WAVELENGTH ACCURACY STUDY FOR HIGH-DENSITY FIBER BRAGG
GRATING SENSOR SYSTEMS USING A RAPIDLY-SWEPT AKINETIC-
LASER SOURCE

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Fiber Bragg grating sensor systems using a
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ABSTRACT

Wavelength accuracy study for high-density Fiber Bragg grating sensor systems using
a Rapidly-Swept Akinetic-Laser source

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This thesis studies the center wavelength accuracy of a Fiber Bragg Grating Sensor system that has a large number of sensor elements both as a function of wavelength and as a function of position. Determining the center wavelength of each of the fiber optic sensors is a critical parameter that ultimately determines sensor accuracy. The high density environment can result in degradation of accuracy of the center wavelength measurement. This thesis aims to quantify this measurement error both with theoretical and experimental studies.

There are many sensing applications where optical fiber sensors are preferred over electrical sensors, such as the oil and gas industry where fiber optic sensors are used to monitor wells and pipelines due to their low signal degradation over long distances and immunity to harsh physical environments. Fiber Bragg grating (FBG) sensors in particular have widespread use because of their versatility, measurement sensitivity, and distributed multiplexing abilities. In conventional wavelength multiplexing, up to 50 FBG sensors are spread out over a band of 100nm, each with a center wavelength difference large enough so that each element can be individually measured. However, numerous sensing applications require several hundred to over a thousand sensors cascaded together on a single fiber. These sensor arrays use a combination of WDM and TDM for measurements, where many FBG sensors with the same center wavelength are separated by a long enough length of fiber so that the reflected signals are separated in time.

These Wavelength-to-Time Domain Multiplexing (W-TDM) measurements are enabled by Insight Photonic's new 'akinetically' swept, all-semiconductor laser. This laser is a Vernier-Tuned Distributed Bragg Reflector (VT-DBR) device, capable of rapidly sweeping through different wavelengths without any moving parts. Attributes that make this laser superior to mechanically-swept lasers include: 1) short and long term consistent sweep-sweep reliability, 2) availability at many wavelengths, 3) a narrow linewidth with single longitudinal mode, and 4) the ability to do non-traditional sweep patterns that facilitate measurement of high-density sensor networks.

In this thesis, experiments will be performed in the lab with the Insight VT-DBR laser to determine how accurately the center wavelength of a single Fiber Bragg grating can be measured. Experiments will also be performed with two and three FBGs to compare different algorithmic approaches to measurements. The second part of the thesis will simulate both single and multiple FBG sensor environments, comparing the center wavelength measurement accuracy results for different parameters including signal-to-noise ratios, wavelength point density, FBG loss and width, and multiple algorithmic approaches. The results of these experiments and simulations will demonstrate how accurate a FBG sensor system is at particular parameters, which will be useful to those designing a sensor network or performing similar experiments.

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Chapter 1: Introduction

1.1 What is VTDBR

The Vernier-Tuned Distributed Bragg Reflector (VT-DBR) is a kinetic laser source is a high-speed, all-semiconductor, tunable laser. Tunable means that the laser's wavelength can be controlled over a certain range. [1] The VT-DBR laser works by selecting the lasing cavity's oscillatory wavelength with two distributed Bragg-reflector mirrors on each end of the cavity.[2] Together, the mirrors perform as a Fabry-Perot resonator that rejects the transmission of a harmonically related set of wavelengths, which are determined by the distributed Bragg-reflector length of separation. The rejected light resonates in the electrically pumped gain medium where a single mode commonly reflected by the mirrors is amplified.

The distance between the DBR mirrors is controlled by applying an electric current to the semiconductor material the mirrors are comprised of, changing their refractive index. [3] A change in refractive index of a material results in a change in the reflective angle of incidence, which changes the light-path distance between the mirrors. This affects the light rejected by the mirrors and causes the laser to output a specific wavelength. The term "Vernier" in "Vernier-Tuned" refers to the Vernier effect used in tuning the laser from the comb reflection spectra of the distributed Bragg reflector structures.

What makes this laser the better alternative compared to other swept lasers is that it is an "Akinetic Swept Laser", which means that there are no physical moving parts. This allows it to avoid mechanically induced noise and mechanical limitations on

tuning speed. Additional noise however, it added from the drive circuitry used in the electronic tuning.

1.2 Capabilities of Packaged Insight Laser

The Insight Akinetic Laser is the laser source used throughout this thesis. It provides the packaging and user interface for the VTDBR laser mentioned above. [4] It uses a digital controls system to change the currents with time in order to precisely sweep through optical frequencies. An equal-in-time sample clock is used, and trigger signals are generated to indicate when measurements should be taken by the user's data acquisition system. The laser package also includes an internal data acquisition system that can measure one sweep at a time at a sampling rate of 400MHz, the default clock rate of the laser. The specific laser used in this thesis is model SLE-101 and has a sweep range of 1522.14nm – 1562.14nm.

Figure 1.1: The front panel of the Insight laser [4]

Figure 1 shows each input and output to the packaged laser. The Start Sweep output lets an external acquisition device know when the sweep is starting so that it can save a

single sweep at a time. The Data Valid output determines whether or not the Laser Out signal is valid over a particular sample. The Laser In input goes to the internal acquisition device. The laser is controlled through a graphical user interface software program built in LabView. Controllable variables include: number of sweep points, minimum and maximum wavelengths, time delay between sweeps, wavelength sweep direction (high-to-low or low-to-high), output power, and clock rate.

1.3 Why you Need a Sensor-Rich Environment

A frequency-swept laser is useful for applications where the sensor acts as a wavelength filter, and in situations where there are multiple sensors in series, each set at a slightly different center wavelength. Many of these applications occur in the oil and gas industry, where fiber sensors are preferred over electrical sensors due to their low signal degradation over long distances and relative immunity to harsh physical environments. One application that uses multiple sensors is pipeline monitoring for leaks, geo-hazards, and intruder detection. In order to be effective, multiple sensors are spread out along the onshore or offshore transmission pipelines, each monitoring a small subsection. This works by using a single optical fiber cable to combine distributed measurements of temperature, strain, and acoustics. Another common use for multiple optic sensors along a single fiber is traffic and bridge monitoring, where Fiber Bragg grating sensors are placed along a bridge to monitor strain and the amount of traffic going across.

1.4 Insight Photonics Multi-Sensor Experiments

Progress has already been made by Insight Photonics, where they ran tests with sensor arrays of 250 and 336 Fiber Bragg grating strain sensors. [5] In these experiments, where the schematic can be seen below in Figure 2, a time-based interrogation technique was used.

Figure 1.2: Schematic of Swept Wavelength to Time Domain Reflectometry Scheme for FBG arrays used by Insight Photonics for their experiments with multi-sensor environments

This technique uses the akinetic, swept laser to enable Wavelength-to-Time Domain Reflectometry (WTDR), which converts the return signals from wavelength-swept optical pulses into unique time-domain arrival signatures. This allows the receiver to separate each sensor in time. The results of this experiment were that the center wavelength of each sensor could be measured with 0.5pm standard deviation, compared to multiple-picometer accuracy of mechanically-swept lasers.

Due to equipment constraints, this particular technique of sending out short pulses with the laser will not be explored with a large number of sensors. Instead, simulations will be done with 10-500 FBGs on a single fiber.

1.5 Purpose of Study

The purpose of this thesis is to find out exactly how accurate measurements are in single and multi-sensor environments using the Insight VT-DBR laser. Accuracy is defined as the repeatability of the measurements of the center wavelength of a FBG sensor. The results will provide a benchmark that can be referenced by future applications and experiments. This would let a system designer quickly figure out what Fiber Bragg grating sensor specifications are needed for a given amount of sensors. For example, if the requirements call for 200 sensors and measurement accuracy to within 25 picometers, then a reflectivity of 0.8% and FBG width of 0.1nm would be the best choice. Similarly, if an experiment is being performed with a certain signal-to-noise ratio, then the results of this thesis would help determine the maximum number of FBG sensors able to be accurately measured.

1.6 Thesis Summary

Chapter 2 reviews the basics of Fiber Bragg gratings, fiber optic networks, and measurement devices. The experimental process will be explained in detail, and a single FBG sensor will be measured, and establish an understanding of how accurate the measurements are. Chapter 3 covers the simulations of a single FBG device, and multiple FBG sensors, and how accurate measurements are in different environments. Chapter 4 will experimentally repeat a couple of the simulations from chapter 3, and the

results will be compared to the simulation results. Chapter 5 summarizes the results from the simulations and experiments, and shows how they apply to future applications and experiments.

Chapter 2: Experimenting with a Single Fiber Bragg-Grating

2.1 Fiber Bragg Grating Sensors

Fiber Bragg gratings (FBGs) are an optical sensing element used in measurements such as strain, temperature, pressure, and flow. [6] They are created by exposing the core of a germanium-doped optical fiber to direct, single-photon UV light. This creates a periodic deviation of the refractive index along the fiber, resulting in a band rejection known as the Bragg wavelength. The Bragg wavelength is a function of the effective refractive index of the fiber and periodicity as seen in Equation 2.1 below:

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (\text{Eq. 1.1})$$

Where n_{eff} is the effective refractive index, and Λ is the grating periodicity. As the light source sweeps through different wavelengths, the rejected band is reflected back towards the source. An example of the measured reflection from [7] can be seen below in Figure 2.1:

Figure 2.1: Example of the reflected signal from a FBG sensor

From Figure 2.1, it can be seen that the FBG acts as a notch filter for the wavelength of the laser source. The two important measureable characteristics are the peak reflectivity and the FWHM. The peak reflectivity is the maximum amount of light reflected back to the source. The full-width at half-max is the 3dB bandwidth of the sensor in terms of wavelength. These two parameters affect the signal-to-noise ratio and measurement accuracy. They are also the main variables to choose when designing a FBG sensor for a multi-sensor network. Fiber Bragg gratings act as an optical sensor by varying the Bragg wavelength λ_B for certain changes in environmental conditions such as strain or temperature.

For strain measurements, the shift in Bragg wavelength is affected by the applied strain along the longitudinal axis as seen in the following formula:

$$\Delta\lambda_B = \lambda_B(1 - P_E)\epsilon_z \quad (\text{Eq. 1.2})$$

Where λ_B is the Bragg wavelength, P_E is the effective strain-optic constant, and ϵ_z is the applied longitudinal strain.

For temperature measurements, the shift in Bragg wavelength as a result of temperature changes is described by:

$$\Delta\lambda_B = \lambda_B(\alpha - \zeta)\Delta T \quad (\text{Eq. 1.3})$$

Where ΔT is the temperature change, α is the thermal expansion coefficient for the fiber, and ζ is the thermos-optic coefficient.

2.2 Fiber Optic Systems

All of the experiments in this thesis involve fiber optics. The basic components in an optical sensing system are the optical power source, the optical fibers transmitting the light, one or more fiber sensors, and a photodetector receiver. [8]

Figure 2.2: Block diagram of basic fiber optic sensing system

The optical source is either a laser or LED that typically emits infrared light (850nm-1675nm). The optical fiber is a very thin strand of silica glass surrounded by a thicker cladding made up of glass with a lower refractive index than the core. Attenuation in commercial glass fibers is about 4dB/km. Optical fibers can be separated in two different types: singlemode and multimode.[8][9] Singlemode fibers have a small enough core that only allows one path for rays of light to travel through. Multimode fiber has a larger core diameter and supports more than one propagating mode of light. Singlemode fibers are preferred over multimode fibers for strain sensing because most of the equipment used in strain sensing is designed to operate around singlemode fibers at 1550nm. Multimode fibers are preferred for temperature sensing because it allows for more power, and the larger core size results in a higher threshold for nonlinearities.

The sensor measures environmental quantities such as strain, temperature, pressure, and chemical makeup. Most sensors measure the reflected signal instead of the transmitted signal through the sensor. The signal then goes to a photodetector, which is usually comprised of a PIN or avalanche photodiode that converts light to an electric current, and a transimpedance amplifier that converts the current to a voltage.

An example circuit from [10] can be seen below in Figure 2.3:

Figure 2.3: Example photodetector circuit where light is converted by the photodiode to an electric current, and then changed into voltage by the amplifier

The two important photodetector parameters are: the maximum and minimum input power, and wavelength range. Too much input power could damage the photodiode, and not enough input power results in an output signal indiscernible from noise. The wavelength range refers to what wavelengths of light the photodiode can convert into an electric current.

2.3 Experimental Test Setup

The lab experiments are run with the configuration shown below in Figure 2.4:

Figure 2.4: Experimental Test Configuration used in Chapters 2 and 4

Figure 2.5: Image of lab setup used for Chapter 2 experiments. Each board has a Fiber Bragg grating strand attached via paper between tape and the board. The Insight laser is in the top right corner, the ThorLabs photodetector is the black box middle-right, the grey box underneath is the optical coupler, and the white package in the lower right is the Insight photodetector

The laser source is the Insight Photonics SLE-101 VT-DBR Laser. It is set at a constant power output of 7mW, and a wavelength sweep range of 1539.49nm – 1554.9nm at a sweep rate of 24.4081kHz. The value of 7mW was chosen because it is the highest output power the device is capable of, and the higher optical power increases the signal-to-noise ratio. The wavelength range was chosen because it comfortably includes all the FBG center wavelengths being used throughout the experiments. The sweep rate was selected by the laser during its calibration. A 15dB optical attenuator was used for the transmission measurements in order to not exceed the power limit of the ADC. It

was not needed for the reflection measurements, because only 2% of the transmitted power is reflected. Unless otherwise mentioned in an experiment, each fiber connecting the elements in Figure 4.1 is less than 1m long. The optical coupler used is the Hewlett Packard 11890A 1300nm/1550nm LightWave Coupler which was experimentally measured to have a loss of 1.9dB from point (A) to point (B) in Figure 4.1, and a loss of 3.7dB from (B) to (D). These losses include connector losses. The ADC used was the National Instruments 5105 PCI Digitizer, which sampled at a rate of 50MHz. This resulted in a total of 2048 data points for each sweep.

