrated.

In this thesis work, we also build a model of the working principle of a distributed vibration sensing system developed by QPS Photronics Inc., and explore its sensing features. Three different types of sensors (QPS vibrofiber sensor, flat end fiber, and loop mirror) have been used in our experiments. Note that, in our experiments, the whole fiber link is essentially a “vibration sensor”, while the vibration sensor only serves as a reflector. Both fundamental frequency component \( f \) and higher order harmonics (e.g. \( 2f, 3f \)) are observed in experiments for these three sensors, which is consistent with our simulation results. We also find that amplitudes of peaks in the FFT spectrum vary with time. We believe this phenomena is mainly because environmental noise (including temperature drift in the lab, noise from ventilation, etc.) changes...
the polarization state of output light from the source. This leads to a time dependence of amplitudes of peaks in the FFT spectrum, according to our model of the working principle of QPS vibration sensing system.
Dedication

To my beloved parents
Acknowledgements

First I would like to express my deepest gratitude to my senior supervisor, Dr. Li Qian. Her encouragement, guidance and support from the initial to final stages of my graduate study has helped me to develop the skills and perseverance to not only take on the problems that come about in the project, but also take on challenges in my life. It is my great honor to be Li’s student. I am also very grateful to the faculty members who taught the courses I have taken during my Master’s study, especially to Dr. Li Qian and Dr. Joyce Poon, whose excellent courses have stimulated my interests in condensed matter physics. I would also like to thank my colleagues Fei Ye, Zhiyuan Tang, Felix Liao, Yang Yang, Feihu Xu, and Rojina Ghasemi for their valuable suggestions and advice during the course of this work. My appreciation also goes to all of my friends for their enduring support, especially to Ben Zhu, Shuangxing Dai and Jie Zhang. And finally, I would like to thank my parents and my siblings for being there when I needed them, and lady Audrey Hepburn for her moral support during the writing process.

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Chapter 1

Introduction

1.1 Fiber-optic sensing

1.1.1 An overview

Over the past few decades, developments in information technology have completely changed almost every aspect of our daily life. Modern telecommunication technologies allow people from remote areas to connect with each other. According to Marshall McLuhan, a media and communication theorist, the world is fast becoming a global village. Thanks to the invention of laser and low-loss optical fiber in 1960s, fiber optic communication plays a major role in the revolution of telecommunication industry. In a fiber optic communication system, information is carried by modulated optical signals, guided through long distance fibers, and received by photo detectors at the end. Nowadays telephone signals, Internet data, and cable television signals are transmitted through sophisticated networks of optical fibers at very high speed as a result of developments in fiber optic communication technology.

In parallel with these developments, fiber optic sensor technology has been a major user of technologies developed in fiber optic communication industry[1, 2, 3]. Many of the components used in fiber optic sensing industry (e.g. optical amplifier, semiconductor laser, optical coupler, splitter, and photo detector) could not have been realized without the fiber optic communication stimulus.

A fiber optic sensor can be defined as a device in which properties of optical signal (such as intensity, phase, polarization, or wavelength) is modulated in response to change in parameters of interest (e.g. strain, temperature, and pressure). In mathematics, this can be written as

\[ E'(\lambda') = T(X,\lambda)E(\lambda), \]  

(1.1)
where $E'(\lambda')$ and $E(\lambda)$ are optical signals before and after the modulation. $\lambda$ and $\lambda'$ are wavelengths of input and output lights respectively. $T(X, \lambda)$ is the transformation matrix of the sensor, and $X$ is the vector which defines change in parameters of interest.

There are many realizations of fiber optic sensors which are often loosely grouped into two classes: intrinsic sensors and extrinsic sensors[4, 5]. An intrinsic sensor or all fiber sensor keeps optical signal within the fiber all the time while environmental effect modulates the signal as it propagates along the fiber. For extrinsic sensors, optical signals are guided by a fiber into another medium which modulates properties of the signal corresponding to the environmental effect. Each of the two classes of fiber optic sensors in turn has many subclasses. Fiber optic sensors also can be classified by their working principles, including interferometric sensors based on a Sagnac or Mach Zehnder configuration, distributed sensors based on Rayleigh or Raman scattering [6, 7], fiber Bragg grating (FBG) sensors [8, 9], and luminescent fiber optic sensors [10].

Fiber optic sensors have many advantages over traditional electrical sensors[11, 12, 13]. First of all, they are intrinsically immune to electromagnetic interference (EMI) since they are made of non-conducting materials. For instance, they can be used in electric power industry where measurements are often taken place under high voltage hazards[14]. Secondly, fiber optic sensors often weigh less and need less space than metallic sensors, which make them suitable to embedment into structure or structure surface monitoring[15]. Moreover, the cost of optical fibers are reduced dramatically after years of improvements (from $20/m in the 1980s down to $0.1/m in the 1990s)[16]. As a result, sensors made of optical fibers become cheaper and cheaper in price while their optical and mechanical properties improve with time. Furthermore, fiber optic sensors often have high sensitivity, large bandwidth, multiplexability, and high reliability. These advantages offer fiber optic sensors many potential applications in aerospace, medical, civil, oil and gas, power, and mining industries. With the development in fiber optic components and the deduction of cost, fiber optic sensors will continue to play a more and more important role in high performance sensing applications. And fiber optic sensing technology will be more commercially successful and get more market share in the sensing industry.

### 1.1.2 Convectional fiber optic multiplexing techniques

One unique feature of fiber optic sensing techniques is that they can interrogate an array of discrete sensors using a single measurement system[17, 18, 19], which allows one to conveniently monitor the parameters of interest over a long range. Since the key components of the measurement system (e.g. light source, photo detector, or spectrum analyzer) are shared by
all the sensors, the cost of a large-scale fiber optic sensing system can be reduced. Several common topologies for sensor arrays, including serial network configuration, parallel network configuration, and star network configuration, are shown in Fig. 1.1.

Figure 1.1: Common topologies for fiber optic sensor arrays. (a) Serial sensor network configuration with reflective sensors; (b) Parallel sensor network configuration with reflective sensors; (c) Star sensor network configuration with transmissive sensors;

There has been considerable interest recently in multipoint or quasi-distributed fiber-optic
Commonly used multiplexing techniques include the frequency-modulated continuous-wave (FMCW) approach, time-division-multiplexing (TDM), wavelength-division-multiplexing (WDM), and combinations thereof. Note that FMCW was first implemented using regular radar, then used in optical systems. In fiber optic sensing, FMCW approach is also called as optical frequency domain reflectometry (OFDR). From now on, we will use the term of OFDR instead of FMCW in order to distinguish it from the technique used in radar.

**Optical frequency domain reflectometry - OFDR**

In an OFDR system, the frequency of the lightwave is continuously modulated with time. Signals from different sensors have different time delays, which leads to different beat frequencies when they interfere with a local reference waveform. Either a radio-frequency (RF) reference signal, or an optical local oscillator (LO) is required in an OFDR system. Note that OFDR systems measures the beat frequency between the test signal and the reference signal.

There are two different kinds of optical frequency domain reflectometry (OFDR): coherent OFDR (C-OFDR) and incoherent OFDR (I-OFDR). In the C-OFDR method, the frequency of the tunable laser source (TLS) is swept linearly in time. Then, the frequency-modulated optical signal is split into two paths: one is used to probe the device under test (DUT) while the other is used as reference signal. The test signal returning from the DUT interferes with the reference signal at a detector. The beat frequency, which can be resolved after the Fourier transform, is proportional to the time delay \( \tau \) between the two interfering signals. Given time delay \( \tau \), the locations of each reflector can be resolved finally. Fig. 1.2a shows one example configuration of C-OFDR techniques.

In the I-OFDR method, a RF signal, whose frequency is normally swept periodically over a certain frequency range, is used to modify the continuous wavelength (CW) optical probe signal. The probe signal returning from the DUT interferes with the RF signal at a detector. By performing the Fourier transform, the beat frequency of the interference (thus the time delay \( \tau \) between the signals) can be resolved. Fig. 1.2b shows one example configuration of I-OFDR techniques.

The drawback of an OFDR system with an RF reference signal is that a high-bandwidth (fast) optical detector is needed to capture the full bandwidth of the frequency-modulated lightwave. The drawback of an OFDR system with an optical local oscillator is that the measurement range is limited by the coherence length of the source.
Figure 1.2: Experimental setup of two different kinds of OFDR techniques. (a) C-OFDR with a linearly-chirped source, a coupler, a optical detector (PD), and an optical reference arm; (b) I-OFDR with a function generator, a light source, a circulator (Cir), and a RF reference arm.

**Time division multiplexing - TDM**

In time division multiplexing (TDM), optical sensors are interrogated by a short laser pulse, and reflections from different sensors are separated in time domain [39, 40, 41]. Figure 1.3 shows one experimental set up of TDM technique. The time delay between reflected signals are directly measured in time domain, which then converts into the separation between sensors.

Since reflections from different sensors are separated in time domain, a TDM system requires short laser pulses and fast photo detectors to achieve high accuracy time delay measure-
Wavelength division multiplexing - WDM

Wavelength division multiplexing (WDM) is a technique where optical signals of different wavelengths are combined and transmitted onto a single fiber\cite{42, 43}. Along with fiber optic sensors (e.g. fiber Bragg grating sensors), WDM can be used as a type of fiber optic multiplexing techniques\cite{44, 45}. Fig. 1.4 shows one example configuration of WDM fiber optic sensing technique, where a broadband source is used to interrogate a quasi-distributed chain.
of sensors. Each sensor has its own operational wavelength range which does not overlap with one another. The bandwidth of light source in WDM is required to be large enough to cover the entire wavelength range of all the sensors.

In a WDM system, the operational wavelength ranges of sensors cannot overlap with each other, and all have to fall into the bandwidth of the source [26]. Thus, the number of sensors in WDM is limited by the available source bandwidth and the sensors’ dynamic range. If one wants to have a large number of sensors, the source needs to have a large bandwidth. However, this would reduce the power reflected by each sensor since it is proportional to the operational bandwidth divided by the bandwidth of the source.

1.1.3 Frequency shifted interferometry - FSI

Early configurations of frequency shifted interferometry (FSI) were based on a Sagnac loop interferometer where a frequency shifter was placed asymmetrically in it. Fig. 1.5(a) shows an example of such configurations, where an acoustic optical modulator (AOM) is used as the frequency shifter. In general, phase or amplitude modulators can also be used as a frequency shifter. This type of FSI has many applications, including fiber strain sensing [46, 47], fiber length and dispersion measurement [48, 49], and ultrasonic sensing [50]. Another configuration of FSI is based on a Mach Zehnder interferometer, as shown in Fig. 1.5(b). In principle, the frequency shifter AOM can be replaced by a phase or amplitude modulator. However, AOMs have advantages over phase or amplitude modulators in the sense that they work equally well when the light reverses direction. Moreover, AOMs are polarization independent.