2.4 How Data is Analyzed and Processed

The data from the NI 5105 Digitizer is viewed on a computer using a LABVIEW oscilloscope program. This allows the user to observe the sweeps in real time and make any adjustments to the system as needed. Any number of sweeps can be saved to CSD file based on the Sweep Start Signal the laser sends electronically to the digitizer through a separate channel from the data. The laser also has another electronic output called “Data Valid”, that stores an array that shows what measured data is valid, and what data is invalid.

Figure 2.6: Picture of all outputs from the Insight Laser used in each experiment

MATLAB software, which is a numerical computing program by MathWorks, reads in the CSD file holding all the measurement data and is used to process it. After the data is loaded into MATLAB, the measurement data is aligned with the data valid vector, which removes the invalid data. The data is then passed through a low-pass FIR filter at a cut-off frequency of 1.25MHz, which removes the high-frequency noise in the data without distorting the signal, and increases the signal-to-noise ratio from 7 to 20. An example of the received data for a single FBG reflection before and after filtering can be seen below in Figure 2.5:

Figure 2.7: Measurement results for a single FBG sensor reflection before and after being passed through a low-pass FIR filter with cutoff frequency of 1.25MHz

Figure 2.8: Magnified view of measurement results for a single FBG sensor reflection before and after being passed through a low-pass FIR filter with cutoff frequency of 1.25MHz

Figure 2.5 shows that the filter eliminates noise on the reflected FBG peak, and smooths most of the noise elsewhere.

The default sample clock of the VT-DBR laser is 400MHz. This means that the laser changes its optical wavelength output every $\left(\frac{1}{400\text{MHz}}\right) = 2.5\text{ns}$. Because the NI 5105 Digitizer is limited to a sample rate of 50MHz, it can only sample data every $\left(\frac{1}{50\text{MHz}}\right) = 20\text{ns}$, which means that it misses $7/8 = 87.5\%$ of the data. Because the measured sweep data is not a perfect representation of the complete set of data, a

quadratic fit is applied in MATLAB to the reflected peak. This works because the FBG reflection feature is similar to a second-order polynomial.

Figure 2.9: Fitted approximation plotted alongside original measured data for a single FBG reflection measurement

The MATLAB script written finds the maximum value of the polynomial using the roots of the derivative, and then returns the corresponding sample number of the peak. In the above example seen in Figure 2.7, the peak location is calculated to be measured at 18.626 microseconds.

2.5 Single Fiber Bragg Grating Measurement Accuracy

In order to find out how much deviation there is in measurements of the Fiber Bragg grating's center wavelength, an experiment of 100 identical sweeps through a single FBG was performed.

A single Fiber Bragg grating with a center wavelength of 1545.83nm, FWHM of 0.18nm, and reflectivity of 2.08% was used as the device under test. The reflections from the FBG were measured and recorded. The experimental setup is seen in Figure 2.4, where the DUT is a single FBG, and the measurements were made at point D. 100 full sweeps were run at a 50MHz clock. The min wavelength was 1539.49nm, and the max wavelength was 1554.9nm. At a sweep rate of 24.4081 kHz and a sample rate of 50MHz, there were $(50\text{M-samples/sec})/0.0244081\text{MHz} = 2048$ data points per sweep. In order to speed up the data acquisition process, an Excel macro was created that automatically took the data and copied to a new column in Excel. The result of the data-gathering process was a spreadsheet with $100 \times 2048 = 204,800$ unique data values. The data gathered from the first sweep is graphed below:

Figure 2.10: Graphed data for the first sweep out of a total of one-hundred sweeps for the center wavelength measurement accuracy experiment. Shown is the reflected signal of a single FBG with a reflectivity of 2.08%, FWHM of 0.18nm, and center wavelength of 1554.9nm

Each data point was converted into units of sweep wavelength by dividing the 15.41nm wavelength delta by 2048 data points. The standard deviation of all the measurements was 0.14 picometers. This is better than the 0.5pm measurement accuracy from the Insight Photonics multi-FBG experiment discussed in Chapter 1, Section 4. The reason for the accuracy increase is that only one FBG was measured instead of 250 FBG sensors. Another reason is that this FBG had a reflectivity of 2% instead of 0.1%, which resulted in a higher SNR. The 0.14pm measurement accuracy is considered very good,

especially compared to mechanical lasers, and provides a solid base to compare future measurements and simulation results.

Chapter 3: Single and Multiple FBG Simulations

3.1 Introduction

The purpose of this chapter is to find the measurement accuracy of single and multi-sensor networks by modeling the experimental system in MATLAB and simulating different DUTs. Accuracy is defined as the repeatability of the measurements of the center wavelength of a FBG sensor. These DUTs include single Fiber Bragg gratings at various reflectivities and FWHMs, as well as many Fiber Bragg gratings in series at varying center wavelengths. This will result in an accurate approximation of real-world results, which would be useful to someone deciding what FBG characteristics to choose for a specific task. Part A shows how the system is modeled. This includes drafting the experimental layout, calculating system bandwidth and noise, and modeling a FBG with variable parameters such as reflectivity and FWHM. Part B details the simulations of a single FBG sensor to show the maximum measurement accuracy for different signal-to-noise ratios. Part C details the simulations of more than one FBG sensor on the same fiber, and finds the measurement accuracy of each individual device under different setups. Part D concisely summarizes the results from Parts B and C.

3.2 System Modeling

In this section, the system being simulated is described in detail. The physical setup will be shown; the sweep of the laser source is defined, the simulated noise is calculated, and the filter used is found. The default Fiber Bragg grating used in this section has a reflectivity of 2%, a center wavelength of 1545.83nm, and a full-width at half-max of 0.2nm. These particular parameters will be changed in later sections. Other

parameters that will later be experimented with are an output power of 7mW, and an ADC sample rate of 400MHz.

Figure 3.1: Block diagram of the single FBG experimental layout being modelled in MATLAB

Figure 3.1 shows the block diagram of the experimental setup of the simulated system. The laser source is the Insight laser (Model SLE-101) at (A) sweeping from 1540nm – 1551nm at a sweep rate of 26.2605kHz and an output power of 1mW. The coupler has a 3dB loss in each direction. The photodetector is modeled after a ThorLabs PDB130C unit. [11][12] The photodetector output signal at (E) is passed through a low-pass filter with a cutoff frequency of 1.5MHz, and then sampled at a rate of 50×10^6 samples/second at (F).

The FBG is simulated in MATLAB by creating a notch filter with similar characteristics to an actual FBG measured using the setup shown in figure 1. The equations used are: [6]

$$\text{Filter Reflection } R = \frac{\sinh(L\sqrt{k^2 - \sigma^2})}{\cosh(L\sqrt{k^2 - \sigma^2} - \frac{\sigma^2}{k^2})} \quad (\text{Eq. 3.1})$$

Where the general DC coupling coeff. $\sigma = 2\pi n_{\text{eff}} \left(\frac{1}{\lambda} - \frac{1}{2n_{\text{eff}}A} \right) + \sigma_{\text{dc}}, \sigma_{\text{dc}} = 0$ (Eq. 3.2)

and the AC coupling coeff. $k = \frac{2\pi v \delta_n}{\lambda}$ (Eq. 3.3)

The grating length L and induced index change δ_n are variables used to change the FWHM and reflectivity of the filter.

The grating period $A = \lambda_c / 2n_{\text{eff}}$ (Eq. 3.4) is a constant, where $\lambda_c = 1545.83\text{nm}$ is the center wavelength, and $n_{\text{eff}} = 1.4455$ is the effective refractive index. The visibility $v = 0.138$ is also a constant.

To simulate an environment where the transmitted and reflected signals are being measured, the scattering transfer network parameters are used. The following equations from the Agilent AN 154 user's manual [13] show how the parameters are related:

Figure 3.2: Two-Port Network Notation

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (\text{Eq. 3.5})$$

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} -\frac{S_{11} S_{22} - S_{12} S_{21}}{S_{21}} & \frac{S_{11}}{S_{21}} \\ -\frac{S_{22}}{S_{21}} & \frac{1}{S_{21}} \end{bmatrix} \quad (\text{Eq. 3.6})$$

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \frac{T_{12}}{T_{22}} & \frac{T_{11} T_{22} - T_{12} T_{21}}{T_{22}} \\ \frac{1}{T_{22}} & -\frac{T_{21}}{T_{22}} \end{bmatrix} \quad (\text{Eq. 3.7})$$

Where the S variables represent the scattering parameters, and the T variables represent the scattering transfer parameters. This simulation used the variable a1 to represent the laser source, and the variable b1 to represent the reflected signal.

Because just a single FBG is being simulated, only one 2x2 T matrix is used. When there are more elements in the network, multiple T matrices are multiplied together to form a single T matrix. The S values are then extracted from the combined T matrix. S_{11} and S_{22} are equal to the reflection R, and S_{12} and S_{21} are equal to the transmission $1 - R$. The phase shift over the length of fiber was ignored.

Figures 3.3 and 3.4 below show the graphical results of $b_1 = S_{11}a_1 + S_{12}a_2 = S_{11}(1) + 0 = S_{11}$.

Figure 3.3: Simulated FBG reflection at 2% ref, FWHM = 0.2nm, and a center wavelength of 1545.83nm

Figure 3.4: Close-Up of Simulated FBG reflection at 2% ref, FWHM = 0.2nm, and a center wavelength of 1545.83nm

In order to properly model the noise, the bandwidth of the simulated data from part 2 must be identified. The simulated laser sweep with a single FBG sensor is plotted against time:

Figure 3.5: Simulated FBG reflection plotted against time

At a sweep rate of 26.2605 kHz in the 11nm sweep, it takes $(1/26260.5) \cdot (1/11) = 3.46181 \times 10^{-6}$ seconds per nm. If the full-width at half-max of a FBG during simulations is 0.2nm, then the estimated time width of the signal is $(0.2\text{nm})(3.46181\text{us/nm}) = 0.6924\text{us}$. This is inverted to convert to Hz: $\Delta f = (1/(2\pi \cdot 0.6524)) \text{ MHz} = 0.244\text{MHz}$, which should be close to the lower frequency bound for both the bandwidth and the cutoff frequency of a filter. This is repeated for different FWHMs:

Table 3.1: Estimated minimum bandwidth for each FBG FWHM

FWHM (nm)	Minimum Bandwidth Estimate (MHz)
0.1	0.460
0.2	0.244

0.25	0.184
0.3	0.153
0.4	0.115
0.5	0.092

The next method of finding the system bandwidth is to take a fast Fourier transform of the simulated data. The results of which can be seen below in Figure 3.6:

Figure 3.6: Graphical Results of Taking FFT of Simulated FBG at 2% Ref, 0.2nm
FWHM

The FFT results in Figure 3.6 show that the signal power levels off above 1.6MHz. The signal rapidly decreases from 0 to 0.35MHz. This implies that a low-pass filter with a cut-off frequency of 0.4MHz or higher should have a miniscule effect on the signal.

Figure 3.7: Graphical Results of Taking FFT of Simulated FBG at 2% Ref, 0.5nm FWHM

The FFT results in Figure 3.7 show that the signal power levels off above 1MHz. The signal rapidly decreases from 0 to 0.15MHz, which is lower than when the FWHM is smaller at 0.2nm. This supports the initial estimates in Table 3.1.

To find the actual system bandwidth, a low-pass filter will be applied to noiseless data from node (E) in Figure 3.1. The measured voltage is calculated in Equations 3.8 and 3.14. The cutoff frequency will be varied until a minimum frequency is found where there is no degradation to the signal. Using a low-pass FIR filter in MATLAB (see

appendix A) with a filter order of 100, an 0.1dB peak-peak ripple, and an 80dB stopband attenuation, the following results were obtained:

Figure 3.8: FBG peaks vs signal wavelength when passed through LPFs with different cut-off frequencies

Figure 3.9: FBG peaks when passed through LPFs with different cut-off frequencies
(Zoomed in)

In Figures 3.7 and 3.8, it can be seen that the signal becomes increasingly distorted for low-pass filter cutoff frequencies less than 1.5MHz. This implies that the bandwidth of this particular data set is around 1.5MHz, which matches the calculated and FFT results. The noise calculations then will use the value of 1.5MHz for the bandwidth Δf . When the FBG has other values for its FWHM, the following values for bandwidth were chosen based on the filter results similarly to Figures 3.7 and 3.8:

Table 3.2: Chosen system bandwidths for each FWHM during the simulations

FWHM (nm)	Bandwidth (MHz)
0.1	2
0.2	1.5
0.25	1.1
0.3	0.95
0.4	0.71
0.5	0.50

The Bandwidth values in Table 3.2 are on the conservative side, and will be used in the upcoming noise calculations.

Now that the bandwidth is known, the different noises can be calculated. [3]The noise modeling for the simulations is done by calculating and modeling each noise source separately, then combining them together. The circuit diagram in figure 3.9 below shows where the noise occurs in the simulation model. The values for the noise calculations come from the ThorLabs PDB130C datasheet [11][12], and the settings used on the laser during experiments.

Interior Layout of the Photodetector from Figure 3.1:

Figure 3.10: Circuit diagram of the source current (I_s) and following noise sources: relative intensity noise (I_{RIN}), shot noise (I_{NS}), thermal noise (I_{NT}), and excess noise (I_{EXCESS})

The source current I_s is the main signal current from the photodiode and can be found by following formula:

$$I_s = R \cdot P \quad (\text{Eq 3.8})$$

where R [A/W] is the photodiode responsivity, and P is the received optical power. The laser source in the Figure 3.1 circuit has an output power of 1mW, a 2% FBG reflectivity and 3dB loss on the transmission and return path through the coupler. Fiber path attenuation and other losses will be assumed to total 10%. The responsivity of the photodiode is 1 A/W, therefore from Eq. 3.8:

Max Value of Source Current $I_s =$

$$\left(1 \frac{\text{A}}{\text{W}}\right) (P_{\text{Source}})(1 - 3\text{dB Coupler Loss})(2\% \text{ Reflection})(1 - 3\text{dB Coupler Loss})(1 - 10\% \text{ System Loss}) =$$
$$\left(1 \frac{\text{A}}{\text{W}}\right) (1\text{mW})(0.5 \times 0.02 \times 0.5 \times 0.9) = 4.5\mu\text{A}$$

The relative intensity noise (RIN) is defined in [14] as the measure of undesired fluctuations in the laser output power and wavelength. From [14], the relative intensity noise was experimentally determined by measuring the laser output fluctuations when the laser source was set at 5.5mW and a 40nm sweep range around 1550nm. The RIN was measured to be 0.19% of the average output of the laser for sweeps at 20kHz, 100kHz, and 200kHz. It was determined by testing different bandwidths ranging from 5 - 190MHz that bandwidth and sweep rate had no effect on the laser output power fluctuations or RIN. For this study, the RIN will be calculated as:

$$I_{\text{RIN}} = 0.0019 * I_s = (0.0019)(4.5\mu\text{A}) = 8.55\text{nA} \quad (\text{Eq 3.9})$$

The second noise modeled is the shot noise I_{NS} , which in general terms is a noise associated with the particle nature of light that occurs in optical receivers. [8] In the semiconductor junction devices used in photodetectors, incoming optical signals generate discrete charge carriers. Each of these carriers generates a single pulse, which collectively contributes to the total current and is known as shot noise. The mean-squared value can be modeled as follows:

$$I_{NS}^2 = 2eI_S\Delta f = 2(1.6 \times 10^{-19} \text{C})I_S(1.5 \times 10^6 \text{Hz}) = 4.8 \times 10^{-13} I_S = 2.16 \times 10^{-18} \text{A}^2 \quad (\text{Eq 3.10})$$

Where e is the charge of an electron in coulombs, and Δf is the bandwidth of the system in Hz.

The third noise modeled is the thermal noise, also called Johnson noise, which originates within the photodetector's load resistor. [8] Electrons in the resistor continually move because of their thermal energy, even when there is now voltage applied. The motion is random, which results in a randomly-varying current in the resistor. From the photodetector datasheet, the resistor's value is 50Ω . The mean-square value of the thermal noise current is

$$I_{NT}^2 = \frac{4kT\Delta f}{R_L} = \frac{4(1.38 \times 10^{-23} \frac{\text{J}}{\text{K}})(298.15)(1.5 \times 10^6 \text{Hz})}{50\Omega} = 4.937 \times 10^{-21} \text{A}^2 \quad (\text{Eq 3.11})$$

Where k is the Boltzmann constant, and T is the temperature of 25 degrees Celsius converted to Kelvin.

The excess noise I_{Excess} is all of the other noises from the signal passing through the photodetector, particularly the amplification process. The photodetector datasheet [1] says the minimum noise level is $7.4 \text{pW}/\sqrt{\text{Hz}}$. This means that:

$$I_{\text{Excess}} = \left(\frac{1\text{A}}{\text{W}}\right) \frac{7.4 \text{pW}}{\sqrt{\text{Hz}}} \sqrt{1.5 \times 10^6 \text{Hz}} = 9.06 \times 10^{-9} \text{A} = 9.06 \text{nA} \quad (\text{Eq 3.12})$$

The maximum total noise current is the sum of all the individual currents:

$$I_{\text{Total Noise}} = \sqrt{I_{\text{RIN}}^2 + I_{\text{Excess}}^2 + I_{\text{NS}}^2 + I_{\text{NT}}^2} \Rightarrow$$

$$I_{\text{Total Noise}} = \sqrt{(8.55 \times 10^{-9} \text{A})^2 + (9.06 \times 10^{-9} \text{A})^2 + 2.16 \times 10^{-18} \text{A}^2 + 4.937 \times 10^{-21} \text{A}^2}$$

$$= 1.29 \times 10^{-8} \text{A} \quad (\text{Eq 3.13})$$

The signal-to-noise ratio is then:

$$\text{SNR} = \frac{\text{Signal Current}}{\text{Noise Current}} = \frac{4.50 \mu\text{A}}{0.0129 \mu\text{A}} = 349 \quad (\text{Exact MATLAB Calculation} = 358)$$

The peak total input voltage to the LPF and ADC in Figures 3.1 and 3.9 is

$$V_{\text{Total}} = (I_S + I_{\text{Total Noise}}) * 5 \times 10^3 \text{ V/A} = (5000) I_{\text{Total}} [\text{V}] = 0.02256 \text{V} \quad (\text{Eq 3.14})$$

Figure 3.11: FBG Reflection Signal Measured after ADC at (E) in Figure 3.1 with Noise and no Filter

Figure 3.12: Magnified View of FBG Reflection Signal Measured after ADC with Noise and no Filter

In order to improve signal quality, a low-pass filter [15] is added to the system just after the photodetector and before the signal is converted from analog to digital. Because the simulation is entirely discrete in nature, the signal is simply filtered after the final amplification step. To obtain the best results, a MATLAB FIR low-pass filter is used with a filter order of 10, a cutoff frequency of 1.5MHz, a peak-to-peak ripple frequency of 0.01dB and a stopband attenuation of 80dB. The results can be seen below in Figure 3.13:

Figure 3.13: Measured FBG Reflection Signal with Noise and Filtering

Figure 3.14: Close-Up of Signal with and without Filtering

Figure 3.15: Magnified View of Signal with and without Filtering

The SNR of the signal without filtering is 175. This matches exactly what was expected from the calculations. The filter improves the quality of the signal by band-limiting the noise.

The measured SNR and simulation parameters matched the calculated ones, which mean that successful simulations with different parameters are now possible. The amount of noise is reasonable for this type of experiment, and different values of SNR will be obtained by varying the % reflectivity of the simulated FBG.

Jitter is defined as “the short-term variations of significant instants of deviation of a timing signal from ideal positions in time” [1]. For a digital signal, this means that the discrete pulses at a particular frequency may have unexpected arrival times. For an optical analog signal such as the laser used in the experiments throughout the thesis, jitter manifests as changes in frequency, causing time delays to when the signal arrives at the photodetector. A comprehensive analysis by Christian Martens [1] on the Insight Laser used in this thesis revealed that the average amount of jitter exhibited by the VT-DBR laser in terms of the laser’s wavelength is 0.35pm. Because the simulation in this thesis only take into account noise affecting the amplitude of a signal, and not shifts in wavelength, 0.35pm will have to be added onto the measurement accuracies found in the graphs throughout this chapter. The addition is done by taking the root of the sum of the squares of the measurement deviation and average jitter. For example, if the standard deviation of the measurements of the center wavelength of an FBG is 0.5pm, then the actual measurement repeatability would be:

$$\text{Measurement accuracy} = \sqrt{0.5^2 + 0.35^2} = 0.61\text{pm}$$

3.3 Single FBG Simulations

In this section, the system shown in Figure 3.1 will be simulated for every combination of parameters shown in Tables 3.2 and 3.3, including: FBG % reflectivity, FBG FWHM, a laser output power of both 1mW and 7mW, and an ADC sampling rate of both 50MHz and 400MHz. Each combination will be simulated 200 times, with the difference between each of the 200 iterations being the effects of the random noise. The deviation in measurements of the FBG reflection peak location will be used to compare measurement accuracy for each parameter combination. An example simulation is shown below in Figure 3.16, and the process described after:

Figure 3.16: Sample Simulation Measured at ADC after Filtering for 1mW Laser Output, Multiple FBG Reflectivities, and a FBG FWHM of 0.2nm

Figure 3.16 above is an example simulation for every FBG reflectivity at a FWHM of 0.2nm, a laser output power of 1mW, and an ADC sampling rate of 400MHz. The location of each peak is measured and stored in an array, and then an identical simulation is run again and again for a total of 200 instances. The result is a total of 200 peak location measurements for each % reflectivity. The standard deviation of these measurements is calculated and used as the measure of accuracy when comparing the result for each FBG reflection value. This entire process is repeated for each of the other FBG FWHM values, and then again for a sample rate of 50MHz. All of the above will also be simulated for a laser output power of 7mW. The FWHM should also affect the measurement accuracy because if the width of the FBG peak is very small, then it is affected by noise more severely. The sample rate should affect accuracy by reducing measurement variance as the sample rate increases. This is because if the FBG peak is composed of 8 times as many points, then the noise will average itself out more than otherwise.

The different FBG reflectivity values affect the SNR, but because of the way the noise is calculated, it is not a 1:1 ratio. This means that a decrease from 2% to 1% reflectivity does not necessarily mean that the SNR decreases to half the original amount. The reason for this is that some of the noise calculations are based on the peak optical power, which means that the noise amplitude decreases with the signal. The different bandwidths from Table 3.2 also affect the SNR because they are a component in the excess noise, thermal noise, and shot noise.

The measured SNRs are calculated by dividing the value of the measured reflected peak without noise by the amplitude of the noise located at the measured peak.

Table 3.3: SNR for each FBG Reflectivity

FBG Reflectivity (%)	SNR
0.1	9.29
0.25	23.2
0.5	46.3
1	91.5
1.5	135
2	175

As expected, the SNR decreases when the reflectivity also decreases.

As discussed in the preceding paragraphs, the expected measurement accuracy should increase as the SNR increases. The SNR increases when the FBG reflectivity and bandwidth increase. The measurement accuracy should also increase when there is a higher sample point density across the FBG reflection, caused by both an increasing FWHM and sample rate. Finally the increase from a 1mW laser source to a 7mW laser source should also increase the SNR and measurement accuracy. It is

expected that all but the least accurate measurements should have a standard deviation of 1pm or less.

Case 1: 50 MHZ Sample Rate and 1mW, 7mW Laser Output Power

A sample rate of 50MHz corresponds to 1904 total points, and 173.09 pts/nm.

The parameters used in the simulation are as shown below in Table 3.4:

Table 3.4: Parameters for Each 50MS/s Single FBG Simulation

Figure #	% Reflectivity	SNR at 1mW	SNR at 7mW	FWHM (nm)	# of Points/nm	Points Across Peak	Laser Output
3.17 - 3.20	0.1	21.5	144.1	0.1	173.09	17.309	1mW, 7mW
3.17 - 3.20	0.25	53.4	303.8	0.1	173.09	17.309	1mW, 7mW
3.17 - 3.20	0.5	105.0	428.1	0.1	173.09	17.309	1mW, 7mW
3.17 - 3.20	1	197.9	494.3	0.1	173.09	17.309	1mW, 7mW
3.17 - 3.20	1.5	273.0	510.8	0.1	173.09	17.309	1mW, 7mW
3.17 - 3.20	2	330.4	517.0	0.1	173.09	17.309	1mW, 7mW
3.17 - 3.20	0.1	24.8	164.3	0.2	173.09	34.618	1mW, 7mW
3.17 - 3.20	0.25	61.5	332.8	0.2	173.09	34.618	1mW, 7mW
3.17 - 3.20	0.5	120.4	447.4	0.2	173.09	34.618	1mW, 7mW
3.17 - 3.20	1	223.3	501.8	0.2	173.09	34.618	1mW, 7mW
3.17 - 3.20	1.5	302.0	514.5	0.2	173.09	34.618	1mW, 7mW
3.17 - 3.20	2	358.7	519.3	0.2	173.09	34.618	1mW, 7mW
3.17 - 3.20	0.1	28.9	188.6	0.25	173.09	43.2725	1mW, 7mW
3.17 - 3.20	0.25	71.7	363.1	0.25	173.09	43.2725	1mW, 7mW
3.17 - 3.20	0.5	139.3	464.9	0.25	173.09	43.2725	1mW, 7mW
3.17 - 3.20	1	252.7	508.0	0.25	173.09	43.2725	1mW, 7mW
3.17 - 3.20	1.5	333.3	517.6	0.25	173.09	43.2725	1mW, 7mW
3.17 - 3.20	2	387.4	521.2	0.25	173.09	43.2725	1mW, 7mW
3.17 - 3.20	0.1	31.1	200.9	0.3	173.09	51.927	1mW, 7mW
3.17 - 3.20	0.25	77.0	376.8	0.3	173.09	51.927	1mW, 7mW
3.17 - 3.20	0.5	149.1	472.1	0.3	173.09	51.927	1mW, 7mW
3.17 - 3.20	1	267.1	510.4	0.3	173.09	51.927	1mW, 7mW
3.17 - 3.20	1.5	347.8	518.7	0.3	173.09	51.927	1mW, 7mW
3.17 - 3.20	2	400.1	521.8	0.3	173.09	51.927	1mW, 7mW
3.17 - 3.20	0.1	36.0	226.9	0.4	173.09	69.236	1mW, 7mW
3.17 - 3.20	0.25	88.8	402.4	0.4	173.09	69.236	1mW, 7mW
3.17 - 3.20	0.5	170.2	484.2	0.4	173.09	69.236	1mW, 7mW
3.17 - 3.20	1	296.3	514.3	0.4	173.09	69.236	1mW, 7mW
3.17 - 3.20	1.5	375.5	520.6	0.4	173.09	69.236	1mW, 7mW
3.17 - 3.20	2	423.3	523.0	0.4	173.09	69.236	1mW, 7mW
3.17 - 3.20	0.1	42.8	260.4	0.5	173.09	86.545	1mW, 7mW
3.17 - 3.20	0.25	105.2	429.7	0.5	173.09	86.545	1mW, 7mW
3.17 - 3.20	0.5	198.5	495.6	0.5	173.09	86.545	1mW, 7mW
3.17 - 3.20	1	331.7	517.7	0.5	173.09	86.545	1mW, 7mW
3.17 - 3.20	1.5	406.2	522.3	0.5	173.09	86.545	1mW, 7mW
3.17 - 3.20	2	447.3	523.9	0.5	173.09	86.545	1mW, 7mW

The results of the simulations described in Table 3.4 are graphed below in Figures 3.17 through 3.20:

Figure 3.17: Measurement Deviation vs. FBG Reflectivity at 50MHz Sample Rate, 1mW laser output power, and FBG FWHM = 0.1nm – 0.5nm

Figure 3.18: Magnified View of Figure 3.17

The 50MHz sample rate and 1mW laser source simulation results are what was expected. The measurement accuracy steadily increased with FBG FWHM and % reflectivity. The only results that had a measurement standard deviation less than 1pm were the 1-2% reflectivities and a FWHM of at least 0.2nm. This is less than ideal for a real-world application, but should improve with an increase in laser output power.