In a frequency shifted interferometry (FSI) system, a CW lightwave at optical frequency $\nu_0$, together with its frequency-shifted copy at $\nu_0 + f$ (in principle $\nu_0 - f$ is also possible), is launched into the device under test (DUT). After being reflected from the DUT, the original lightwave frequency is shifted by $+f$ so that it interferes with its copy (at $\nu_0 + f$) at a detector. Note that these two signals have the same optical frequency ($\nu_0 + f$), but different phases when interfering at the detector, which is different from OFDR method, where the two interfering signals have different frequencies. The phase difference between the two interfering signals in FSI, which is a function of $f$, contains the information of location of sensor [51, 52, 53]. By sweeping $f$ and performing Fourier transform on the interference signals at the detector, we can resolve locations of sensors.

Frequency-shifted interferometry (FSI) has been demonstrated to be capable of interrogating both the location and the reflectivity of multiple reflective sensors along a fiber [52, 53, 54]. FSI measures the phase difference between the two lightwaves traveling the same path (though frequency shifted at different times). It has many advantages over aforementioned fiber optic
1.1.4 Comparison between different fiber-optical multiplexing techniques

Figure 1.6 shows the basic differences between optical frequency domain reflectometry (OFDR), time-division-multiplexing (TDM), wavelength-division-multiplexing (WDM), and frequency shifted interferometry (FSI).
## Chapter 1. Introduction

<table>
<thead>
<tr>
<th>Method</th>
<th>Distinguishing Features</th>
<th>Operation principle</th>
</tr>
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</table>
| OFDR   | • Input is a frequency-swept CW light source  
        • Require a reference signal (either in RF or optical frequency)  
        • Signals interfere at different frequencies  
        • Beat frequency is a function of time delay $\tau$ | ![OFDR Diagram](image) |
| TDM    | • Input is a temporal pulse  
        • Test signals are separated in time domain  
        • Measure time delay $\tau$ directly | ![TDM Diagram](image) |
| WDM    | • Input is broadband source  
        • Test signals are separated in wavelength domain | ![WDM Diagram](image) |
| FSI    | • Input is unmodulated CW light source  
        • Self-interference, no need for reference signal  
        • Signals of the same frequency interfere with different phase  
        • Phase difference of signals is a function of time delay $\tau$ as well as the frequency shift $f$ | ![FSI Diagram](image) |

Figure 1.6: Comparison between different fiber optic multiplexing techniques.
CHAPTER 1. INTRODUCTION

1.1.5 Vibration sensing with fiber-optic system

Nowadays, constructions in the field of civil and mechanical engineering require more and more use of smart structures [55, 56]. A smart structure is defined as a structural system which can sense and adapt to environmental changes [57]. This technology can provide early warning of the problem, enhance the survivability of the system, and improve its life cycle. As a result, maintenance cost of the structure is reduced significantly.

Among all the conditions need to be monitored, vibration sensing and control becomes more and more crucial in many of the smart structure systems, including bridges, airplanes, dams, etc. [58, 59]. Conventional methods for the measurement of vibration are based on capacitive and piezoelectric sensors [60, 61]. However, these sensors are not immune to electromagnetic interference (EMI) because electrical signals are used to detect vibrations [61]. Moreover, sensor deformation may be introduced by changes in temperature since piezoelectric materials are also pyroelectric [62].

In recent years, fiber optic sensors have drawn lots of attention in the field of vibration sensing [63, 64, 65]. Compared with conventional vibration sensors, they have many advantages, such as small in size, light in weight, immune to EMI, and highly sensitive. As a result, fiber optic vibration sensors are widely used in smart civil structure monitoring [59], pipeline monitoring [66], wind turbine vibration monitoring [67], etc..

1.2 Motivation behind the thesis

1.2.1 Frequency shifted interferometry

As mentioned before, FSI can be used in fiber optic multiplexing, and it has many advantages over conventional multiplexing techniques. However, earlier FSI demonstrations [51, 52, 53] used an acoustic optical modulator (AOM) as the frequency shifter in a Sagnac configuration, resulting in low spatial resolution, typically 5m, due to the frequency scanning range of the AOM. Moreover, the coherent length of the TLS used in FSI may limit the minimum separation between two adjacent sensors, since undesirable multiple reflections may occur [53]. Last but not least, the measurement time of FSI technique has the order of minutes, which is mainly constrained by the AOM sweep speed and the TLS wavelength scan speed. The measurement would in principle be reduced if a faster frequency sweep scheme is applied.

Recently, B. Qi et al. showed that, using a phase modulator and a single-arm configuration, sensor multiplexing could be achieved through interference of side bands generated by the modulator [54]. This technique was so called single-arm frequency shifted interferometry (SA-FSI). In contrast to previous FSI technique, a much higher spatial resolution (∼ 0.1m) was
CHAPTER 1. INTRODUCTION

achieved due to a much larger frequency sweep range.

One objective of this thesis is to investigate and develop the SA-FSI technique demonstrated in [54], especially to improve its performance in fiber optic multiplexing. We want to overcome the weaknesses of previous FSI demonstrations while keeping all the advantages over conventional fiber optic multiplexing methods. Another goal of the thesis is to explore the limitations of this technique and discover potential directions for improvements.

1.2.2 Vibration sensing with fiber-optic system

Another objective of the thesis is to explore features of a commercialized fiber-optic vibration sensing system developed by QPS Photronics Inc.. QPS Photronics Inc. is a privately owned company which specializes in condition monitoring solutions using its VibroFibre invention (a fiber gratings cavity sensor). This VibroFibre sensor is able to detect vibration at a location where the sensor is placed. QPS Photronics Inc. has requested us to explore the capability of distributed vibration sensing using existing instrument developed by the company. Preliminary experimental results show that the QPS instrument does response to vibration along the fiber link, not necessarily to the vibration on the sensor site. We would like to explore the capability of distributed sensing of the system, and build a model of its working principle.

1.3 Contributions of the thesis

One major contribution of the thesis is the improvement of the performance of SA-FSI technique. In this thesis, we further improve upon [54] and demonstrate a simpler and more compact SA-FSI configuration with additional advantages: 1) We show that the laser source used in [54] can be replaced by a low-coherence broadband source, which reduces the cross-talk among sensors, allowing closer spacing between sensors. 2) We eliminate the need for a narrow bandpass filter in [54], allowing a much broader spectral range for sensing. 3) We have significantly increased the sensing range by more than an order of magnitude.

Another contribution of the thesis is that we have built a model of the working principle of a vibration sensing system developed by QPS Photronics Inc., and explored its sensing features. Vibration sensors of different reflectivities are tested. By comparing simulation results based on our model with experimental results for these sensors, we find that our model effectively captures all the essential features of QPS vibration sensing system.

My work has also contributed to several journal and conference publications:

Refereed journal publications

• Y. Zhang, F. Ye, B. Qi, H.-K. Lo, and L. Qian, “Broadband multipoint sensing with
single-arm frequency-shifted interferometry”, in *Conference on Lasers and Electro-Optics*, Technical Digest (Optical Society of America, 2013), paper JTu4A.


### 1.4 Outline of the thesis

In this thesis we study the theory of SA-FSI, investigate two different configurations of this technique, and discuss some results for these configurations. In Chapter 2 we study the theory of SA-FSI with one or several sensors along fiber link. In Chapter 3 we investigate two different realizations of SA-FSI: one with sensors along several fiber links, the other with multiple sensors along one fiber link. Experimental results for these two configurations are presented. Optimization of the working point of amplitude modulator used in our experiments is also discussed in this chapter. In Chapter 4 we build a model of mechanical vibration sensing for a sensing system developed by QPS Photronics Inc.. Experimental results for three different types of reflective terminations are presented to test our model. We also explore the sensing sensitivity of the QPS vibration sensing system. We present our conclusions and future work in Chapter 5.
Chapter 2

Principle of Single-arm Frequency-shifted Interferometry

In this chapter, we introduce the principle of single-arm frequency-shifted interferometry (SA-FSI) and the method to characterize its performance. In a SA-FSI system, frequencies of forward and backward traveling lightwaves are shifted by the same amount $f$ at different times $t_1$ and $t_2$, the same as in other FSI systems. This leads to interferences at an optical detector as a function of $f$ and $\Delta t = t_1 - t_2$. By sweeping the RF frequency $f$ and taking the fast Fourier Transform (FFT) of the interference signal, we can resolve both the locations and the reflectivity of weak reflectors along one or multiple fibers.

We first derive the expression of interferences at an optical detector for a SA-FSI system with only one reflector along the fiber link. Based on this, one can get the expression of interferences for a SA-FSI with multiple reflectors along one or multiple fiber links.

### 2.1 Single-arm frequency-shifted interferometer with one reflector

Fig. 2.1 shows the simplest configuration of SA-FSI with a broadband source (BBS), an optical circulator (Cir), an amplitude modulator (AM), a polarization controller (PC), a slow photo detector (PD), and one weak reflector (R_1). We consider light field from the incoherent broadband source as a summation of narrow-band “spectral lines”, i.e.

$$E_{in}(t) = \sum_{\nu} E_{\nu}(t) = \sum_{\nu} E_{0\nu} \cos(2\pi\nu t + \phi_{\nu}),$$

(2.1)
where $\nu$ and $E_0\nu$ are the frequency and amplitude of each “spectral line” respectively, and $\phi_\nu$ is the phase of $E_\nu(t)$, which can be considered independent of time for a sufficiently narrow “spectral line”.

When light enters the amplitude modulator (AM), driven by an RF signal at frequency $f$, from port 2 of the fiber directional coupler, each “spectral line” $E_\nu(t)$ is modulated by the AM and produces sidebands at frequency $\nu \pm nf$. Note that the amplitude modulator used in our experiment was a Mach-Zehnder-Interferometer (MZI), and the driving RF voltage is
sinusoidal (as shown in Fig. 2.2). After the AM, the electric field $E'_v(t)$ is given by [68, 69]

$$E'_v(t) \propto J_0\left(\frac{\alpha \pi}{2}\right) \cos\left(\frac{\pi}{2} \varepsilon\right) \cos(2\pi v t + \phi_v)$$

where $\alpha = V_{RF}/V_{\pi}$ is the modulation depth, and $\varepsilon = V_{bias}/V_{\pi}$ characterizes the DC bias applied to the modulator. $V_{RF}$, $V_{bias}$ and $V_{\pi}$ are the amplitude of the RF driving signal, the DC bias voltage of the AM, and the half-wave voltage of the AM, respectively. $J_m$ are the Bessel functions of the first kind.\(^1\) Amplitudes of sidebands are controlled by parameters $\varepsilon$ and $\alpha$. In the experiments, we fine tuned these parameters so that we considered only the first order sideband and ignored higher order ones.