Figure 3.19: Measurement Deviation vs. FBG Reflectivity at 50MHz Sample Rate, 7mW laser output power, and FBG FWHM = 0.1nm – 0.5nm

Figure 3.20: Magnified View of Figure 3.19

The 50MHz sample rate and 7mW laser source simulation results show that a much higher accuracy value is obtainable with a 7mW output power than 1mW. All parameter combinations had sub-1pm measurement accuracy except for the 0.1% FBG reflectivity and 0.1nm FWHM. The only interesting feature was that a FWHM of 0.25nm had less deviation in its measurements than everything else. A similar sample point density per FBG width will be compared in the 400MHz sample rate simulations to see if it was an anomaly or not.

Case 2: 400 MHz Sample Rate and 1mW, 7mW Laser Output Power

A sample rate of 400MHz corresponds to 15232 total data points and 1385 pts/nm. The parameters used in the simulation are shown below in Table 3.5:

Table 3.5: Parameters for Each 400MS/s Single FBG Simulation

Figure #	% Reflectivity	SNR at 1mW	SNR at 7mW	FWHM (nm)	# of Points/nm	Points Across Peak	Laser Output
3.21 - 3.24	0.1	21.5	144.1	0.1	1385	138.5	1mW, 7mW
3.21 - 3.24	0.25	53.4	303.8	0.1	1385	138.5	1mW, 7mW
3.21 - 3.24	0.5	105.0	428.1	0.1	1385	138.5	1mW, 7mW
3.21 - 3.24	1	197.9	494.3	0.1	1385	138.5	1mW, 7mW
3.21 - 3.24	1.5	273.0	510.8	0.1	1385	138.5	1mW, 7mW
3.21 - 3.24	2	330.4	517.0	0.1	1385	138.5	1mW, 7mW
3.21 - 3.24	0.1	24.8	164.3	0.2	1385	277	1mW, 7mW
3.21 - 3.24	0.25	61.5	332.8	0.2	1385	277	1mW, 7mW
3.21 - 3.24	0.5	120.4	447.4	0.2	1385	277	1mW, 7mW
3.21 - 3.24	1	223.3	501.8	0.2	1385	277	1mW, 7mW
3.21 - 3.24	1.5	302.0	514.5	0.2	1385	277	1mW, 7mW
3.21 - 3.24	2	358.7	519.3	0.2	1385	277	1mW, 7mW
3.21 - 3.24	0.1	28.9	188.6	0.25	1385	346.25	1mW, 7mW
3.21 - 3.24	0.25	71.7	363.1	0.25	1385	346.25	1mW, 7mW
3.21 - 3.24	0.5	139.3	464.9	0.25	1385	346.25	1mW, 7mW
3.21 - 3.24	1	252.7	508.0	0.25	1385	346.25	1mW, 7mW
3.21 - 3.24	1.5	333.3	517.6	0.25	1385	346.25	1mW, 7mW
3.21 - 3.24	2	387.4	521.2	0.25	1385	346.25	1mW, 7mW
3.21 - 3.24	0.1	31.1	200.9	0.3	1385	415.5	1mW, 7mW
3.21 - 3.24	0.25	77.0	376.8	0.3	1385	415.5	1mW, 7mW
3.21 - 3.24	0.5	149.1	472.1	0.3	1385	415.5	1mW, 7mW
3.21 - 3.24	1	267.1	510.4	0.3	1385	415.5	1mW, 7mW
3.21 - 3.24	1.5	347.8	518.7	0.3	1385	415.5	1mW, 7mW
3.21 - 3.24	2	400.1	521.8	0.3	1385	415.5	1mW, 7mW
3.21 - 3.24	0.1	36.0	226.9	0.4	1385	554	1mW, 7mW
3.21 - 3.24	0.25	88.8	402.4	0.4	1385	554	1mW, 7mW
3.21 - 3.24	0.5	170.2	484.2	0.4	1385	554	1mW, 7mW
3.21 - 3.24	1	296.3	514.3	0.4	1385	554	1mW, 7mW
3.21 - 3.24	1.5	375.5	520.6	0.4	1385	554	1mW, 7mW
3.21 - 3.24	2	423.3	523.0	0.4	1385	554	1mW, 7mW
3.21 - 3.24	0.1	42.8	260.4	0.5	1385	692.5	1mW, 7mW
3.21 - 3.24	0.25	105.2	429.7	0.5	1385	692.5	1mW, 7mW
3.21 - 3.24	0.5	198.5	495.6	0.5	1385	692.5	1mW, 7mW
3.21 - 3.24	1	331.7	517.7	0.5	1385	692.5	1mW, 7mW
3.21 - 3.24	1.5	406.2	522.3	0.5	1385	692.5	1mW, 7mW
3.21 - 3.24	2	447.3	523.9	0.5	1385	692.5	1mW, 7mW

The results of the simulations described in Table 3.5 are graphed below in Figures 3.21 through 3.24:

Figure 3.21: Measurement Deviation vs. FBG Reflectivity at 400MHz Sample Rate and 1mW Source

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 400MHz Sample Rate

Figure 3.22: Measurement Deviation vs. FBG Reflectivity at 400MHz and 1mW (Close-Up)

The 400MHz sample rate and 1mW laser source simulation results show a big improvement in accuracy compared to the same parameters at a 50MHz sample rate. All the simulations with a 0.5% or higher reflectivity are accurate to within 1pm. This is about what accuracy was expected for these parameters, and will only improve when the laser output power is increased.

Figure 3.23: Measurement Deviation vs. FBG Reflectivity at 400MHz Sample Rate

Figure 3.24: Measurement Deviation vs. FBG Reflectivity at 400MHz Sample Rate
(Close-Up)

The 400MHz sample rate and 7mW laser output power simulation results show the best measurement accuracy out of all the simulations. All of the measurements are accurate to within 1pm, with measurement deviations as low as 0.1pm. Because this set of simulated data had the highest SNR, it was expected to be the most accurate. The only anomaly was at a FBG FWHM of 0.4nm and % reflectivity of 2%, the extreme end of all of the simulation parameters where the SNR was the highest, at just under 500.

The results of the simulations met the expectation for the most part that the measurements would be accurate to within 1pm. The simulations at a 50MHz sample rate and 1mW laser output power had trouble getting to sub picometer accuracy because of their low signal-to-noise ratio. These parameters however would probably

not be used in a real-world application because a 400MHz sample rate and 7mW output power are easily attainable and provide much better results. The single FBG simulation results provide an accuracy benchmark to compare the results of multi-FBG simulations to.

3.4 Multi-Sensor FBG Simulations – De-Embedding Method

In this section, two FBGs with very similar center wavelengths will be simulated, and the measurement accuracy of each one will be recorded and compared for different parameters. The parameters are the same as in Part B, except that the separation of center wavelength is now also a factor.

De-Embedding the Signal:

When the measured peaks of multiple Fiber Bragg gratings overlap each other, finding the center wavelength of each one is not as simple as when there is just a single peak.

Reflection Spectra for Two FBGs at 2% Ref. with 0.1nm Center Wavelength Diff.

Figure 3.25: Example Measurement of Two Fiber Bragg Gratings Cascaded Together

Figure 3.26: Example Measurement of Two Different Fiber Bragg Gratings Plotted on Same Graph

Figure 3.33 shows the measurement of two Fiber Bragg gratings cascaded together. This can be compared to the same FBGs measured separately and plotted on the same graph in Figure 3.34. When the FBGs are convolved together like in Figure 3.33, the same measurement methods used in Part A no longer work. Instead, the signal has to be de-embedded. This means that all the FBGs not being measured must be modelled and mathematically deconvolved from the measurement data, leaving only the target FBG peak.

This is done by finding the scattering parameters of the measured data, which is easily done by reversing the simulation process until the S parameters are calculated for the RBG needing to be measured. Recalling Figure 3.2:

Figure 3.2: Two-Port Network Notation

Where a_1 is the source and b_1 is the measured data calculated by

$$b_1 = S_{11}a_1 + S_{12}a_2 = S_{11}a_1 + 0 = S_{11}a_1$$

Noise and the appropriate losses/amplifications are applied to the b_1 data, and then the new scattering parameters are found for the system using equations derived from Eq. 3.5-3.7:

$$S_{11} = S_{22} = b_1/a_1, S_{21} = S_{12} = b_2/a_1 \quad (\text{Eq. 3.15})$$

$S \rightarrow T$ from Eq. 3.6, then because $T = T_1 * T_2$:

$$T_1 = T/T_2, T_2 = \text{inverse}(T_1) * T_2 \quad (\text{Eq. 3.16})$$

The S parameters for each FBG are calculated from their T matrices using Eq. 3.7. The measurement data for each FBG is found by calculating b_1 from the S matrix. The de-embedding results for two identical FBGs with center wavelengths of 1545.83nm and 1545.73nm can be seen below in Figure 3.35:

Figure 3.27: Measurement Data of Two FBG Reflections Cascaded Together on the Same Plot as the Individual De-embedded Reflections

Each of the two FBGs now has its own set of data and the process from Part B will be applied.

Because there are only two FBGS, the measurement accuracy results should be similar to the single FBG results, perhaps slightly worse. It is expected that as the difference in center wavelength between the two FBGs increases, the accuracy will also increase. It is also expected that the first FBG will be able to be measured slightly more accurate than the second, because it's amplitude will be exactly 2% of the optical power, while the second one will be $(98\%)(98\%)(2\%)$ of the input optical power. The analysis of the results can be found on page 68.

All of the parameter combinations in Tables 3.5 and 3.4 will be simulated at each of the following FBG center wavelengths:

Table 3.6: FBG Center Wavelength Spacing Parameters

First FBG Center Wavelength	Second FBG Center Wavelength
1545.78nm	1545.83nm
1545.73nm	1545.83nm
1545.68nm	1545.83nm
1545.58nm	1545.83nm

Each set of parameters will have 4 different graphs: accuracy vs reflectivity (FBG 1), accuracy vs FWHM (FBG 1), accuracy vs reflectivity (FBG 2), accuracy vs FWHM (FBG 2), plus a magnified view of each one.

Table 3.7: Simulation Parameters for Figures 3.28 – 3.31

Figure #	% Reflectivity	SNR	FWHM (nm)
3.28 - 3.31	0.1% - 2%	21.5 - 447	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
173.09	17.3-86.5	1mW	.05nm

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 1st FBG

Figure 3.28: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.78nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 1st FBC

Figure 3.29: Magnified area of Figure 3.36

Figure 3.30: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 2nd FBG

Figure 3.31: Magnified area of Figure 3.30

Table 3.8: Simulation Parameters for Figures 3.32– 3.35

Figure #	% Reflectivity	SNR	FWHM (nm)
3.32 - 3.35	0.1% - 2%	21.5 - 447	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
173.09	17.3-86.5	1mW	.1nm

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 1st FBG

Figure 3.32: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.73nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 1st FBG

Figure 3.33: Magnified View of Figure 3.32

Figure 3.34: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 2nd FBG

Figure 3.35: Magnified View of Figure 3.34

Table 3.9: Simulation Parameters for Figures 3.36 – 3.39

Figure #	% Reflectivity	SNR	FWHM (nm)
3.36 - 3.39	0.1% - 2%	21.5 - 447	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
173.09	17.3-86.5	1mW	.15nm

Figure 3.36: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.68nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 1st FBG

Figure 3.37: Magnified area of Figure 3.36

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 2nd FBG

Figure 3.38: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 2nd FBG

Figure 3.39: Magnified area of Figure 3.38

Table 3.10: Simulation Parameters for Figures 3.40 – 3.42

Figure #	% Reflectivity	SNR	FWHM (nm)
3.40 - 3.42	0.1% - 2%	21.5 - 447	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
173.09	17.3-86.5	1mW	.25nm

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 1st FBG

Figure 3.40: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.58nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Figure 3.41: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 50MHz sample rate, 1mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 1mW Source, 50MHz, 2nd FBG

Figure 3.42: Magnified area of Figure 3.41

In this section, the best-case accuracy measurements for 2 FBG simulations will be explored. The only change from the previous section is that the laser output power is increased to 7mW, and the sample rate is increased to 400MHz.