Both the baseband and sidebands travel along the same fiber link together, and are reflected back by optical sensors. When the reflected signals pass through the AM for the second time at $t + \delta t$, where $\delta t = 2nL/c$ is the round-trip propagation time between the AM and the sensor $R_1$, each of the returning signals will be modulated and generate new baseband and sideband signals, as shown in Fig. 2.3. Detailed expressions for each optical signal after the second modulation is presented in Table 2.1. For a slow photo detector (bandwidth $\ll f$), we found that only certain interference terms, such as $< |E''_{v11} + E''_{v23}|^2 >$, $< |E''_{v11} + E''_{v32}|^2 >$, $< |E''_{v12} + E''_{v21}|^2 >$, $< |E''_{v13} + E''_{v31}|^2 >$ and $< |E''_{v23} + E''_{v32}|^2 >$, will be detected at the slow photo detector. Here $< \cdot \cdot \cdot >$ refers to the time average over the detector integration time. Therefore, the interference intensity caused by the reflection from the sensor $R_1$ is given by

$$I(f) \propto DC + \sum_v \left\{ < |E''_{v11} + E''_{v23}|^2 > + < |E''_{v11} + E''_{v32}|^2 > + < |E''_{v12} + E''_{v21}|^2 > + < |E''_{v13} + E''_{v31}|^2 > + < |E''_{v23} + E''_{v32}|^2 > \right\}$$

\[ DC + \sum_v \left\{ J_0^2\left(\frac{\alpha \pi}{2}\right) J_1^2\left(\frac{\alpha \pi}{2}\right) \sin^2(\pi \varepsilon) \cos(\Delta \psi) \\
+ J_1^4\left(\frac{\alpha \pi}{2}\right) \sin^4\left(\frac{\pi \varepsilon}{2}\right) \cos(2\Delta \psi) \right\} \]

\[ \sim DC + \sum_v J_0^2\left(\frac{\alpha \pi}{2}\right) J_1^2\left(\frac{\alpha \pi}{2}\right) \sin^2(\pi \varepsilon) \cos(\Delta \psi), \quad (2.3) \]

\(^1\)See Appendix A for details.
where \( DC \) refers to a constant background, \( \Delta \psi = \pm 2\pi (2nL/c) f \), \( L \) is distance between the AM and the sensor \( R_i \), \( n \) is the effective index of the single-mode fiber, and \( c \) is the speed of light in vacuum [54]. We ignored the term involving \( \cos(2\Delta \psi) \) since its amplitude is hundreds of times smaller than that of the \( \cos(\Delta \psi) \) term. Note that \( \phi_v \) disappears in the interference intensity, and the phase shift \( \Delta \psi \) is independent of the optical baseband frequency \( \nu \) when dispersion is negligible over the bandwidth of the broadband source. Thus, the interference contributions from all \( E_v \) are additive, which means even a broadband source can generate

Figure 2.3: Optical signals after the the baseband is modulated by the AM for the second time.

<table>
<thead>
<tr>
<th>Field components after the 1st modulation</th>
<th>Field components after the 2nd modulation (on return)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\nu_1}' = J_0(\alpha \frac{\pi}{2}) \cos(\frac{\pi}{2} \nu \nu \nu) \cos(2\pi 2\pi 2\pi f + \phi_v) )</td>
<td>( E_{\nu_1}'' = J_0(\alpha \frac{\pi}{2}) \cos(\frac{\pi}{2} \nu \nu \nu) \cos(2\pi 2\pi 2\pi f + \phi_v) )</td>
</tr>
<tr>
<td>( E_{\nu_2}' = -J_1(\alpha \frac{\pi}{2}) \sin(\frac{\pi}{2} \nu \nu \nu) \cos(2\pi 2\pi 2\pi (\nu - f) + \phi_v) )</td>
<td>( E_{\nu_2}'' = J_1(\alpha \frac{\pi}{2}) \sin(\frac{\pi}{2} \nu \nu \nu) \cos(2\pi 2\pi 2\pi (\nu - f) + \phi_v) )</td>
</tr>
<tr>
<td>( E_{\nu_3}' = -J_1(\alpha \frac{\pi}{2}) \sin(\frac{\pi}{2} \nu \nu \nu) \cos(2\pi 2\pi 2\pi (\nu + f) + \phi_v) )</td>
<td>( E_{\nu_3}'' = J_1(\alpha \frac{\pi}{2}) \sin(\frac{\pi}{2} \nu \nu \nu) \cos(2\pi 2\pi 2\pi (\nu + f) + \phi_v) )</td>
</tr>
</tbody>
</table>

Table 2.1: Field components after the 1st and 2nd modulation of the AM. \( \delta t \) is the round-trip propagation time between the modulator and sensors.
such interference. As a result, the output of the photo-detector can be described by [54]

\[ I(f) \propto DC + R \cos\left(2\pi \frac{2nL}{c} f\right) \]
\[ = DC + R \cos(2\pi F f), \]

(2.4)

where \( R \) is the reflectivity of the sensor, and \( F = \frac{2nL}{c} \).

![Figure 2.4](image.png)

Figure 2.4: The interference signal of a single-arm frequency-shifted interferometry with one sensor as \( f \) is swept linearly.

From Eq.(2.4) one can find that interference signal \( I(f) \) is a function of RF frequency \( f \). Note that \( F \) serves as the oscillating frequency of a sinusoid as a function of \( f \), though it has a unit of time. This suggests that we may obtain the information about location of the sensor \( L \) by sweeping \( f \) and measuring the interference signal \( I(f) \), since \( F \) is proportional to \( L \). When the RF frequency \( f \) is linearly swept, the output signal becomes a sinusoidal functions of \( f \) having a “frequency” \( F = \frac{2nL}{c} \), which is determined by the location of the reflector \( L \) (see Fig. 2.4).

### 2.2 Single-arm frequency-shifted interferometer with multiple reflectors

A SA-FSI system can also interrogate an array of discrete sensors along fiber links, which allows one to conveniently monitor parameters of interest over the path. Fig. 2.5 shows two configurations of SA-FSI with a broadband source (BBS), an optical circulator (Cir), an amplitude modulator (AM), a polarization controller (PC), a slow photo detector (PD), and several weak reflectors \( R_i \). In configuration shown in Fig. 2.5(b), the light was split into two by a 50/50 fiber directional coupler and entered into two different fiber links afterwards. Each fiber link has several weak reflectors along the path. This configuration was used to demonstrate...
that SA-FSI has the capability of fiber optic multiplexing for multiple fiber links. The other configuration, as shown in Fig. 2.5(c), has only one fiber link with more reflectors in it. The separation between them is larger than that in the first configuration. Here we would like to demonstrate the capacity of long range sensing of a SA-FSI system.

![Experimental setup of SA-FSI](image)

Figure 2.5: The experimental setup of SA-FSI with a broadband source (BBS), an optical circulator (Cir), an amplitude modulator (AM), a polarization controller (PC), a slow photo detector (PD), and several weak reflectors ($R_i$). **a)** is the interrogation system, **b)** **c)** are two types of sensing configurations.

When light from the incoherent broadband source enters into the interferometer from port 2 of the fiber directional coupler, each reflection site ($R_1, R_2, R_3, \ldots, R_N$) along the fiber link contributes a unique interference signal $I_i(f)$ at the slow detector. From Eq.(2.4), the interference intensity caused by the reflection from the $i^{th}$ sensor is given by

$$I_i(f) \propto DC + R_i \cos(2\pi F_i f),$$  \hspace{1cm} (2.5)$$

where $DC$ refers to a constant background, $R_i$ is the reflectivity of the $i^{th}$ sensor, and $F_i = 2nL_i/c$. Here $L_i$ is the distance between the AM and the $i^{th}$ sensor, $n$ is the effective index of the single-mode fiber, and $c$ is the speed of light in vacuum [54]. Since $I_i(f)$ is independent of the frequency of lightwave from the broadband source, the total interference signal contributed by all the reflectors is a summation of sinusoids. As a result, the output of the photo-detector can be described by [54]

$$I(f) = \sum_{i=1}^{N} I_i(f) \propto DC + \sum_{i=1}^{N} R_i \cos(2\pi F_i f),$$  \hspace{1cm} (2.6)$$

where $R_i$ is the reflectivity of the $i^{th}$ sensor, and $F_i = 2nL_i/c$. 
Figure 2.6: Performing Fourier transform on the interference signal obtained from a single-arm frequency-shifted interferometry. (a) the interference signal $I(f)$; (b) the Fourier spectrum of $I(f)$ in (a).

From Eq.(2.6) one can find that interference signal $I(f)$ is a function of RF frequency $f$. Note that $F_i$ serves again as the oscillating frequency of a sinusoid as a function of $f$, though it has a unit of time. Since $F_i$ is proportional to $L_i$, we may obtain the information about locations of each reflector, $L_i$, by sweeping $f$ and measuring the interference signal $I(f)$. This also implies that $L_i$ should be different in order not to have locations overlapped.

When the RF frequency $f$ is linearly swept, the output signal becomes a summation of sinusoidal functions of $f$, each having a “frequency” $F_i = 2nL_i/c$, which is determined by the location of the $i^{th}$ reflector. The interference signal $I(f)$ is a summation of sinusoids at different frequency $F_i$, as shown in Fig. 2.6(a). By taking the fast Fourier Transform (FFT) of the interference $I(f)$, we can resolve both the locations $L_i$ of the sensors and their reflectivity $R_i$ respectively[see Fig. 2.6(b)]. This method produces interference with low-coherence source, and is essentially a zero-path-length-difference interferometer, which is fundamentally akin to the FSI technique using a Sagnac loop [49] or a linear Sagnac configuration [52, 51].

### 2.3 Characterization of the performance of a SA-FSI system

The performance of a SA-FSI system is characterized by two parameters: spatial resolution $\delta L$ and spatial sensing range $L_{max}$. Spatial resolution in a SA-FSI system refers to the minimum resolvable separation between two adjacent sensors along the fiber link. And spatial sensing
range in a SA-FSI refers to the maximum distance between the system and a sensor that is detectable.

**2.3.1 Spatial resolution**

From Eq.(2.5), we know that oscillation “frequency” $F_i$ is defined as $F_i = 2nL_i/c$. Thus, the spatial resolution $\delta L$ of SA-FSI is given by

$$\delta L = \frac{c}{2n}\delta F_i.$$  \hspace{1cm} (2.7)

According to the theory of fast Fourier transform [70], the resolution of $F_i$ is given by $\delta F_i = 1/\Delta$, where $\Delta$ is the RF frequency sweep range. As a result, the spatial resolution $\delta L$ has the form of

$$\delta L = \frac{c}{(2n\Delta)}.$$  \hspace{1cm} (2.8)

Note that $\delta L$ is not necessary the physical separation between two sensors, since the fiber between them is free to wound.

**2.3.2 Spatial sensing range**

From Eq.(2.5) we know that the distance between the modulator and the $i^{th}$ sensor, $L_i$, is proportional to the frequency of the interference signal $F_i$. According to Nyquist theorem, the sampling frequency (which refers to the reciprocal of the frequency sweeping step of the RF signal here) should be larger than $2F_i$, i.e. $1/f_{step} \geq 2F_i = 4nL_i/c$. Thus, the maximum sensing range is given by

$$L_{max} = \frac{c}{(4nf_{step})}.$$  \hspace{1cm} (2.9)

Thus, higher spatial resolution and larger measurement range can be achieved with a larger scanning range at a finer scanning step.

**2.4 Comparison of SA-FSI with other types of FSI**

As mentioned in Chapter one, FSI measures the phase difference between the two lightwaves traveling the same path (though frequency shifted at different times). Earlier FSI demonstrations used an acoustic optical modulator (AOM) as the frequency shifter in a Sagnac configuration [52, 53]. SA-FSI inherits all the key features of earlier FSI demonstrations. Moreover, SA-FSI has its own advantages over them:
• The maximum frequency sweep range of the AOM used in earlier FSI system is 20 MHz. As a result, its spatial resolution is very poor (typically \(~5\text{m}\)). SA-FSI has a much better spatial resolution (\(~0.1\text{m}\)) since it uses a amplitude or phase modulator as the frequency shifter, which allows a larger frequency sweep range (\(~1\text{GHz}\)).

• Earlier FSI system used a tunable laser as the light source. The coherence length of the light source may limit the minimum separation between two adjacent sensors, since crosstalk may occur when light reflected from one sensor interferes with light reflected from another sensor. In SA-FSI system, a broadband source with low coherence length was employed. This reduces crosstalk among sensors, allowing closer spacing between sensors.

• The measurement time of FSI system is of the order of minutes, which is mainly constrained by the AOM sweep speed and the light wavelength scan speed of the source. The measurement time of SA-FSI system is much shorter (typically \(~10\text{s}\)), due to the high frequency sweep speed of a RF driver.

• SA-FSI is simpler and more compact than earlier FSI demonstrations in terms of the configuration.

2.5 Summary

This chapter introduced the principle of SA-FSI and the characterization of the performance of a SA-FSI system. In single-arm frequency-shifted interferometry (SA-FSI), light from a broadband source (1530-1565 nm) can be considered as a summation of narrow-band spectral “lines”. Each “line”, at optical frequency \(\nu\), is modulated by an amplitude modulator, producing sidebands at \(\nu + nf\) and \(\nu - nf\) with respect to the baseband optical frequency \(\nu\), where \(f\) is the frequency of the RF driving signal and \(n\) is an integer. Both the baseband and sidebands propagate along the fiber together, and are reflected back by weak reflectors. When the reflected signals pass through the amplitude modulator for the second time, new sideband signals are generated from the baseband, resulting in a sinusoidal interference signal \(I(f)\). By sweeping the RF frequency \(f\) and taking the fast Fourier Transform (FFT) of the interference signal, we can resolve both the locations and the reflectivity of weak reflectors along one or multiple fibers. Characterization on the performance of SA-FSI system, which is done by spatial resolution \(\delta L\) and spatial sensing range \(L_{\text{max}}\), has been discussed. Moreover, advantages of SA-FSI over earlier FSI demonstrations are presented. The following chapter will present experimental results on two different configurations of SA-FSI.
In this chapter, we demonstrated the capability of fiber-optic multiplexing of SA-FSI, using two different configurations shown in Fig. 2.5. After performing the FFT, locations and reflectivities of reflection sites along fiber links were clearly resolved. We also found that the separations measured by SA-FSI were in excellent agreement with the results obtained by either a scale ruler or time-of-flight measurement (TOF).

3.1 Experimental setup

3.1.1 Configuration one – multiple fiber links

First, we demonstrate the multiplexing of 5 weak reflectors (loose fiber connectors) both in series and in parallel. The experimental setup is shown in Fig. 3.1. An amplified sponta-
neous emission (ASE) source (AFC, BBS 1550A-TS) with a bandwidth spanning from 1530 to 1565 nm, is used as our light source. Sideband signals are generated by a LiNbO$_3$ AM (JDS Uniphase, OC-192), which is driven by a RF signal generator (Agilent, E8257D). The interference signals are collected by a slow photo detector (New Focus 1811), whose sampling rate is of order of the 10k/s in the experiment. The light source is non-polarized, however, the transmission of the AM is polarization-dependent. Thus, a polarization controller (PC) is needed to adjust the polarization of the reflected signals. Note that the PC cannot be optimized for all reflectors, which affects the intensity of interference from each reflector.

3.1.2 Configuration two – large sensing range

![Experimental setup diagram](image)

Figure 3.2: The experimental setup of SA-FSI with a broadband source (BBS), an amplitude modulator (AM), a polarization controller (PC), a slow optical detector (PD), and 4 weak reflectors along one fiber link.

Next, to demonstrate large sensing range of our system, we locate four weak reflectors in series along the fiber link, as shown in Fig. 3.2. The length of the fiber link we used was around 1km. Two of the weak reflectors, $R_1$ and $R_2$, were placed close to the amplitude, while the other two reflectors were placed at the end of the fiber link. The rest components, such as light source, amplitude modulator, and RF signal generator, are the same as those in previous configuration.

3.2 Working point of the amplitude modulator

Since optical waveforms in a SA-FSI system are modulated by a AM along both the normal and reverse directions, we need to know the RF frequency response of the AM used in out experiments to find a proper RF frequency sweeping range. Moreover, the AM is driven by
both a DC bias and a RF signals. In order to maximize the amplitude of interferences coming from the first order sideband while keeping high order sidebands negligible, the DC bias and the modulation depth of the AM should be carefully set.

### 3.2.1 Calibration on the frequency response of the amplitude modulator

We measured the frequency responses of the AM used in our experiments with a broadband source, and a low speed optical power meter. The experimental setup is shown in Fig. 3.3.

![Figure 3.3: The experimental setup to calibrate the amplitude modulator. BBS: broadband source; AM: amplitude modulator; DC: DC bias of amplitude modulator; PM: powermeter used to measure the output optical power.](image)

During the experiment, the frequency of the RF source is scanned between 0 GHz to 11 GHz at a step of 0.2 GHz. At each frequency, we first turn off the RF source and adjust the DC power supply to minimize the optical power through the amplitude modulator. This optical power is measured by an optical power meter as $P_0$. We then turn on the RF source and the optical power measured by the power meter is $P_1$. We use $P = P_1 - P_0$ to quantify the frequency response of the amplitude modulator. Note, when the modulation depth is small, $P$ is the optical power in the first sideband. We measure $P$ in the frequency range of 0-11GHz for both forward direction (which means light passing through the modulation along the normal direction) and backward direction (which means light passing through the modulation along the reverse direction). The experimental results are show in Fig. 3.4 (normalized to the forward direction).

From Fig. 3.4, we find that the forward response of the AM is fairly constant between 2.5 GHz and 3.5 GHz; while its backward response doesn’t change dramatically with RF frequencies. Note that the backward response in this frequency range is also larger than that of higher frequencies. Thus, 2.5 - 3.5 GHz is the frequency range for RF sweeping in our experiments.
Figure 3.4: The experimental results of calibration on the amplitude modulator (normalized to the forward response at 0.2 GHz).

In principle, we could have larger sweeping range of the RF frequency by extending the lower limit of the sweeping range to 0.2 GHz. However, this will add noise to the interference signal due to the quick change of AM response with RF frequencies.

In the first configuration of SA-FSI, we would like to achieve high spacial resolution in the results. Thus, the sweeping range of RF frequency is 2.5 GHz-3.5 GHz at a step of 1 MHz. This leads to a spacial resolution of 0.1 m and a measurement range of 50 m, according to Eq. (2.8) and Eq. (2.9). In the second configuration, we would like to extend the measurement range of SA-FSI, while keeping the spacial resolution as high as possible. As we know, the smaller sweeping step size is, the longer it will take to get the measurements for a given sweeping range. Taking care of the measurement time, the step size of RF frequency is chosen to be 41.7 KHz, and the sweeping range is 2.5 GHz-3.5 GHz, which leads to a measurement range of 1.22 Km and a spacial resolution of 0.2 m, according to Eq. (2.9) and Eq. (2.8).

### 3.2.2 DC bias and the modulation depth of the amplitude modulator

As mentioned in Chapter 2, we consider optical waveforms from the incoherent broadband source as a summation of narrow-band “spectral lines”, i.e.

\[
E_{in}(t) = \sum_{\nu} E_{\nu}(t) = \sum_{\nu} E_{0\nu} \cos(2\pi \nu t + \phi_{\nu}),
\]

where \nu and \(E_{0\nu}\) are the frequency and amplitude of each “spectral line” respectively, and \(\phi_{\nu}\) is the phase of \(E_{\nu}(t)\), which can be considered independent of time for a sufficiently narrow
“spectral line”.

Each “spectral line” $E_\nu(t)$ is modulated by an amplitude modulator (AM) driven by an RF signal at frequency $f$, producing sidebands. Note that the amplitude modulator used in our experiment was a Mach-Zehnder-Interferometer (MZI), and the driving RF voltage is sinusoidal. After the AM, the electric field $E'_\nu(t)$ is given by [68, 69]

$$E'_\nu(t) \propto J_0(\frac{\alpha \pi}{2}) \cos\left(\frac{\pi}{2} \epsilon\right) \cos(2\pi \nu t + \phi_\nu)$$

$$- J_1(\frac{\alpha \pi}{2}) \sin\left(\frac{\pi}{2} \epsilon\right) \cos(2\pi (\nu - f) + \phi_\nu)$$

$$- J_1(\frac{\alpha \pi}{2}) \sin\left(\frac{\pi}{2} \epsilon\right) \cos(2\pi (\nu + f) + \phi_\nu)$$

$$- J_2(\frac{\alpha \pi}{2}) \cos\left(\frac{\pi}{2} \epsilon\right) \cos(2\pi (\nu - 2f) + \phi_\nu)$$

$$- J_2(\frac{\alpha \pi}{2}) \cos\left(\frac{\pi}{2} \epsilon\right) \cos(2\pi (\nu + 2f) + \phi_\nu)$$

$$+ \ldots, \quad (3.2)$$

where $\alpha = \frac{V_{RF}}{V_\pi}$ is the modulation depth, and $\epsilon = \frac{V_{bias}}{V_\pi}$ characterizes the DC bias applied to the modulator. $V_{RF}$, $V_{bias}$ and $V_\pi$ are the amplitude of the RF driving signal, the DC bias voltage of the AM, and the half-wave voltage of the AM, respectively. $J_m$ are the Bessel functions of the first kind.

Figure 3.5: Plot of $J_0^2(\frac{\alpha \pi}{2})J_1^2(\frac{\alpha \pi}{2})$ vs the modulation depth $\alpha$.