Table 3.11: Simulation Parameters for Figures 3.43 – 3.46

Figure #	% Reflectivity	SNR	FWHM (nm)
3.43 - 3.46	0.1% - 2%	144 - 524	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
1385	138.5-692.5	7mW	0.05nm

Figure 3.43: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.78nm, 400MHz sample rate, 7mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 1st FBG

Figure 3.44: Magnified area of Figure 3.43

Figure 3.45: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 400MHz sample rate, 7mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 2nd FB

Figure 3.46: Magnified area of Figure 3.45

Table 3.12: Simulation Parameters for Figures 3.47 – 3.50

Figure #	% Reflectivity	SNR	FWHM (nm)
3.47 - 3.50	0.1% - 2%	144 - 524	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
1385	138.5-692.5	7mW	0.1nm

Figure 3.47: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.73nm, 400MHz sample rate, 7mW laser source, and total of two FBGs in cascade

Figure 3.48: Magnified area of Figure 3.47

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 2nd FB

Figure 3.49: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 400MHz sample rate, 7mW laser source, and total of two FBGs in cascade

Figure 3.50: Magnified area of Figure 3.49

Table 3.13: Simulation Parameters for Figures 3.51 – 3.53

Figure #	% Reflectivity	SNR	FWHM (nm)
3.51 - 3.53	0.1% - 2%	144 - 524	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
1385	138.5-692.5	7mW	0.15nm

Figure 3.51: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.68nm, 400MHz sample rate, 7mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 1st FBG

Figure 3.52: Magnified area of Figure 3.51

Figure 3.53: Magnified area of Figure 3.52

Table 3.14: Simulation Parameters for Figures 3.54 – 3.57

Figure #	% Reflectivity	SNR	FWHM (nm)
3.54 - 3.57	0.1% - 2%	144 - 524	0.1 - 0.5
# of Points/nm	Points Across Peak	Laser Output	Difference in Center Wavelength
1385	138.5-692.5	7mW	0.25nm

Figure 3.54: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.58nm, 400MHz sample rate, 7mW laser source, and total of two FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 1st FBG

Figure 3.55: Magnified area of Figure 3.54

Figure 3.56: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 400MHz sample rate, 7mW laser source, and total of two FBGs in cascade

Figure 3.57: Magnified area of Figure 3.56

The simulation results of two FBGs cascaded together show that each FBG can be measured with the same amount of accuracy as just a single FBG. The maximum measurement accuracy for the double FBG simulations is about 0.1pm at a 400MHz sample rate, 7mW source, 1% reflectivity, and 0.5nm FWHM, while the most accurate measurements for the single FBG sims were consistently less than 0.05pm for 2% reflectivity. For more realistic parameters of 0.5% reflectivity and 0.25nm FWHM, accuracy for the double FBG measurements was within 0.25pm, still well within the goal of the 1pm std. deviation for FBG peak measurements.

The difference in measurement accuracy between the first and second FBG measurement was almost negligible. The least accurate measurements were exactly the same for the first and second FBG. The most accurate measurements were about

0.005pm more accurate for the first FBG than the second one. This is because the first FBG had the full 2% of the input power reflected, while the second one had a 2% loss through the first FBG twice, resulting in $(0.98)(0.98)(2\%) = 1.92\%$ of the original input optical power reflected back through the fiber.

The only unusual result for the two-FBG accuracy measurements is that FBG reflectivities of both 1% and 1.5% resulted in better accuracy than a reflectivity of 2%. The reason for the reduced accuracy for higher reflectivities in multi-sensor systems is that a higher reflectivity means that less optical power arrives at each consecutive sensor. This might cause signal distortion based on the amount of noise. The result is an optimal FBG reflectivity value that allows for the most accurate measurements. For this case, the optimal value is 1%, although 0.5% and 1.5% also produce good results.

In this next section, three FBGs will be cascaded together, each with different center wavelengths. The outer FBGs will be separated from the center one by the same distance in center wavelength. The de-embedding process works exactly the same as in the previous section with two FBGs, except that there will now be three scattering transmission or “T” matrices multiplied together. Figures 3.99 and 3.100 each show an example simulation including noise and filtering:

Figure 3.58: Example simulation of three equally-spaced Fiber Bragg gratings with center wavelengths of 1545.73nm, 1545.83nm, and 1545.93nm, and a FWHM = 0.2nm.

Figure 3.59: Example simulation of three equally-spaced Fiber Bragg gratings with center wavelengths of 1545.82nm, 1545.83nm, and 1545.84nm, and a FWHM = 0.2nm.

In Figure 3.58, the center wavelengths are ten times as far apart as in Figure 3.59. This results in a combined total signal with significantly smaller amplitude than when the FBGs are nearly directly stacked on each other. In order to not overwhelm this analysis with data that might not be useful, only the following parameters will be simulated:

Table 3.15: Parameters used in simulations of three FBGs in cascade at 400MHz

sample rate

Figure #	% Reflectivity	SNR at 7mW	FWHM (nm)	# of Points/nm	Points Across Peak	Laser Output	Center WL Spacing
3.60 - 3.65	0.1	144.1	0.1	1385	138.5	7mW	0.01nm
3.60 - 3.65	0.25	303.8	0.1	1385	138.5	7mW	0.01nm
3.60 - 3.65	0.5	428.1	0.1	1385	138.5	7mW	0.01nm
3.60 - 3.65	1	494.3	0.1	1385	138.5	7mW	0.01nm
3.60 - 3.65	1.5	510.8	0.1	1385	138.5	7mW	0.01nm
3.60 - 3.65	2	517.0	0.1	1385	138.5	7mW	0.01nm
3.60 - 3.65	0.1	164.3	0.2	1385	277	7mW	0.01nm
3.60 - 3.65	0.25	332.8	0.2	1385	277	7mW	0.01nm
3.60 - 3.65	0.5	447.4	0.2	1385	277	7mW	0.01nm
3.60 - 3.65	1	501.8	0.2	1385	277	7mW	0.01nm
3.60 - 3.65	1.5	514.5	0.2	1385	277	7mW	0.01nm
3.60 - 3.65	2	519.3	0.2	1385	277	7mW	0.01nm
3.66 - 3.71	0.1	144.1	0.1	1385	138.5	7mW	0.05nm
3.66 - 3.71	0.25	303.8	0.1	1385	138.5	7mW	0.05nm
3.66 - 3.71	0.5	428.1	0.1	1385	138.5	7mW	0.05nm
3.66 - 3.71	1	494.3	0.1	1385	138.5	7mW	0.05nm
3.66 - 3.71	1.5	510.8	0.1	1385	138.5	7mW	0.05nm
3.66 - 3.71	2	517.0	0.1	1385	138.5	7mW	0.05nm
3.66 - 3.71	0.1	164.3	0.2	1385	277	7mW	0.05nm
3.66 - 3.71	0.25	332.8	0.2	1385	277	7mW	0.05nm
3.66 - 3.71	0.5	447.4	0.2	1385	277	7mW	0.05nm
3.66 - 3.71	1	501.8	0.2	1385	277	7mW	0.05nm
3.66 - 3.71	1.5	514.5	0.2	1385	277	7mW	0.05nm
3.66 - 3.71	2	519.3	0.2	1385	277	7mW	0.05nm
3.72 - 3.77	0.1	144.1	0.1	1385	138.5	7mW	0.1nm
3.72 - 3.77	0.25	303.8	0.1	1385	138.5	7mW	0.1nm
3.72 - 3.77	0.5	428.1	0.1	1385	138.5	7mW	0.1nm
3.72 - 3.77	1	494.3	0.1	1385	138.5	7mW	0.1nm
3.72 - 3.77	1.5	510.8	0.1	1385	138.5	7mW	0.1nm
3.72 - 3.77	2	517.0	0.1	1385	138.5	7mW	0.1nm
3.72 - 3.77	0.1	164.3	0.2	1385	277	7mW	0.1nm
3.72 - 3.77	0.25	332.8	0.2	1385	277	7mW	0.1nm
3.72 - 3.77	0.5	447.4	0.2	1385	277	7mW	0.1nm
3.72 - 3.77	1	501.8	0.2	1385	277	7mW	0.1nm
3.78 - 3.83	1.5	514.5	0.2	1385	277	7mW	0.1nm
3.78 - 3.83	2	519.3	0.2	1385	277	7mW	0.1nm
3.78 - 3.83	0.1	144.1	0.1	1385	138.5	7mW	0.15nm
3.78 - 3.83	0.25	303.8	0.1	1385	138.5	7mW	0.15nm
3.78 - 3.83	0.5	428.1	0.1	1385	138.5	7mW	0.15nm
3.78 - 3.83	1	494.3	0.1	1385	138.5	7mW	0.15nm
3.78 - 3.83	1.5	510.8	0.1	1385	138.5	7mW	0.15nm
3.78 - 3.83	2	517.0	0.1	1385	138.5	7mW	0.15nm
3.78 - 3.83	0.1	164.3	0.2	1385	277	7mW	0.15nm
3.78 - 3.83	0.25	332.8	0.2	1385	277	7mW	0.15nm
3.78 - 3.83	0.5	447.4	0.2	1385	277	7mW	0.15nm
3.78 - 3.83	1	501.8	0.2	1385	277	7mW	0.15nm
3.78 - 3.83	1.5	514.5	0.2	1385	277	7mW	0.15nm
3.78 - 3.83	2	519.3	0.2	1385	277	7mW	0.15nm

Three FBGs, Simulation 1: Center Wavelength Separation = 0.01nm

Figure 3.60: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.82nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Figure 3.61: Magnified area of Figure 3.60

Figure 3.62: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Figure 3.63: Magnified area of Figure 3.62

Figure 3.64: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.84nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 3rd FBG

Figure 3.65: Magnified area of Figure 3.64

Three FBGs, Simulation 2: Center Wavelength Separation = 0.05nm

Figure 3.66: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.78nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 1st FBG

Figure 3.67: Magnified area of Figure 3.66

Figure 3.68: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.78nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 2nd FBG

Figure 3.69: Magnified area of Figure 3.68

Figure 3.70: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.78nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Figure 3.71: Magnified area of Figure 3.70

Three FBGs, Simulation 3: Center Wavelength Separation = 0.1nm

Figure 3.72: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.73nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Figure 3.73: Magnified area of Figure 3.72

Figure 3.74: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 2nd FBG

Figure 3.75: Magnified area of Figure 3.74

Figure 3.76: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.93nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Figure 3.77: Magnified area of Figure 3.76

Three FBGs, Simulation 4: Center Wavelength Separation = 0.15nm

Figure 3.78: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.68nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Figure 3.79: Magnified area of Figure 3.78

Figure 3.80: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.83nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Measurement Accuracy vs FBG Reflectivity for 7mW Source, 400MHz, 2nd FBG

Figure 3.81: Magnified area of Figure 3.80

Figure 3.82: Measurement std. deviation vs reflectivity of de-embedded FBG at a center wavelength of 1545.98nm, 400MHz sample rate, 7mW laser source, and total of three FBGs in cascade

Figure 3.83: Magnified area of Figure 3.82

The results of the triple FBG simulations follow the trend set in the two-FBG simulations: that accuracy slightly decreases with each consecutive FBG sensor and that there is an optimal FBG reflectivity value. Like in the two-FBG simulations, the best % reflectivity is 1%. Unlike the two-FBG simulations however, a % reflectivity of 0.5% now results in more accurate measurements than 1.5%, although they are all still very close. The reason for this change is that the signal reaching the third FBG is attenuated twice now, at a rate of $1 - R = 0.98$ per FBG for a 2% reflectivity, and 0.985 for 1.5%.

In summary, the only useful information from this section is that very good, sub-1pm accuracy is still possible, and the lower % reflectivities result in more accurate measurements compared to the highest % reflectivities.

3.5 Multi - FBG Simulations Wavelength-to-Time Domain Reflectometry Method

In this section, multiple FBGs will be simulated with random center wavelengths. 10, 100, 300, and 500 FBGs will be cascaded in series. Wavelength-to-Time Domain Reflectometry (W-TDR) works by physically separating the FBGs by an optical fiber with length L , so that the additional signal travel time separates the reflected FBG peaks enough that they can be measured individually. If the FWHM of the FBG is 0.1nm, then the base is close to 0.2nm wide, and the FBGs should be separated by at least $2 \times$ (one-half the base width) = 0.2nm. If the sweep rate $f = 26.2605\text{kHz}$, and the wavelength range swept through is $\Delta\lambda = 1551 - 1540 = 11\text{nm}$, then the sweep time/nm:

$$1/(f\Delta\lambda) = 1/(26.2605\text{kHz} \times 11\text{nm}) = 3.462 \text{ us/nm} \quad (\text{Eq. 3.17})$$

The separation distance between FBGs in terms of time is $(0.2\text{nm})(3.462\text{us/nm}) = 0.6924\text{us}$. Because the measured FBG reflections are spaced 0.6924us apart, the distance of fiber in between must be equal to:

$$L_{\text{Fiber}} = (1/2)(\text{time})(\text{speed of light})/(\text{refractive index of fiber}) = 0.5(0.6924\text{us})(3 \times 10^8\text{m/s})/1.5 = 69.24\text{m}. \quad (\text{Eq. 3.18})$$

In order to choose a common length of fiber, the length L is rounded up to 75m, which corresponds to a Δt between FBG reflected peaks of 0.75us. For a FBG FWHM of 0.2nm instead of 0.1nm, the fiber length L is 125m, and the time separation is 1.25us. Each FBG will have a center wavelength within a specified tolerance of 1545nm. For example, if the FBGs have a tolerance of 0.01nm, then each FBG could have any center wavelength between 1544.99nm and 1545.01nm. The following tolerances will

be tried: 0.01nm, 0.02nm, 0.05nm, and 0.1nm. This mimics how FBGs are chosen in real applications. The system designer will choose a center wavelength tolerance depending on how accurate the system needs to be, and how costly the FBG sensors are. The first, middle, and last FBG in each different number of sensors will have its measurement accuracy found over 200 iterations with different random noise for every iteration.