From Eq. (3.2), we find that interferences from the first order sidebands have a amplitude
of $J_0^2(\alpha \frac{\pi}{2})J_1^2(\alpha \frac{\pi}{2})\sin(\pi \varepsilon)$. The maximum of $J_0^2(\alpha \frac{\pi}{2})J_1^2(\alpha \frac{\pi}{2})$ occurs at $\alpha = 0.69$ (as shown in Fig. 3.5). As a result, $\alpha = 0.69, \varepsilon = \pm 0.5$ is the working point of the AM in our experiments. $\varepsilon = 0.5$ means that the AM should be modulated at its quadratic point.

When doing experiments, one needs to find the quadratic point for each AM by hands. Assuming the amplitude of baseband reaches its maximum at $V_{bias} = V_0$ without applying RF modulation signals, the quadratic point of the AM is given by $V_{bias} = V_0 \pm 0.5V_\pi$. As for the modulation depth, $\alpha = 0.69$ means the output voltage of the RF driver is $V_{RF} = 0.69V_\pi$. Since the measured $V_\pi$ of the AM used in our experiments is about 3V, $V_{RF}$ should roughly be set to 2V, which corresponds to an output power of the RF driver of about 19 dBm. However, the maximum output power of our RF driver is 16 dBm. As a result, 16 dBm is the modulation depth of the AM in our experiments, which means $\alpha$ was equal to 0.47 in our experiments.

Since $\alpha = 0.47$, the ratio of $J_1(\alpha \frac{\pi}{2})$ to $J_2(\alpha \frac{\pi}{2})$ is equal to 7. As a result, one can ignore the second order sidebands in Eq. (3.2). So do the higher order ones.

3.3 Experimental results

In this section, we present the experimental results for two different SA-FSI configurations described in the beginning of this chapter.

3.3.1 Configuration one – multiple fiber links

![Image](image.png)

Figure 3.6: Performing Fourier transform on the interference signal obtained from a single-arm frequency-shifted interferometry. (a) the interference signal $I(f)$; (b) FFT spectrum of $I(f)$ in (a). The five peaks correspond to the reflections at 5 weak reflectors ($R_1 \sim R_5$).

In the first configuration (shown in Fig. 3.1), the frequency of the driving RF signal was swept from 2.5 to 3.5 GHz at steps of 1 MHz. This leads to a spatial resolution of 0.1 m and
a measurement range of 50 m, according to Eq. (2.8) and Eq. (2.9). The interference signal at the photo detector and its corresponding FFT spectrum are shown in Fig. 3.6, where a standard zero-padding technique was used before performing FFT. From Eq. (2.5), we find that the frequency components in the FFT spectrum are given by

$$F_i = \frac{2nL_i}{c}. \quad (3.3)$$

Thus, the location of each reflector has the form of

$$L_i = F_i c \frac{c}{2n}. \quad (3.4)$$

As a result, we can convert the horizontal axis in Fig. 3.6(b) into the location of each reflector.

In the FFT spectrum of the interference axis (Fig. 3.6(b)), five peaks can be clearly identified. With negligible loss and a polarization independent AM, the peak intensity is proportional to the reflectivity of $R_i$, as shown in Eq.(2.4). The signal-to-noise ratio (SNR) in Fig. 3.6(b), which is defined as the ratio of the highest peak signal to the average background level, is around 27 dB. Note that the SNR here is much higher than that in our previous work [54], where we used a continuous wave laser as the light source. The main reason is that the coherence length of the light source used here is much shorter than the coherence length of the tunable CW laser used in our previous work, which would reduce cross talks in the system.

To check the accuracy of measurements of a SA-FSI system, we also measured the separations between sensors using a scale rule, which has a resolution of 1 mm. The separations between adjacent reflectors, measured by both SA-FSI and a scale ruler, are shown in Table 3.1, illustrating excellent agreement with those carried out by a scale ruler.

<table>
<thead>
<tr>
<th>Methods</th>
<th>$d_{12}(m)$</th>
<th>$d_{23}(m)$</th>
<th>$d_{45}(m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruler</td>
<td>2.08</td>
<td>5.07</td>
<td>0.32</td>
</tr>
<tr>
<td>SA-FSI</td>
<td>2.08</td>
<td>5.06</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table 3.1: Separations between adjacent reflectors measured by both SA-FSI and a scale ruler, where $d_{ij}$ refers to the distance between reflector $R_i$ and $R_j$.

### 3.3.2 Configuration two – large sensing range

In the second configuration (shown in Fig. 3.2), the frequency of the driving RF signal was swept from 2.7 to 3.2 GHz at steps of 41.7 KHz, which leads to a spatial resolution of 0.2 m and a measurement range of 1.22 km. The FFT spectrum of the interference signal are shown in Fig. 3.7, where a standard zero-padding technique has been used before performing FFT.
Chapter 3. SA-FSI Experiments and Results

Figure 3.7: Performing Fourier transform on the interference signal obtained from a single-arm frequency-shifted interferometry. (a) the interference signal $I(f)$; (b) FFT spectrum of $I(f)$ in (a). 4 different reflection peaks, at positions of 6.35 m, 7.46 m, 1006.51 m, and 1007.57 m respectively, are clearly observed.

Again, the horizontal axis has been converted into the location of each reflector.

From Fig. 3.7(b), four principle peaks, corresponding to the reflections from R₁ to R₄, can be clearly identified. They are at positions of 6.35 m, 7.46 m, 1006.51 m, and 1007.57 m respectively. The separations between the reflectors are $d_{12} = 1.11 m, d_{23} = 999.05 m$, and $d_{34} = 1.06 m$, where $d_{ij}$ refers to the distance between reflector Rᵢ and Rⱼ. As a comparison, we measured the distances between adjacent reflectors in a different way, and found that $d_{12} = 1.10 m, d_{34} = 1.09 m$, by a scale ruler, and $d_{23} = 998.98 m$, by time-of-flight measurement (TOF). The results are in excellent agreement with the measurement carried out by SA-FSI, as shown in Table 3.2.
### Table 3.2: Separations between adjacent reflectors, measured by SA-FSI and other methods.

<table>
<thead>
<tr>
<th>Methods</th>
<th>$d_{12}(m)$</th>
<th>$d_{23}(m)$</th>
<th>$d_{34}(m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-FSI</td>
<td>1.11</td>
<td>999.05</td>
<td>1.06</td>
</tr>
<tr>
<td>Ruler</td>
<td>1.10</td>
<td>×</td>
<td>1.09</td>
</tr>
<tr>
<td>TOF</td>
<td>×</td>
<td>998.98</td>
<td>×</td>
</tr>
</tbody>
</table>

#### 3.4 Summary

Above experiments demonstrate a simple and low-cost SA-FSI for multiple sensing based on sidebands interference. With a broadband source and a slow photo detector, the locations of multiple weak reflections along the fiber can be resolved. Two configurations of SA-FSI have been introduced in this chapter. In one configuration, 5 weak reflectors were put in series along two fiber links, as shown in Fig. 3.1. The frequency of the driving RF signal was swept from 2.5 to 3.5 GHz at steps of 1 MHz, which leads to a spatial resolution of 0.1 m and a measurement range of 50 m, according to Eq. (2.8) and Eq. (2.9). In the other configuration, we located four weak reflectors in series along the fiber link, as shown in Fig. 3.2. By sweeping the amplitude modulator driving frequency in the range between 2.7 and 3.2 GHz at steps of 41.7 KHz, a spatial resolution of 0.2 m and a measurement range of about 1 km have been demonstrated.
Chapter 4

Distributed vibration sensing with fiber-optic system

In this chapter, we use a vibration sensing system developed by QPS Photronics Inc. to test mechanical vibration on a fiber link. QPS Photronics Inc. is a privately owned company which specializes in condition monitoring solutions using its VibroFibre invention (a fiber gratings cavity sensor). This VibroFibre sensor is able to detect vibration at a location where the sensor is placed. QPS Photronics Inc. has requested us to explore the capability of distributed vibration sensing using existing instrument developed by the company. Preliminary experimental results show that the QPS instrument does response to vibration along the fiber link, not necessarily to the vibration on the sensor site. In this chapter, we explore the capability of distributed sensing of the system, and build a model of its working principle.

We first derive the expression of interferences for distributed vibration sensing using a QPS system. Then, we run simulations of the intensity of light and its FFT spectrum. Experimental setup and results of distributed vibration sensing are presented at the end of this chapter.

4.1 Principle of distributed vibration sensing

Fig. 4.1 shows one example of a distributed vibration sensing setup using a QPS unit (an interrogation unit provided by QPS Photronics Inc.), a data logger, a vibration source, and a reflective termination. To explore the capability of distributed sensing of the system, vibration is introduced to a short section of the fiber link. In this case, the whole fiber link is essentially a “vibration sensor”. Inside the QPS unit, there are a distributed feedback (DFB) laser, used as the light source, a photo detector, and some data processing devices. Light is reflected back from both the connector at the output end of the QPS unit and the reflective termination as
it travels along the fiber link. When there is vibration on a short fiber section between the fiber connector and the reflective termination, polarization states of the light reflected from the reflective termination vary with vibration because of birefringence \[71, 72, 73\]. As a result, interference of light received by a photo detector becomes a function of the vibration signal.

Let \(\vec{E}_0\) and \(\vec{E}_1\) denote optical signals at the photo detector which are reflected from the connector at the output end of the QPS unit and the reflective termination, respectively. Since the coherence length of the DFB laser is larger than the round trip length of fiber between two reflectors, \(\vec{E}_0\) and \(\vec{E}_1\) can be written as

\[
\vec{E}_0 = A_0 e^{i(\omega t + \beta_0 z_0 + \phi_0)} \begin{bmatrix} \alpha \\ \beta \end{bmatrix}, \\
\vec{E}_1 = A_1 e^{i(\omega t + \beta_0 z_1 + \phi_0)} \begin{bmatrix} \alpha \\ \beta e^{i\psi} \end{bmatrix}, \tag{4.1}
\]

where \(A_0\) and \(A_1\) are the amplitudes of \(E_0\) and \(E_1\) respectively. \(\omega\) is the angular frequency of the optical signal, \(\phi_0\) is the initial phase, and \(\beta_0\) is the wavevector. \(z_0\) and \(z_1\) are distances traveled by optical signals reflected from connector at the output end of the QPS unit and the reflective termination, respectively. \(\alpha\) and \(\beta\) defines the polarization state of input light, and \(\psi\) is the phase retardation of the round trip between the output end of the QPS unit and the reflective termination.

\(\alpha\) and \(\beta\) are generally complex. Since one can always rotate the polarization reference frame to make \(\vec{E}_0\) a linear polarization, we assume \(\alpha\) and \(\beta\) are real in the following discussion. When there is vibration on a short fiber section, it may change the values of parameters \(\alpha\), \(\beta\), and \(\psi\). For simplicity, in the following we will discuss their impact for two different cases: Case I, the vibration signal only changes values of \(\alpha\) and \(\beta\); Case II, the vibration signal only
CHAPTER 4. DISTRIBUTED VIBRATION SENSING WITH FIBER-OPTIC SYSTEM

affects parameter \( \psi \). In principle, these two cases may occur at the same time.

### 4.1.1 Case I - vibration only changes values of \( \alpha \) and \( \beta \)

In this case, \( \vec{E}_0 \) and \( \vec{E}_1 \) have forms of

\[
\vec{E}_0 = A_0 e^{i(\omega t + \beta_0 z_0 + \phi)} \\
\vec{E}_1 = A_1 e^{i(\omega t + \beta_0 z_1 + \phi)} e^{i\psi},
\]

(4.2)

where \( v(t) \) defines the vibration on the fiber section, and \( |\alpha v(t)|^2 + |\beta'|^2 = 1 \) since the loss of fiber is negligible. As a result, the total electric field \( \vec{E} \) is given by

\[
\vec{E} = \vec{E}_0 + \vec{E}_1 \\
= e^{i(\omega t + \beta_0 z_0 + \phi)} \left[ A_0 \alpha + A_1 \alpha v(t) e^{i\Delta\phi} \right] e^{i\phi} + A_1 \beta' e^{i(\Delta\phi + \psi)},
\]

(4.3)

where \( \Delta\phi = \beta_0 z_1 - \beta_0 z_0 \) is the phase shift between the two reflected optical signals. The intensity of light at the photo detector is then given by

\[
I = |\vec{E}|^2 = A_0^2 + A_1^2 + 2A_0A_1 \alpha^2 v(t)\cos\Delta\phi + 2A_0A_1 \beta' \cos(\Delta\phi + \psi),
\]

(4.4)

Given \( |\alpha|^2 + |\beta|^2 = |\alpha v(t)|^2 + |\beta'|^2 = 1 \), we have \( \beta'^2 = 1 - \alpha^2 v^2(t) \) and \( \beta^2 = 1 - \alpha^2 \). As a result, the intensity of light has a form of

\[
I = A_0^2 + A_1^2 + 2A_0A_1 \alpha^2 v(t)\cos\Delta\phi + 2A_0A_1 \sqrt{1 - \alpha^2} \sqrt{1 - \alpha^2 v^2(t)}\cos(\Delta\phi + \psi)
\]

(4.5)

Assuming change in \( \alpha \) has a linear response to vibration signals, we can rewrite \( v(t) \) as \( v(t) = 1 + a \mu(t) \) where \( a \) is the coefficient of response to vibration signals. \( \mu(t) \) is the function of vibration. For a short fiber section that is under vibration and weak vibration signals, change in polarization states of light due to vibration is very small. Thus, coefficient \( a \) is small and will be our perturbation parameter.

Expanding \( \sqrt{1 - \alpha^2 v^2(t)} \) in terms of \( a \), we have

\[
\sqrt{1 - \alpha^2 v^2(t)} = \sqrt{1 - \alpha^2} \left( 1 - \frac{\mu(t)\alpha^2 a}{1 - \alpha^2} - \frac{\mu^2(t)\alpha^2 a^2}{2(1 - \alpha^2)^2} + \ldots \right).
\]

(4.6)

Keeping the first and second order terms of \( a \) in Taylor expansion, one can write the intensity
of light as

\[
I = A_0^2 + A_1^2 + 2A_0A_1 \alpha^2 \cos \Delta \phi + 2A_0A_1(1 - \alpha^2) \cos(\Delta \phi + \psi) \\
+ 2A_0A_1 \alpha^2 a \mu(t) (\cos \Delta \phi - \cos(\Delta \phi + \psi)) - A_0A_1 \frac{\alpha^2}{1 - \alpha^2} a^2 \mu^2(t) \cos(\Delta \phi + \psi). \tag{4.7}
\]

In principle, one can include more terms of \(a\) in above Taylor expansion.

**Simulation study of experiments**

In our experiment, a speaker (i.e. the vibration source) is driven by a function generator whose output is a sinusoidal function of time. Thus, the vibration function \(\mu(t)\) can be written as \(\mu(t) = \sin(2 \pi f t)\), where \(f\) is the frequency of vibration. Due to the change in temperature, mechanical vibration of instruments, etc., there is always extra noise added to the signal. In our simulation, some normally distributed random noise is added to the intensity signal. As a result,

\[
I = DC + 2A_0A_1 \alpha^2 \sin(2 \pi f t) (\cos \Delta \phi - \cos(\Delta \phi + \psi)) \\
- A_0A_1 \frac{\alpha^2}{2(1 - \alpha^2)} a^2 (1 - \cos(4 \pi f t)) \cos(\Delta \phi + \psi) + \text{random noise}, \tag{4.8}
\]

where \(DC\) refers to the first two terms in Eq. (4.7). From Eq. 4.8, we find that performing fast Fourier transform (FFT) on intensity \(I\) can resolve the frequency \(f\) of the vibration signal on the fiber section, along with a second harmonic component \(2f\).

Due to the space-charge effect, photodetectors saturate when the input intensity of light is very high, which results in reduced gain and sharply-increased harmonic distortion. As a result, the same \(AC\) input produces much weaker peaks in the FFT spectrum after a photo detector saturates. To include this saturation effect, we perform FFT on \(I/DC\) instead of \(I\) in the following simulations.

Fig. 4.2 shows one example simulation of the intensity \(I\) and the FFT spectrum of \(I/DC\) for chosen values of parameters \(A_0, A_1, \alpha\), etc.. Note that the intensity of light is normalized to \(A_0^2\) in Fig. 4.2(a). Two frequency components \(f = 200Hz\) and \(2f = 400Hz\) are observed in the FFT spectrum. However, the second harmonic is much weaker than the fundamental vibration signal, and it is almost buried by the background noise. From Fig. 4.2(b) and (c), we find that increasing \(A_1\), which is proportional to the reflectivity of the reflective termination, leads to weaker frequency components in the FFT spectrum. As mentioned before, this is mainly because of the photodetector saturation at high DC input.
Figure 4.2: (a): Simulation of intensity of light $I$ which is normalized to $A_0^2$. (b), (c): FFT spectrum of $I/DC$ for parameters $\alpha = \sqrt{2}/2$, $\beta = \sqrt{2}/2$, $\Delta \phi = \pi/4$, $\psi = \pi$, $a = 0.3$ and $f = 200\text{Hz}$. 
4.1.2 Case II - vibration only affects $\psi$

In this case, vibration on the fiber section only affects the phase retardation of light, $\psi$, obtained from the round-trip travel between the output end of the QPS unit and the reflective termination. Thus, $\vec{E}_0$ and $\vec{E}_1$ can be written as

$$
\vec{E}_0 = A_0 e^{i(\omega t + \beta_0 z_0 + \phi_0)} \begin{bmatrix} \alpha \\ \beta \end{bmatrix},$
$$
$$
\vec{E}_1 = A_1 e^{i(\omega t + \beta_0 z_1 + \phi_0)} \begin{bmatrix} \alpha \\ \beta e^{i\psi} \end{bmatrix}. \tag{4.9}
$$

We assume the loss of fiber can be ignored, i.e. $|\alpha|^2 + |\beta|^2 = 1$. Total electric field $\vec{E}$ at the detector has a form of

$$
\vec{E} = \vec{E}_0 + \vec{E}_1 = e^{i(\omega t + \beta_0 z_0 + \phi_0)} \begin{bmatrix} A_0 \alpha + A_1 \alpha e^{i\Delta \phi} \\ A_0 \beta + A_1 \beta e^{i(\Delta \phi + \psi)} \end{bmatrix}, \tag{4.10}
$$

where $\Delta \phi = \beta_0 z_1 - \beta_0 z_0$ is the phase shift between the two reflected optical signals. As a result, the intensity of light at the photo detector has a form of

$$
I = |\vec{E}|^2 = A_0^2 + A_1^2 + 2A_0 A_1 (\alpha^2 \cos \Delta \phi + \beta^2 \cos(\Delta \phi + \psi)). \tag{4.11}
$$

Let us assume that $\psi$ has a linear response to vibration signals. Thus, $\psi$ can be written as $\psi = \psi_0 + a v(t)$, where $\psi_0$ is the phase retardation without vibration, $v(t)$ is the function of vibration, and $a$ is the coefficient of response to vibration signals. For a short fiber section that is under vibration and weak vibration signals, change in polarization states of light due to vibration is very small. Thus, coefficient $a$ is small, and will be our perturbation parameter.

Performing Taylor expansion on intensity $I$ to the second order of $a$, we have

$$
I \simeq A_0^2 + A_1^2 + 2A_0 A_1 \cos \Delta \phi + 2A_0 A_1 \beta^2 (\cos(\Delta \phi + \psi_0) - \cos \Delta \phi) - 2A_0 A_1 \beta^2 \sin(\Delta \phi + \psi_0) a v(t) - A_0 A_1 \beta^2 \cos(\Delta \phi + \psi_0) a^2 v^2(t). \tag{4.12}
$$

Simulation study of experiments

The speaker, which is the vibration source used in our experiment, is driven by a function generator whose output is a sinusoidal function of time, i.e. $v(t) = \sin(2\pi ft)$, where $f$ is the frequency of vibration on the fiber section. Once again, some normally distributed random
Figure 4.3: (a): Simulation of intensity of light $I$ which is normalized to $A_0^2$. (b), (c): FFT spectrum of $I/DC$ for parameters $\alpha = \sqrt{2}/2$, $\beta = \sqrt{2}/2$, $\Delta\phi = \pi/4$, $\psi = \pi$, $a = 0.3$ and $f = 200Hz$. 
noise is added to the intensity signal. As a result,

$$I = DC - 2aA_0A_1\beta^2\sin(\Delta\phi + \psi_0)\sin(2\pi ft)$$

$$- \frac{1}{2}A_0A_1\beta^2a^2\cos(\Delta\phi + \psi_0)(1 - \cos(4\pi ft)) + \text{random noise},$$ (4.13)

where $DC$ refers to the first three terms in Eq. (4.12). Performing FFT on intensity $I$, one can resolve the frequency $f$ of the sinusoidal vibration on the fiber section, along with a second harmonic component $2f$. Once again, we perform FFT on $I/DC$ instead of $I$ in the following simulations to include photodetector saturation effect.

Fig. 4.3 shows one example of simulations of the intensity $I$ and the FFT spectrum of $I/DC$ for chosen values of parameters $A_0, A_1, \alpha, \text{etc.}$. Note that the intensity of light is normalized to $A_0^2$ in Fig. 4.3(a). Two frequency components $f = 200\text{Hz}$ and $2f = 400\text{Hz}$ are observed in Fig. 4.3(b). However, the second harmonic is much weaker than the fundamental vibration signal, and almost merges into the background noise. From Fig. 4.3(b) and (c), we find that increasing $A_1$, proportional to the reflectivity of the reflective termination, leads to weaker frequency components in the FFT spectrum. As mentioned before, this is mainly because of the photodetector saturation at high DC input.