Figure 3.84: Example simulation of ten FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.1nm, SNR of 144.1, and physical spacing of 125m between FBGs

Figure 3.85: Example simulation of ten FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.2nm, SNR of 144.1, and physical spacing of 125m between FBGs

Table 3.16: Simulation Parameters for 10 FBGs in Series Each Separated by 75m
Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.86	0.10%	144.1	0.1
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	138.5	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Measurement Accuracy vs FBG Center Wavelength Variation of 10 FBGs in Series

Figure 3.86: Measurement std. deviation vs reflectivity simulation results for ten FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.1nm, SNR of 144.1, and physical spacing of 125m between FBGs

Table 3.17: Simulation Parameters for 10 FBGs in Series Each Separated by 125m

Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.87	0.10%	144.1	0.2
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	277	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Figure 3.87: Measurement std. deviation vs reflectivity simulation results for ten FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.2nm, and physical spacing of 125m between FBGs

The measurement accuracy for ten FBGs in series, separated in time is very similar to the measurement accuracy found for a single FBG. This is expected, because the whole concept behind W-TDR is to put enough physical distance between the FBG sensors so that the return signals for each FBG can be easily measured without interference from the other FBGs.

The different center wavelength tolerances affected measurement accuracy more severely for the simulations where the FBG FWHM = 0.1nm, as opposed to 0.2nm. The reason is that the FBGs with the FWHM of 0.2nm were spaced farther apart from each

other, so the reflection of each FBG was not really affected by the ones nearby. Because there was only ten Fiber Bragg gratings in series, each with a 0.1% reflectivity, the measurement accuracy did not change much between the first and last ones.

Figure 3.88: Example simulation of one-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.1nm, and physical spacing of 75m between FBGs

Figure 3.89: Magnified view of upper-left corner of Figure 3.88

Figure 3.90: Example simulation of one-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.2nm, and physical spacing of 125m between FBGs

Table 3.18: Simulation Parameters for 100 FBGs in Series Each Separated by 75m

Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.91	0.10%	144.1	0.1
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	138.5	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Figure 3.91: Example simulation of one-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.1nm, and center wavelength spacing in time of 0.692us.

Table 3.19: Simulation Parameters for 100 FBGs in Series Each Separated by 125m

Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.92	0.10%	144.1	0.2
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	277	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Figure 3.92: Example simulation of one-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.2nm, and center wavelength spacing in time of 0.692us.

The measurement accuracy for one-hundred FBGs in series, separated in time follows the same patterns as the ten cascaded FBG simulations, but with reduced accuracy. The first FBG measurement accuracy stays the same because it is not affected by the number of FBGs behind it. The measurement deviation of the 50th FBG is higher than the first FBG, and the measurement deviation of the 100th FBG is higher than the 50th. This is because the reflected signals become weaker as they take a 0.001% loss for each FBG they pass through, which decreases the signal amplitude and increases the signal noise.

Figure 3.93: Example simulation of three-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.1nm, and physical spacing of 75m between FBGs

Table 3.20: Simulation Parameters for 300 FBGs in Series Each Separated by 75m

Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.94	0.10%	144.1	0.1
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	138.5	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Figure 3.94: Example simulation of three-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.1nm, and center wavelength spacing in time of 0.692us

Table 3.21: Simulation Parameters for 300 FBGs in Series Each Separated by 125m

Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.95	0.10%	144.1	0.2
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	277	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Figure 3.95: Example simulation of three-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.2nm, and center wavelength spacing in time of 0.692us

Analysis of 300 FBG Simulations:

The center wavelength measurement accuracy for three-hundred FBGs in series, separated in time follows the same patterns as the one-hundred cascaded FBG simulations, but with reduced accuracy. The sub-1pm accuracy is only obtained when the center wavelength tolerance is less than 0.05nm for the FBGs with a FWHM of 0.1nm. The FBGs with a tolerance of 0.2nm are still relatively unaffected by the tolerance amounts.

In this section, five-hundred FBGs will be cascaded together and simulated at different FWHMs. The center wavelength of each one will be randomly chosen from within a maximum wavelength range, or tolerance centered on 1545nm.

Table 3.22: Simulation Parameters for 500 FBGs in Series Each Separated by 75m

Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.96	0.10%	144.1	0.1
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	138.5	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Figure 3.96: Example simulation of five-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.1nm, and center wavelength spacing in time of 0.692us

Table 3.23: Simulation Parameters for 500 FBGs in Series Each Separated by 125m

Optical Fiber

Figure #	% Reflectivity	SNR	FWHM (nm)
3.97	0.10%	144.1	0.2
# of Points/nm	Points Across Peak	Laser Output	Center Wavelength Tolerance
1385	277	7mW	0.1nm, 0.05nm, 0.02nm, 0.01nm

Measurement Accuracy vs FBG Center Wavelength Variation of 500 FBGs in Series

Figure 3.97: Example simulation of five-hundred FBGs in series with an average center wavelength of 1545nm, a tolerance of 0.02nm, a reflectivity of 0.1%, a FBG FWHM of 0.2nm, and center wavelength spacing in time of 0.692us

The center wavelength measurement accuracy for five-hundred FBGs in series, separated in time follows the same patterns as the three-hundred cascaded FBG simulations, but with reduced accuracy. The sub-1pm accuracy is only obtained when the center wavelength tolerance is less than 0.05nm for the FBGs with a FWHM of both

0.1nm and 0.2nm. There is a 0.3pm increase in measurement variance for a tolerance of 0.1nm from a tolerance of 0.05nm. This shows the importance of keeping the reflected FBG peaks separated, as the probability of a measurement error increases along with the number of FBGs in series.

3.6 Chapter 3 Conclusion

Chapter 3 started by modelling a Fiber Bragg grating, then adding a source, detection system, and noise. During the rest of the chapter, simulations were run for 1, 2, 3, 10, 100, 300 and 500 FBGs cascaded together. The measurement accuracy was found for each setup by measuring the center wavelength of an FBG repeatedly over 200 iterations with different random noise each time, then finding the standard deviation of all of the measurements. The goal of the accuracy measurements for the 1-3 FBG simulations is to obtain the best and worst-case scenarios for different parameters such as the FBG % reflectivity, 3dB bandwidth (FWHM), laser output power, and ADC sampling rate. It was determined that a laser output power of 7mW and 400MHz sample rate were the most practical, and were exclusively used in the rest of the simulations. The simulations of one, two, and three FBGs are useful in establishing benchmarks of exactly how accurate FBGs can be measured for a variety of parameters. In addition, when FBGs are separated in time, such as in Part D, each FBG can be measured individually without needing to de-embed it from a combined signal, and then the single –FBG measurement accuracy results can be applied.

For the single FBG simulations, the center wavelength measurement accuracy ranged from 0.04pm to 20pm. The parameters for the extremely low accuracy of 20pm are: 50MHz Sample Rate, 1mW laser output power, FBG FWHM = 0.1nm, and FBG reflectivity = 0.1%. The parameters for the extremely low measurement deviation of 0.04pm are: 400MHz sample rate, 7mW laser output power, FBG FWHM = 0.5nm, and FBG reflectivity = 2%. These results and the results of the rest of the single FBG simulations mean that measurement accuracy improves when: 1) the ADC sample rate is increased, 2) the laser output power is increased, 3) the FBG FWHM is increased, and 4) when the FBG reflectivity is increased. In the multi-FBG simulations, it was found that increasing the distance apart of the FBG sensor elements from each other also increased measurement accuracy because the information from one sensor does not affect the data received from the other sensor.

The most useful results from this chapter are from Part D: Wavelength-to-Time Domain Reflectometry (W-TDR). In this section, the Fiber Bragg gratings were separated in time by inserting a 75m or 125m length of optical fiber in between each FBG. Because it takes time for the signal to travel back and forth through the length of fiber, each FBG reflection peak arrived at the ADC later than the previous one by enough time to fully separate the peaks from each other. The main parameters varied in this section are the total number of FBG sensors in series, and the listed tolerance of the FBG center wavelength. The measurement accuracies obtained during these simulations ranged between 0.5 and 1.2pm. This is on the high side, but the FBG FWHM and % reflectivity parameters chosen were on the extreme side. A FWHM = 0.1nm, and % ref. = 0.1% had proved to result in less accurate measurements than the

other parameters during the single FBG simulations. They were chosen because a small width and low FBG loss resulted in the smallest and least obtrusive field elements on an array with hundreds or even a thousand of them.

The results from this chapter can be used by a system designer who is designing a FBG sensor strand. For example, if 100 FBG sensors spaced apart by 125m are needed on a fiber, and each FBG will have a FWHM of 0.2nm and reflectivity of 0.1%, then the maximum center wavelength tolerance necessary for sub-0.5pm accuracy is 0.05nm. This can be found by referencing Figure 3.92 in Part D of this chapter. All of the other simulation results can be used in a similar manner for someone who is designing a FBG sensor system.

Chapter 4: Experimental Measurements of Multiple Fiber Bragg Gratings

4.1 Introduction:

In this chapter, experiments will be run with the Insight VT-DBR Laser and one or more Fiber Bragg gratings at a time. The purpose of these experiments is to determine how accurate measurements can be with multiple Fiber Bragg gratings, and compare the results to the single FBG measurement experiment in Chapter 2, and the simulations in Chapter 3. It is expected that the measurement accuracy of multiple FBGs will be less than that of a single FBG, due to the additional fiber connections and FBG shadowing. The results are also expected to show less measurement accuracy than the simulations because of power loss and additional noises from imperfect fiber connections and slight bending in the fiber. The experimental layout is shown below in Figure 4.1:

Figure 4.1: Physical Equipment Layout for the Chapter 4 Experiments. The DUT can be comprised of one or more Fiber Bragg gratings and additional lengths of fiber in between

Figure 4.2: Lab setup for experiment 5, which uses 150m of fiber between DUTs. Each board has a Fiber Bragg grating strand attached via paper between tape and the board. The Insight laser is in the top right corner, the ThorLabs photodetector is the black box middle-right, the grey box underneath is the optical coupler, and the white package in the lower right is the Insight photodetector

The laser source is the Insight Photonics SLE-101 VT-DBR Laser. It is set at a constant power output of 7mW, and a wavelength sweep range of 1539.49nm – 1554.9nm at a sweep rate of 24.4081kHz. The value of 7mW was chosen because it is the highest output power the device is capable of, and the higher optical power increases the signal-to-noise ratio. The wavelength range was chosen because it comfortably includes all the FBG center wavelengths being used throughout the

experiments. The sweep rate was selected by the laser during its calibration. A 15dB optical attenuator was used for the transmission measurements in order to not exceed the power limit of the ADC. It was not needed for the reflection measurements, because only 2% of the transmitted power is reflected. Unless otherwise mentioned in an experiment, each fiber connecting the elements in Figure 4.1 is less than 1m long. The optical coupler used is the Hewlett Packard 11890A 1300nm/1550nm LightWave Coupler which was experimentally measured to have a loss of 0.97dB from point (A) to point (B) in Figure 4.1, and a loss of 2.75dB from (B) to (D). The ADC used was the National Instruments 5105 PCI Digitizer, which sampled at a rate of 50MHz. This resulted in a total of 2048 data points for each sweep.

The Fiber Bragg gratings used were purchased from Technica, a fiber technology company. Three of the FBG strands have a single FBG on them, while the fourth has three in series on a single length of fiber. About 1 meter of fiber separates the FBG from the fiber termination on each side of the strand. Each FBG strand is assigned a Device-under-Test (DUT) number and the specifications are shown below in Table 4.1 and Figure 4.2.

Table 4.1: Fiber Bragg Grating Specifications

DUT	# of FBGs	% Reflectivity	Center Wavelength at 3dB	Width at 3dB
1	1	2.08%	1545.83nm	0.18nm
2	1	2.15%	1545.84nm	0.18nm
3	1	2.21%	1545.78nm	0.18nm
4	3	2.23%	1541.81nm	0.19nm
		2.17%	1545.79nm	0.17nm
		2.11%	1549.62nm	0.17nm

Figure 4.3: Visual representation of DUTs used throughout the experiments

The parameters of the experiments being performed are summarized below in

Table 4.2:

Table 4.2: Chapter 4 Experiment Parameters Summary

Experiment #	DUTs in Series	Laser Power	Min WL	Max WL	Sweep Rate
1	Individual	7mW	1539.49nm	1554.9nm	24.4081kHz
2	2,3,4	7mW	1539.49nm	1554.9nm	24.4081kHz
3	1,2,4	7mW	1539.49nm	1554.9nm	24.4081kHz
4	1,3,4	7mW	1539.49nm	1554.9nm	24.4081kHz
5	3,2	7mW	1539.49nm	1554.9nm	24.4081kHz
6	3,2,1	7mW	1539.49nm	1554.9nm	24.4081kHz

The purpose of Experiment 1 is to measure each DUT individually over a single sweep with identical sweep conditions, so that the data can be used to de-embed a specific DUT when there are several in series. Both the transmission and reflection data at points (D) and (C) in Figure 4.1 will be measured and stored for five complete sweeps for each DUT. The end result will be 40 datasets, each plotted against measurement time on a graph to show what was measured.

Experiments 2-4 are measurements of combinations of two single FBG strands, and a three-FBG strand. The goal of these experiments is to experimentally determine how accurate the de-embedding process of measuring a single FBG peak is compared to Experiments 5 and 6.

Experiments 5-6 are Wavelength-to-Time Domain Reflectometry (W-TDR) measurements of combinations of 2 or 3 single FBGs separated by 100m of optical fiber. The goal of these experiments is to determine how accurate measurements are when the FBGs are separated in time. The results will be compared to all previous experiments, as well as the Chapter 3 simulations.