### 4.1.3 Discussions

In reality, there is always environmental noise (e.g. mechanical vibration, drift in temperature, etc.) added to the setup of our experiment. In principle, environmental noise is a function of time. Thus, parameters $\alpha$ and $\beta$ may vary with time as well. As a result, the amplitudes of frequency components in the FFT spectrum of $I$ are functions of time, according to Eq. (4.7) and Eq. (4.12). High order harmonics are much weaker than the fundamental frequency component and may be buried in the noise floor as both the harmonics and noise floor vary with time.

Increasing reflectivities of reflective terminations results in large DC input to the photodetector, which may lead to photodetector saturation. As a result, the frequency components in the FFT spectrum become weaker, even nonvisible in the spectrum.

### 4.2 Experimental setup and results

#### 4.2.1 Experimental setup of distributed vibration sensing

Fig. 4.4 shows our experimental setup of distributed vibration sensing using a QPS unit, a data logger (NI USB-6009), a speaker, and a reflective termination. As mentioned in Sec.4.1,
the whole fiber link is essentially a “vibration sensor”. A DFB laser, which is placed inside the QPS unit, is used as the light source. Photo detector inside the QPS unit converts optical signals into analog signals, which are then converted into digital signals by the data logger. Digital signals from the data logger are processed by software developed by QPS Photronics Inc. The speaker is driven by a function generator (Agilent 33120A) which produces different types of vibration signals. A small section of fiber was attached to the membrane of the speaker to absorb vibration signals.

Three different types of reflective terminations, QPS VibroFibre sensor (14% reflectivity), flat end fiber (4% reflectivity), and a fiber loop mirror (\(\sim 90\%\) reflectivity), were used in our experiments in order to test our model of vibration sensing introduced in Sec.4.1. Note that QPS VibroFibre sensor is essentially a pair of fiber Bragg gratings (FBG), and its reflectivity corresponds only to a certain bandwidth of the DFB laser. To test the sensitivity of our vibration sensing system, we explored the lower limit of vibrating frequencies that can be captured by the system.

### 4.2.2 Experimental results of distributed vibration sensing

In this section, we present the experimental results for three different types of reflective terminations (QPS VibroFibre sensor, flat end fiber, and fiber loop mirror). Note that they all serve as a reflector. To test our model of the working principle of the QPS system, we use the same vibration signal to test responses from these sensors. Then, we use vibration signals of different frequencies to test responses from the same termination (QPS VibroFibre sensor) to test the sensitivity of the QPS vibration sensing system.

Fig. 4.5 shows the FFT spectrum obtained in experiments for three different sensors, where the speaker was driven by a sinusoidal function of 200Hz. Both fundamental frequency (200Hz)
and high order harmonics (400Hz, 600Hz, etc.) are observed for all three cases. These spectrum may look different from our simulations, where only fundamental frequency (200Hz) and
second harmonic (400Hz) were observed. However, in our simulations, we only keep the first and second order terms in the Taylor expansion, as shown in Eq. (4.7) and Eq. (4.8). In principle, one can include more terms in the expansion. Thus, we believe that higher order frequency components should also be observed in our simulations of the FFT spectrum when we keep more terms in the Taylor expansion.

In the FFT spectrum for a fiber loop mirror termination, amplitudes of peaks are much weaker than those in the other two cases. This phenomena is consistent with our simulation result where using fiber loop mirror termination results in much noisier FFT spectrum, as shown in Fig. 4.2 (c) and Fig. 4.3(c). We believe this is because of photodetector saturation effect, where the gain of a photo detector becomes very small.

Figure 4.6: FFT spectrum of the same vibration signal for QPS VibroFibre sensor termination at different times.
Fig. 4.6 shows the FFT spectrum obtained in experiments for QPS VibroFibre sensor at different times, \( t_1 \) and \( t_2 \). From Fig. 4.6(a) and (b), we find that amplitudes of peaks in the FFT spectrum vary with time. As discussed in Sec.4.1.3, we believe this is mainly because environmental noise appears in experiments, including temperature drift in the lab, mechanical noise from ventilation, etc..

Next, to test the sensitivity of the QPS vibration sensing system, we explored the lower limit of frequencies of vibration that can be captured by the system. Fig. 4.7 shows the experimental results of FFT spectrum of vibration signals, where a QPS VibroFibre sensor was used. 5Hz vibration signal can be detected by the sensing system, while 4Hz vibration signal cannot be clearly observed in the FFT spectrum. Thus, 5Hz is the minimum vibration frequency that can be detected by the QPS vibration sensing system.

![FFT spectrum of vibration signals](image1)

![FFT spectrum of vibration signals](image2)

Figure 4.7: FFT spectrum of different vibration signals for QPS VibroFibre sensor termination.

The capability of measuring low frequency vibration offers QPS sensing system a broad
field of applications, for example, vibration monitoring in wind turbine. Low frequency vibrations may cause bearing and stator winding failures for wind turbines, which requires lots of effort to repair as they are frequently installed in remote locations. Frequencies of these vibrations often range from several Hz to 10s Hz [74, 75], which lie right in the detection range of QPS vibration sensing system.

4.3 Summary

Based on change in polarization states of light, this chapter introduced a model of the working principle of distributed vibration sensing using the QPS system. In distributed vibration sensing, the whole fiber link is essentially a “vibration sensor”. Vibration on a short fiber section changes the polarization states of light reflected from the reflective termination, which leads to interferences at an optical detector as a function of vibration. By taking the fast Fourier Transform (FFT) of the interference signal, we can resolve the frequency components of vibration signals. Experimental results for three different types of reflective terminations were presented in this chapter. These results are consistent with our simulations, and demonstrate that the QPS system is capable of distributed vibration sensing. We also explored the lower limit of vibration frequencies (5Hz) that can be detected by the QPS vibration sensing system. Potential application of such system includes, but not limited to, vibration monitoring in wind turbine, pipeline monitoring, and civil structure monitoring.
Chapter 5

Conclusions and Future Work

In this final chapter, I summarize the principle of a single-arm frequency shifted interferometry (SA-FSI), its advantages over conventional fiber optic sensing techniques, and the main experimental results in this thesis work. Moreover, I suggest some future research directions that could provide the next steps along the path to a practical and widely applicable fiber optic sensing system. I also summarize the principle of vibration sensing for the system developed by QPS Photronics Inc. and main experimental results obtained from the system. Multiple-point distributed vibration sensing has been left as future work for this system to be developed and demonstrated.

5.1 Conclusions

5.1.1 Single-arm frequency-shifted interferometry

Fiber optic sensing techniques have drawn a lot of attention in the past few decades due to their advantages over traditional electrical sensing techniques, for example, low signal loss, small in size, and immunity to electromagnetic environment (EMI). Many multipoint or quasi-distributed fiber optic sensing techniques, such as time-division-multiplexing (TDM), wavelength-division-multiplexing (WDM), the frequency-modulated continuous-wave (FMCW) have been developed and identified to have great importance in sensing industry. Recently, a new fiber optic sensing technique, frequency-shifted interferometry (FSI), has been demonstrated that it can also be applied to fiber optic multiplexing. One focus of this thesis work, single-arm frequency-shifted interferometry (SA-FSI), is a modified version of FSI. In this thesis work, I further developed the theory of SA-FSI, and successfully demonstrated that SA-FSI can achieve long distance and high sensitivity sensing multiplexing.

In a SA-FSI system, light from a broadband source is modulated by an amplitude modulator
(or a phase modulator), producing sidebands at $\nu + nf$ and $\nu - nf$ with respect to the baseband optical frequency $\nu$, where $f$ is the frequency of the RF driving signal and $n$ is an integer. Both the baseband and sidebands propagate along the fiber together, and are reflected back by weak reflectors. When the reflected signals pass through the amplitude modulator for the second time, new sideband signals are generated from the baseband, resulting in a sinusoidal interference signal $I(f)$. By sweeping the RF frequency $f$ and taking the fast Fourier Transform (FFT) of the interference signal, we can resolve both the locations and the reflectivity of weak reflectors along one or multiple fibers.

SA-FSI has many advantages over conventional fiber optic multiplexing techniques, such as TDM, WDM, and FMCW. TDM requires for short pulses and fast detectors to achieve high spatial resolution, while SA-FSI needs only a broadband source and a slow detector. In a WDM system, the operational wavelength ranges of sensors cannot overlap with each other, in contrast to SA-FSI which allows the sensors to overlap spectrally. In an FMCW technique, either a radio-frequency (RF) reference signal, or an optical local oscillator (LO) is required. The drawback of an FMCW system with an RF reference signal is that a high-bandwidth (fast) optical detector is needed to capture the full bandwidth of the frequency-modulated lightwave. The drawback of an FMCW system with an optical local oscillator is that the measurement range is limited by the coherence length of the source. However, SA-FSI has no need for reference signal since it is an self-referenced technique. SA-FSI also has several advantages over earlier FSI demonstrations, including a higher spacial resolution, less crosstalk among sensor, shorter measurement time, and simpler and more compact configuration.

Two configurations of SA-FSI have been introduced in this thesis work. In one configuration, 5 weak reflectors were put in series along two fiber links. The frequency of the driving RF signal was swept from 2.5 to 3.5 GHz at steps of 1 MHz, which leads to a spatial resolution of 0.1 m and a measurement range of 50 m. In the other configuration, we located four weak reflectors in series along a single fiber link. By sweeping the amplitude modulator driving frequency in the range between 2.7 and 3.2 GHz at steps of 41.7 KHz, a spatial resolution of 0.2 m and a measurement range of about 1 km have been demonstrated.

In summary, SA-FSI is a simple, compact, practical, and versatile fiber optic sensing technique which has many advantages over conventional techniques. Based on our experimental results, we believe it has many potential applications in fiber optic sensing industry, and further development on SA-FSI will open a number of new and interesting possibilities.
5.1.2 Distributed vibration sensing with QPS fiber-optic system

Fiber optic sensing techniques are playing more and more important role in vibration sensing in power industry due to their advantages over conventional capacitive and piezoelectric vibration sensors, including immune to EMI and high voltage, longer life, small in size, etc.. Recently, QPS Photronics Inc. has developed a fiber-optic vibration sensing system which is capable of detecting vibration in induction motor. In collaboration with the company, we build a model of the working principle of this vibration sensing system.

In a QPS distributed vibration sensing system, light is reflected back by both the connector at the output end of an interrogation unit and a reflective termination as it travels along the fiber link. When there is vibration on a short fiber section, polarization states of the light reflected from the termination vary with vibration. This leads to interferences at an optical detector as a function of vibration. By taking the fast Fourier Transform (FFT) of the interference signal, we can resolve the frequency components of the vibration signal.

Three different types of reflective terminations (QPS vibrofiber sensor, flat end fiber, and loop mirror) have been used in our experiments. Both fundamental frequency component $f$ and higher order harmonics (e.g. $2f, 3f$) are observed in experiments for these three sensors, which is consistent with our simulation results. We also find that amplitudes of peaks in the FFT spectrum vary with time. As discussed in Sec.4.1.3, we believe this phenomena is mainly because environmental noise (including temperature drift in the lab, noise from ventilation, etc.) changes the polarization state of output light from the source. As a result, parameters $\alpha$ and $\beta$ become functions of time. This leads to a time dependence of amplitudes of peaks in the FFT spectrum, according to Eq. (4.7) and Eq. (4.12).