4.2 Chapter 4 Experiments

The goal of Experiment 1 is to collect transmission and reflection measurement data for each of the four Fiber Bragg grating DUTs described in Table 4.1 and Figure 4.3. The measurements were all repeated five times and averaged in order to get the most accurate dataset possible for de-embedding purposes in Experiments 2-4. After the data was acquired from the ADC, it was loaded into MATLAB, where a digital low-pass filter with a cut-off frequency of 1.25 MHz was used to filter out the noise. The graphed datasets for each measurement are shown below in Figures 4.4 – 4.12. Every measurement included the entire 2048 data points, but each graph will only focus on the relevant data so that variations between sweeps are visible. The x-axis of the graphs is in units of time, and corresponds to when each datapoint was measured for a sweep starting at 0 seconds.

Figure 4.4: DUT 1 reflection measurements for Exp. 1. Five sweeps are run for a single FBG

Figure 4.5: Magnified view of top of single FBG reflection measurement repeated five times. There appear to be only slight variations of power amplitude, not any wavelength/time shifts

Figure 4.6: DUT 1 reflection measurements for Exp. 1. Five sweeps are run for a single FBG (Signal vs Wavelength)

Figure 4.7: Magnified view of top of single FBG reflection measurement repeated five times (Signal vs Wavelength)

Figure 4.8: DUT 1 transmission measurements for Exp. 1. Five sweeps are run for a single FBG

Figure 4.9: DUT 2 reflection measurements for Exp. 1. Five sweeps are run for a single FBG

Figure 4.10: DUT 2 transmission measurements for Exp. 1. Five sweeps are run for a single FBG

Figure 4.11: DUT 3 reflection measurements for Exp. 1. Five sweeps are run for a single FBG

Figure 4.12: DUT 3 transmission measurements for Exp. 1. Five sweeps are run for a single FBG

Figure 4.13: DUT 4 reflection measurements for Exp. 1. Five sweeps are run for the three-FBG strand

Figure 4.14: DUT 4 reflection measurements for Exp. 1. Five sweeps are run for the three-FBG strand (Signal vs Wavelength)

Figure 4.15: DUT 4 transmission measurements for Exp. 1. Five sweeps are run for the three-FBG strand

The reflection measurements have almost no perceptible noise, because the only time a signal reached the photodetector is when the FBG peak is reflected. The high-frequency noise is all filtered out. The only noise left is most likely from the coupler being used, due to imperfect fiber connections or an internal issue. The average value of the five sweeps for each DUT was averaged into a single set of data and stored for use with Experiments 2-4.

For Experiment 2, a triple FBG sensor strand of fiber was connected in series with two other FBGs. The center FBG on the triple-strand had approximately the same center wavelength as the two single FBGs. The purpose of this experiment is to determine the location of the center wavelength of a single FBG reflected peak by de-

embedding it from the peak cluster of three Fiber Bragg gratings combined. The purpose of the extra FBGs on the sides seen below in Figure 4.13 is to calibrate the measurement time to a specific laser wavelength. That way, the exact center wavelength of the de-embedded FBG can be found if the time of measurement is known. The three DUTs used in this experiment are shown individually on the same graph below in Figure 4.13:

Figure 4.16: Plots of FBG reflections from DUTs 2, 3, and 4. There are three FBGs with near-identical center wavelengths, and two FBGs with center wavelengths 4nm away from the center for time-wavelength calibration

Figure 4.17: Zoomed-in view of center FBGS from Figure 4.16

Figure 4.18: Plots of FBG reflections from DUTs 2, 3, and 4. There are three FBGs with near-identical center wavelengths, and two FBGs with center wavelengths 4nm away from the center for time-wavelength calibration (signal vs time)

Figure 4.19: Zoomed-in view of center FBGS from Figure 4.18

Figure 4.20: Filtered reflection measurements for Exp. 2, which is DUTs 2, 3, and 4 connected in series

Figure 4.15 shows that the three Fiber Bragg gratings in the center have close enough center wavelengths that the combined reflection stacks on itself, with a total height of 1V, compared to the 0.4V amplitude of the single FBG reflections from Figure 4.13. This means that the center peak is between 2 and 3 times the height of a single peak, which is exactly what is expected for three FBGs with center wavelengths spaced 0.03-0.06nm away from each other, and 3dB widths of 0.18nm.

The goal of this section is to find out the exact location of each of the middle FBGs in Figure 4.15 in terms of center wavelength. Based on the experiment results from Chapter 2, and the simulation results from Chapter 3, the expected measurement accuracy should be about 5 picometers within the actual value. Network de-embedding

techniques similar to those used in Chapter 3 are applied by treating the system as a two-port network. From [1], the definition of a two-port network is:

Figure 4.21: Definition of a two-port Scattering-Parameter network

In Figure 4.16, a_1 is the input signal, b_1 is the reflected signal, and b_2 is the transmitted signal. For this experiment, the network DUT is three FBGs cascaded together, which means that a_1 is the laser output, b_1 is the FBG combined reflections, and b_2 is the transmitted signal through the three FBGs. Because of the noise in the circuit, only a 100-sample window around the combined center peak in Figure 4.15 was used to calculate the S parameters. This results in unique S-parameters for each of the 100 samples. The individual S-parameters for DUTs 2, 3, and 4 for the same 100 samples were also found using the reflection and transmission measurements for each individual Fiber Bragg grating. The S-parameters are converted to scattering transmission T-parameters using Eq. 3.6 from Chapter 3. The T-parameter matrices are multiplied together to form a single T-matrix for the entire system.

$$\text{Experiment 5} \rightarrow \text{S-parameters} \rightarrow T_{\text{System}} = T_{\text{DUT2}} T_{\text{DUT3}} T_{\text{DUT4}} \quad (\text{Eq. 4.1})$$

If DUT 2 is unknown, its T-parameters can be solved for by dividing T_3 and T_3 from T_{System} :

$$T_{\text{DUT2}} = T_{\text{System}} / (T_{\text{DUT3}} T_{\text{DUT4}}) \quad (\text{Eq. 4.2})$$

The S-parameters for DUT 2 are calculated from T_{DUT2} using Equation 3.7, and then the FBG reflection is constructed by solving for b_1 in Figure 4.10, and just using a value of 1 for a_1 .

$$b_1 = S_{11}a_1 + S_{12}a_2 = S_{11}a_1 + 0 = S_{11}a_1 \quad (\text{Eq. 4.3})$$

The fitting method in Chapter 2, Part 5 was used to find the center wavelength of the estimated FBG reflection peak. The FBG in DUT 4 with a center wavelength of 1541.81nm was used to assign each sample point to a wavelength. The results are tabulated below:

Table 4.3: Measurement Accuracy Results for Experiment 2

Experiment	Measured FBG	Estimated Center Wavelength	Actual Center Wavelength	Difference Between Estimated and Measured
2	DUT 2	1545.852nm	1545.84nm	0.012nm
2	DUT 3	1545.819nm	1545.78nm	0.039nm
2	DUT 4: Middle FBG	1545.758nm	1545.79nm	0.032nm

The results for measuring the center wavelength of each FBG range from 12 – 39pm within the correct value. This is more than the expected error of 6 picometers. A

cause for this is that the measurement irregularities are caused by noise, which is amplified by matrix multiplication in the de-embedding process. These results do not make the de-embedding method of FBG center wavelength measurement look useful. Experiments 3 and 4 will be performed to compare against the poor measurement accuracy of Experiment 2.

Experiment 3 is nearly identical to Experiment 2. The only difference is the exact specifications of the Fiber Bragg gratings used as the DUTs. DUTs 1, 2, and 4 are used instead of 2, 3, and 4. The measured and filtered reflection data is plotted below in Figure 4.22:

Figure 4.22: Filtered reflection measurements for Exp. 3, which is DUTs 1, 2, and 4 connected in series

Similarly to Figure 4.15 in Experiment 2, Figure 4.17 shows the reflected peak created from the combined FBG reflected signals of DUTs 1, 2, and 4. The peak amplitude is 0.1V less than in Experiment 2, because DUT 1 was measured to have a smaller peak amplitude than DUTs 2 or 3. The same de-embedding method used in the previous experiment yielded the following results:

Table 4.4: Measurement Accuracy Results for Experiment 3

Experiment	Measured FBG	Estimated Center Wavelength	Actual Center Wavelength	Difference Between Estimated and Measured
3	DUT 1	1545.799nm	1545.83nm	0.031nm
3	DUT 2	1545.786nm	1545.84nm	0.054nm
3	DUT 4: Middle FBG	1545.794nm	1545.79nm	0.004nm

The results for measuring the center wavelength of each FBG range from 4 – 54pm within the correct value. This is more than both the expected error of 6 picometers and the Experiment 2 results. This supports the theory from Experiment 2 that the de-embedding method is less than ideal for accurate measurements. Experiment 4 should also confirm this.

Experiment 4 is nearly identical to Experiments 2 and 3. The only difference is the exact specifications of the Fiber Bragg gratings used as the DUTs. DUTs 1, 3, and 4 are used instead of the other two combinations. The measured and filtered reflection data is plotted below in Figure 4.23:

Figure 4.23: Reflection measurements for Exp. 4, which was DUTs 1, 3, and 4 connected in series

Similarly to Experiments 2 and 3, Figure 4.23 shows the reflected peak created from the combined FBG reflected signals of DUTs 1, 3, and 4. The peak amplitude is about 0.1V less than in Experiment 2, because DUT 1 was measured to have a smaller peak amplitude than DUTs 2 or 3. The same de-embedding method used in the previous experiments yielded the following results:

Table 4.5: Measurement Accuracy Results for Experiment 4

Experiment	Measured FBG	Estimated Center Wavelength	Actual Center Wavelength	Difference Between Estimated and Measured
4	DUT 1	1545.820nm	1545.83nm	0.010nm
4	DUT 3	1545.831nm	1545.78nm	0.051nm
4	DUT 4: Middle FBG	1545.776nm	1545.79nm	0.014nm

The results for measuring the center wavelength of each FBG range from 10 – 51pm within the correct value. This confirms the measurement accuracy results of Experiments 2 and 3. The FBG center wavelength measurement accuracy results from Experiments 2, 3, and 4 are summarized below in Table 4.6:

Table 4.6: Measurement Results for Experiments 2, 3, and 4

Experiment	Measured FBG	Estimated	Actual Center	Difference
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		Center Wavelength	Wavelength	Between Estimated and Actual
2	DUT 2	1545.852nm	1545.84nm	0.012nm
2	DUT 3	1545.819nm	1545.78nm	0.039nm
2	DUT 4: Middle FBG	1545.758nm	1545.79nm	0.032nm
3	DUT 1	1545.799nm	1545.83nm	0.031nm
3	DUT 2	1545.786nm	1545.84nm	0.054nm
3	DUT 4: Middle FBG	1545.794nm	1545.79nm	0.004nm
4	DUT 1	1545.820nm	1545.83nm	0.010nm
4	DUT 3	1545.831nm	1545.78nm	0.051nm
4	DUT 4: Middle FBG	1545.776nm	1545.79nm	0.014nm

The results for measuring the center wavelength of each FBG range are 4 – 54pm, within the correct value. The only consistency is that the middle of the three FBGs in series has the worst measurement accuracy. The average measurement difference for the first FBG is 17.7pm, the middle FBG is 48pm, and the last FBG in series is 16.7pm. The middle FBG was DUT 3 in Exp. 2, DUT 2 in Exp. 3, and DUT 3 in Exp. 4, so the FBG parameters do not appear to affect the results. The only explanation for the increase in measurement inaccuracy of the center FBG is that the mathematical equation used to find its S-parameters somehow amplifies the noise more than the equation used for the first and last FBGs. For example, if FBGs 1, 2, and 3 are in series in that same order, then the S-parameters are calculated for each one as follows:

$$T_{\text{System}} = T_1 T_2 T_3$$

$$T_1 = T_{\text{System}} / (T_2 T_3)$$

$$T_2 = \text{Inverse}(T_1) T_{\text{System}} / T_3$$

$$T_3 = \text{Inverse}(T_1 T_2) T_{\text{System}}$$

Then Equation 3.7 is used to calculate the S-parameters from each T-matrix. There is no reason for the process of obtaining T_2 to amplify noise more than calculating T_1 or T_3 would. The lower measurement accuracy for the middle FBG must be attributed to coincidence.

The overall measurement accuracy in these experiments was very poor. The 100 Sweep experiment at the end of Chapter 2 showed that a single FBG could be measured accurately within 3pm. The average measurement deviation for the de-embedded FBGs in Experiments 2-4 ranges from 5-16 times the 3 picometer capability for a single FBG. This is not accurate enough for real-world measurements, so another measurement method will be explored in Experiment 5.

In Experiment 5, Wavelength-to-Time Domain Reflectometry (W-TDR) is used to measure each reflected FBG peak separately. For two FBGs, this is accomplished by placing a certain length of optical fiber in between the FBGs, resulting in a delayed measurement of the second FBG. The most accurate measurements would be where the bases of each FBG reflected peak are barely touching each other. Using the data in Experiment 1, it was found that when measuring a single FBG reflected peak, each side

of the base is 1.1us apart. If the sweep rate $f = 24.4081\text{kHz}$, and the wavelength range swept through is $\Delta\lambda = 1554.9\text{nm} - 1539.49\text{nm} = 15.41\text{nm}$, then the sweep time/nm:

$$1/(f\Delta\lambda) = 1/(24.408\text{kHz} \cdot 15.41\text{nm}) = 2.659 \text{ us/nm} \quad (\text{Eq. 4.4})$$

The FBG base time-width 1.1us divided by the sweep time/nm = $1.1\text{us}/2.659\text{us/nm} = 0.414\text{nm}$, which is the base width of the FBG filter in terms of wavelength. If the measured FBG reflections are spaced 1.1us apart, then the distance of fiber in between must be equal to:

$$L_{\text{Fiber}} = (1/2)(\text{time})(\text{speed of light})/(\text{refractive index of fiber}) = 0.5(1.1\text{us})(3 \times 10^8\text{m/s})/1.5 = 110\text{m}. \quad (\text{Eq. 4.5})$$

Because only 25m and 50m lengths of fiber were available, a length of 100m was chosen as the length of fiber in between the FBGs. Adding the 1m length of fiber from each grating strand brings the total up to 102m. A visual representation of the experimental layout can be seen below in Figure 4.24:

Figure 4.24: Physical layout of DUTs for Experiment 5

The two FBGs were connected by 2x 50m lengths of fiber for a total of 100m of additional fiber in between each DUT. Only the reflection measurements were recorded, and the sweep was run five times.