5.2 Future work for SA-FSI

Although the results presented in the thesis have demonstrated that SA-FSI is an effective fiber optic sensing technique, it could be further developed in several ways:

5.2.1 Bi-directional modulator

As shown in Fig. 3.4, backward transmission of the amplitude modulator is much smaller than its forward transmission, which reduces amplitudes of waveforms interfering at the optical detector. In order to get clear interferences, the output power of the broadband source has to be fairly high (about 10 dBm) which adds more noise to the interference signals. A bi-directional amplitude modulator can be explored to improve the backward transmission. One scheme is to design a bi-directional modulator using two unidirectional modulators and circulators, as
shown in Fig. 5.1. This also allows a larger frequency sweeping range of the RF driver, i.e. from 1 GHz up to several GHz, which would improve the spatial resolution of a SA-FSI system.

Figure 5.1: The experimental setup of bi-directional amplitude modulator using two unidirectional amplitude modulators (AM) and two circulators (Cir). Green arrow indicates the traveling direction of waveforms.

Alternative way to get high backward transmission of a amplitude modulator is to buy a commercial bi-directional modulator. However, the price is normally of several thousands dollars, which increases the cost of our system dramatically.

5.2.2 RF Amplifier

In section 3.2, we explored the working point of the amplitude modulator used in our experiments. The optimized modulation depth is $\alpha = 0.7$, which means the output power of the RF driver should be around 19 dBm. For a given output power of the broadband source, $\alpha = 0.7$ leads to the maximum amplitude of the interference signals at the detector. However, the maximum output power of the RF driver used in our experiments is 16 dBm which is less than the optimized output. One way to solve this problem is to use a RF amplifier to increase the output power up to 19 dBm, as shown in Fig. 5.2. This would increase the amplitude of interference signals, and effectively improves the signal to noise ratio in the FFT spectrum.

5.2.3 Other possible developments

Despite the potential developments discussed above, there are still room for the improvement of SA-FSI performance. The minimum step size of RF frequency sweeping used in our experiments is 41.7 KHz, which leads to a measurement time of 10s of seconds. Using a smaller step
size would result in longer measurement time, which adds more environmental noise to the signal. If the RF frequency can be sept at a higher speed, a smaller step size can be explored in experiments. This would extend the measurement range of a SA-FSI system.

### 5.3 Future work for QPS vibration sensing system

One interesting future research direction in QPS vibration sensing system is to explore its capability of detecting multiple vibrations along the fiber link. Fig. 5.3 shows an example configuration where there are multiple vibration sources along the fiber link. In principle, these vibration sources could work at different frequencies.

---

**Figure 5.2:** The experimental setup of SA-FSI with a broadband source (BBS), an optical circulator (Cir), an amplitude modulator (AM), a RF amplifier, a polarization controller (PC), a slow photo detector (PD), and one weak reflector (R₁).

**Figure 5.3:** The experimental setup of multiple-point distributed vibration sensing with a QPS unit, a data logger, multiple vibration sources, and one reflective termination.
Appendix A

Bessel functions expansion

Figure A.1: Operation principle of the Mach-Zehnder modulator used in the experiment.

The amplitude modulator used in our experiment is a Mach-Zehnder modulator (as shown in Fig. A.1). A sinusoidal modulating voltage with frequency $f$, together with the bias applied to the modulator, can be described as

$$V(t) = \varepsilon V_\pi + \alpha V_\pi \cos(2\pi ft),$$  \hspace{1cm} (A.1)

where $\varepsilon = V_{bias}/V_\pi$ and $\alpha = V_{RF}/V_\pi$ are the normalized bias point of the modulator and the normalized amplitude of the drive-voltage respectively. As a result, the output field from the modulator is given by

$$E(t) = \cos \left( \frac{\pi}{2} \left[ \varepsilon + \alpha \cos(2\pi ft) \right] \right) \cos(2\pi vt + \phi_v),$$  \hspace{1cm} (A.2)

where $v_0$ is the frequency of the input lightwave.
If the modulator is biased at $\varepsilon = 0.5$ and the modulation depth $\alpha$ is small enough, Eq. (A.2) can then be written as

$$E(t) \simeq \left( \cos\left(\frac{\pi}{4}\right) - \sin\left(\frac{\pi}{4}\right) \cos(2\pi ft) \right) \cos(2\pi \nu t + \phi\nu)$$

$$= \cos\left(\frac{\pi}{4}\right) \cos(2\pi \nu t + \phi\nu)$$

$$- \frac{1}{2} \sin\left(\frac{\pi}{4}\right) \left( \cos(2\pi(\nu + f) + \phi\nu) + \cos(2\pi(\nu - f) + \phi\nu) \right), \quad (A.3)$$

which leads to a carrier wave and two sidebands at $\nu_0 \pm f$.

However, the modulation depth is not small in our experiment ($\alpha = 0.69$), which means Eq. (A.3) is not a good approximation to Eq. (A.2). Thus, we need to expand Eq. (A.2) with Bessel functions. We first rewrite Eq. (A.2) as

$$E(t) = \Re\left[ e^{i\frac{\pi}{4}(\varepsilon + \alpha \cos(2\pi ft))} \cos(2\pi \nu t + \phi\nu) \right]. \quad (A.4)$$

According to Jacobi-Anger expansion [76],

$$e^{jz \cos \theta} = \sum_{n=-\infty}^{\infty} j^n J_n(z) e^{in\theta}, \quad (A.5)$$

where $J_n(z)$ is $n^{th}$ Bessel function. Using $J_{-n}(z) = (-1)^n J_n(z)$, we have

$$e^{jz \cos \theta} = J_0(z) + 2 \sum_{n=1}^{\infty} j^n J_n(z) \cos n\theta. \quad (A.6)$$

Let $\frac{\pi}{2} \varepsilon = x$, $\frac{\pi}{2} \alpha = y$. As a result,

$$E(t) = \cos(2\pi \nu t + \phi\nu) \Re\left[ e^{ix} \left( J_0(y) + 2 \sum_{n=1}^{\infty} j^n J_n(y) \cos(2\pi fn) \right) \right]$$

$$= \cos(2\pi \nu t + \phi\nu) \Re\left[ e^{ix} \left( J_0(y) + 2iJ_1(y) \cos(2\pi ft) - 2J_2(y) \cos(2 \cdot 2\pi ft) + \ldots \right) \right]$$

$$= \cos(2\pi \nu t + \phi\nu) \left\{ J_0(y) \cos(x) - 2J_1(y) \sin(x) \cos(2\pi ft) - 2J_2(y) \cos(x) \cos(2 \cdot 2\pi ft) + \ldots \right\}$$

$$= J_0(y) \cos(x) \cos(2\pi \nu t + \phi\nu)$$

$$- 2J_1(y) \sin(x) \cos(2\pi ft) \cos(2\pi \nu t + \phi\nu)$$

$$- 2J_2(y) \cos(2 \cdot 2\pi ft) \cos(2\pi \nu t + \phi\nu)$$

$$+ \ldots \quad (A.7)$$

Given $2 \cos(a) \cos(b) = \cos(a) \cos(b) + \cos(a) \cos(b)$, one can simplify Eq. (A.7) further as
\[ E(t) = J_0(\alpha \frac{\pi}{2}) \cos(\frac{\pi}{2} \varepsilon) \cos(2\pi v t + \phi_v) \\
- J_1(\alpha \frac{\pi}{2}) \sin(\frac{\pi}{2} \varepsilon) \cos(2\pi t (v - f) + \phi_v) \\
- J_1(\alpha \frac{\pi}{2}) \sin(\frac{\pi}{2} \varepsilon) \cos(2\pi t (v + f) + \phi_v) \\
- J_2(\alpha \frac{\pi}{2}) \cos(\frac{\pi}{2} \varepsilon) \cos(2\pi t (v - 2f) + \phi_v) \\
- J_2(\alpha \frac{\pi}{2}) \cos(\frac{\pi}{2} \varepsilon) \cos(2\pi t (v + 2f) + \phi_v) \\
+ \ldots \quad (A.8) \]

We have substituted \( x = \frac{\pi}{2} \varepsilon \) and \( y = \frac{\pi}{2} \alpha \), and assumed that the input field is normalized to unity in Eq. (A.8).
Appendix B

Matlab code for performing FFT on experiment data
% Title: FFT of the experiment data to resolve the locations and reflectivities of weak reflectors
% Author: Yiwei Zhang
% Comments: Here we select a portion of the raw data to reduce the data-processing time. This is controlled by a parameter "step". Zero-padding and Hanning window are applied to FFT.

tic;

Data = dlmread('file path');    % read experiment data into a file
data = Data(:,1);
trigger = Data(:,2);
step = 5;                       % set up the step size of data-selection
newlength = floor((length(data)-1)./step)+1;

newdata = zeros(newlength,1);
newtrigger = zeros(newlength,1);

i =1;            % write the selected data into "newdata" and "newtrigger"
for id = 1:length(data)
    if mod((id-1),step) == 0
        newdata(i,1) = data(id);
        newtrigger(i,1) = trigger(id);
        i = i+1;
    end
end

avg = mean(newdata);          % get rid of the DC background
newdata = newdata - avg;
newtrigger = newtrigger - avg;

plot(newdata);              % plot the newdata and newtrigger to find out "start" and "off" point of newdata in one RF frequency scanning range
hold all;
plot(newtrigger);
toc;

%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% FFT on the selected data in one RF scanning range
% start = 6.578e4;              % start and end of newdata in one RF
% off = 9.597e5       ;
% range = off - start +1;

```matlab
```
APPENDIX B. MATLAB CODE FOR PERFORMING FFT ON EXPERIMENT DATA

```matlab
s_data = zeros(range,1);
s_trigger = zeros(range,1);

for id = start:off
    s_data(id-start+1) = newdata(id);
s_trigger(id-start+1) = newtrigger(id);
end

win_data = hann(length(s_data)).*s_data;
FFT_size = 2^23;                           % zero-padding of FFT
F_data = abs(fft(win_data,FFT_size));
c = 299792458;        % speed of light in m/s
n = 1.47;             % effective index of the SMF
del_f = 1000*10^6;    % frequency sweep range in Hz

del_f_eff = del_f/(length(s_data)-1)*(FFT_size-1);
dL = c/(2*n*del_f_eff);
L = (0:1:FFT_size-1)'*dL;

% plot out the FFT result
plot(L(1:floor(length(L)/2)), F_data(1:floor(length(L)/2)),'.-');
xlabel('Distance (m)','fontsize',14);
ylabel('Amplitude [a.u.],'fontsize',14);
toc;
```
Bibliography