Figure 4.25: W-TDR reflection measurements of DUTs 3 (Left) and 2 (Right) with 100m of optical fiber in between. (Signal vs Time)

Figure 4.26: Zoomed-in view of W-TDR reflection measurements of DUTs 3 and 2 with 100m of optical fiber in between. (Signal vs Time)

Figure 4.27: W-TDR reflection measurements of DUTs 3 (Left) and 2 (Right) with 100m of optical fiber in between. (Signal vs Wavelength)

Figure 4.28: Zoomed-in view of W-TDR reflection measurements of DUTs 3 and 2 with 100m of optical fiber in between. (Signal vs Wavelength)

The center wavelength of each FBG peak was measured for every sweep. The standard deviation over five sweeps was 0.36pm for DUT 3 (tall peak on left), and 0.47pm for DUT 2 (short peak on right). These are higher values than the 0.14pm measurement deviation from Chapter 2, but there are only five sets of data in this Experiment as opposed to the 100 sweeps in Chapter 2. The deviation for DUT 2 is 11pm higher than DUT 3 because its amplitude is less than the amplitude of DUT 3, which results in it being more affected by noise. The pre-filtered SNR for DUT 3 is 50, while the SNR for DUT 2 is only 17. A measurement deviation of less than 0.5pm is close to the deviation calculated by various simulations of a two FBGs at similar parameters. The only concern is the increase in measurement deviation from DUT 3 to

2. This could be solved by having the two FBGs on the same fiber which would get rid of the losses from all of the fiber-fiber connections used in this experiment. The measurement accuracies are summed up in the table below:

Table 4.7: Exp. 5 FBG Center Wavelength Accuracy Results Comparison

	Exp. 5 3 FBGs 50MS/s 2% Ref	100 Sweeps Experiment from Ch. 2	Simulations 10 FBGs at 400MS/s, 0.1% Ref.	Simulations Single FBG 50MS/s, 2% Ref.
DUT 3 (First)	0.36pm	0.14pm	0.42pm	0.29pm
DUT 2 (Middle)	0.47pm	-	0.44pm	-
DUT 1 (Last)	-	-	0.44pm	-

The separation in time between the two FBG peaks was measured to be exactly 1.07us. Using Equation 4.5, this corresponds to a fiber of 107m between FBGs, which is 4.7% off from the actual value of 102m. This result helps to confirm that the experiment was set up correctly, and that the results can be trusted.

In Experiment 6, Wavelength-to-Time Domain Reflectometry (W-TDR) is used to measure each reflected FBG peak separately. For three FBGs, this is accomplished by placing a certain length of optical fiber in between the FBGs, resulting in a delayed

measurement of the second FBG. The calculated lengths of 100m are used from Experiment 5, because the time-differential between the second and third FBG is the same as the first two.

Figure 4.29: Physical layout of DUTs for Experiment 6

Figure 4.30: W-TDR reflection measurements of DUTs 3 (Left), 2 (Middle), and 1 (Right) with 100m of optical fiber in between (Signal vs Wavelength)

Figure 4.31: W-TDR reflection measurements of DUTs 3 (Left), 2 (Middle), and 1 (Right) with 100m of optical fiber in between (Signal vs Wavelength)

Figure 4.32: W-TDR reflection measurements of DUTs 3 (Left), 2 (Middle), and 1 (Right) with 100m of optical fiber in between (Signal vs Time)

Figure 4.33: W-TDR reflection measurements of DUTs 3 (Left), 2 (Middle), and 1 (Right) with 100m of optical fiber in between (Signal vs Time)

The center wavelength of each FBG peak was measured for every sweep. The standard deviation over five sweeps was 0.31pm for DUT 3 (tall peak on left), 0.55pm for DUT 2 (short peak in center), and 0.68pm for DUT 1 (shortest peak on right side). These are higher values than the 0.14pm measurement deviation from Chapter 2, and similar values to the accuracy measurements obtained in Experiment 5. A table comparing all the relevant measurement accuracies is shown below:

Table 4.8: Exp 6 FBG Center Wavelength Accuracy Results Comparison

	Exp. 6 3 FBGs 50MS/s 2% Ref	100 Sweeps Experiment from Ch. 2	Simulations 10 FBGs at 400MS/s, 0.1% Ref.	Simulations Single FBG 50MS/s, 2% Ref.
DUT 3 (First)	0.31pm	0.14pm	0.42pm	0.29pm
DUT 2 (Middle)	0.55pm	-	0.44pm	-
DUT 1 (Last)	0.68pm	-	0.44pm	-

Because multiple short optical fibers were used to create physical distance between the FBGs, the losses are significant. The first FBG, DUT 3, has an amplitude of 0.37V, 6 times as high as the 0.06V amplitude of DUT 2. This is a loss of 84%, which is much higher than the expected 2-4% loss from the signal passing through the first FBG. The consequences of these heavy losses are that this system is limited to a maximum of three FBGs in series, if sub-pm measurement accuracy is to be maintained. The W-TDR simulations at the end of Chapter 3 showed that hundreds of FBGS could be placed in series with only a minimal loss in accuracy. The losses of this experimental system could be reduced if the FBGs were connected to each other on a single fiber, so that there are no losses in the connections.

4.3 Chapter Conclusion

The results of the peak detection measurements for Experiments 2-4 show that the de-embedding method is not ideal for accurate measurements. The results appear to be completely random. Each measurement was between 4pm and 54pm within the correct value, with the least accurate measurements belonging to the center FBG in the series. This is significantly worse than the expected 0.5pm measurement error. One reason for the error is the large amount of noise in the transmission measurements. The signal-to-noise ratio of the transmission measurements was 3, which was really low compared to the SNR of 50 found in the reflection measurements. Another source of error is that each individual device under test was measured in a separate sweep, which might have resulted in slight delays or timing errors when comparing them.

The results of the W-TDR peak detection measurements for Experiments 5 and 6 shows a large improvement in accuracy compared to the de-embedding method from the previous experiments. FBG center wavelength measurement deviations of 0.36 and 0.47pm match what was expected based on the way the experiment was constructed. The deviation is higher than the 0.1-0.2pm found in the simulations and in the single FBG 100-sweeps experiment. The reason for this is that there were losses in the many fiber connectors throughout the circuit. If everything between the laser source and the photodetector was a continuous fiber, the losses would be significantly lower, and the SNR could increase up to about 500 or so, as seen in the Chapter 3 simulations. The results are tabulated below for comparison to experiments and theoretical simulations.

Table 4.9: FBG Center Wavelength Accuracy Results Comparison for all Experiments

	Exp. 6 3 FBGs 50MS/s 2% Ref	Exp. 5 3 FBGs 50MS/s 2% Ref	100 Sweeps Experiment from Ch. 2	Simulations 10 FBGs at 400MS/s, 0.1% Ref.	Simulations Single FBG 50MS/s, 2% Ref.
DUT 3 (First)	0.31pm	0.36pm	0.14pm	0.42pm	0.29pm
DUT 2 (Middle)	0.55pm	0.47pm	-	0.44pm	-
DUT 1 (Last)	0.68pm	-	-	0.44pm	-

From Table 4.7 above, the first FBG measurement accuracy for Experiments 5 and 6 matches the results from the theoretical simulations, and is 0.2pm less accurate than the 100 sweeps experiment from Chapter 2. The big difference between the theory and experiments is that there is a heavy decrease in accuracy as the number of FBGs in series increases. It was determined that the measurement accuracy could be greatly improved by a custom DUT that has all of the FBGs in series on a single strand of fiber. This would eliminate all the lossy connections that were used to connect the several shorter strands of fiber in the experiments.

Chapter 5: Conclusion and Future Work

5.1 Thesis Conclusion

In Chapter 2, the experimental test setup was explained in detail. The Insight VT-DBR electronically-swept laser is used as the optical source for all experiments. One or more Fiber Bragg gratings (FBGs) connected in series is the device under test (DUT). A partial signal is reflected off of the FBGs back to a photodetector, where the location of the peak in terms of sweep wavelength is determined. A test that ran 100 laser sweeps through a single FBG found that the center wavelength could be measured with accuracy to 0.14pm, which is an improvement on the 0.5pm accuracy in the Insight W-TDR experimented mentioned in Chapter 1. The single FBG accuracy could be even better if the optical coupler used in the experiment was replaced with one that had less connection issues.

In Chapter 3, a Fiber Bragg grating was modelled in MATLAB. System noise was also calculated and modelled. Simulations were run to find the measurement accuracy of the center wavelength of an FBG with noise added for one, two, three, ten, one-hundred, and three-hundred FBGs cascaded together in series. Parameters such as laser output power, ADC sampling frequency, FBG % reflectivity, and FBG FWHM were changed for each simulation so that measurement accuracy could be obtained for a variety of situations. The measurement accuracy for a single FBG with typical parameters of a 7mW laser source, 400MHz sample rate, 0.5% reflectivity, and a FBG FWHM of 0.2nm was a standard deviation of 0.13pm. This is considered an acceptable amount of accuracy and was what was expected for these parameters. In the 2 and 3 -

FBG simulations, the FBG being measured was de-embedded from the rest of them using network scattering parameters. For the simulations with 10-500 FBGs in series, the Wavelength-to-Time Domain Reflectometry (W-TDR) method is used. In this section, the Fiber Bragg gratings were separated in time by inserting a 75m or 125m length of optical fiber in between each FBG. Because it takes time for the signal to travel back and forth through the length of fiber, each FBG reflection peak arrived at the ADC later than the previous one by enough time to fully separate the peaks from each other. The main parameters varied in this section are the total number of FBG sensors in series, and the listed tolerance of the FBG center wavelength. The measurement accuracies obtained during these simulations ranged between 0.5 and 1.2pm. This is on the high side, but the FBG FWHM and % reflectivity parameters chosen were on the extreme side. A FWHM = 0.1nm, and % ref. = 0.1% had proved to result in less accurate measurements than the other parameters during the single FBG simulations. They were chosen because a small width and low FBG loss resulted in the smallest and least obtrusive field elements on an array with hundreds or even a thousand of them. The measurement accuracy results from the simulations are summarized below:

Table 5.1: FBG Center Wavelength Accuracy Results Comparison for Theoretical Simulations

Sample	Laser	FBG	FBG %	# of	FBG	Measurement
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Rate	Output	FWHM	Refl.	FBGs	Measured	Accuracy
50MHz	7mW	0.2nm	2%	1	First	0.3pm
400MHz	7mW	0.2nm	2%	1	First	0.07pm
400MHz	7mW	0.2nm	0.1%	10	First	0.413pm
400MHz	7mW	0.2nm	0.1%	10	Last	0.419pm
400MHz	7mW	0.2nm	0.1%	100	Last	0.435pm
400MHz	7mW	0.2nm	0.1%	300	Last	0.68pm
400MHz	7mW	0.2nm	0.1%	500	Last	0.81pm

The results measurement accuracy results for the multi-FBG simulations in Table 5.1 had a center wavelength tolerance of 0.01nm. An increase in tolerance from 0.01nm to 0.1nm resulted in a measurement accuracy decrease of 0.15pm on average across the simulations.

The results from this chapter can be used by a system designer who is designing a FBG sensor strand. For example, if 100 FBG sensors spaced apart by 75m are needed on a fiber, and each FBG will have a FWHM of 0.1nm and reflectivity of 0.1%, then the maximum center wavelength tolerance necessary for sub-1pm accuracy is 0.05nm. This can be found by referencing Figure 3.91 in Part D of Chapter 3. All of the other simulation results can be used in a similar manner for someone who is designing a FBG sensor system.

In Chapter 4, a similar experimental test setup to the one in Chapter 2 was constructed. Experiments with three Fiber Bragg gratings at similar center wavelengths were performed. The goal was to find out how accurate the FBG reflection peak

measurements were compared to their actual values. The results were very poor, with measurements ranging from 4-54 picometers from the datasheet values. The poor and inconsistent results mean the de-embedding method of isolating the FBG peak employed in these experiments is not reliable and should be avoided if possible. The final experiment for this chapter used the W-TDR method, which showed a large improvement in accuracy compared to the de-embedding method from the previous experiments. FBG center wavelength measurement deviations of 0.36 and 0.47pm match what was expected based on the way the experiment was constructed. The deviation is higher than the $< 0.2\text{pm}$ found in the simulations and in the single FBG 100-sweeps experiment. The reason for this is that there were losses in the many fiber connectors throughout the circuit. If everything between the laser source and the photodetector was a continuous fiber, the losses would be significantly lower, and the SNR could increase up to about 500 or so, as seen in the Chapter 3 simulations. A table summarizing the experimental results is shown below:

Table 5.2: FBG Center Wavelength Accuracy Results Comparison for Thesis

Experiments

Sample Rate	Experiment	# of FBGs	FBG Measured	Measurement Accuracy
50MHz	Single FBG, 100 Sweeps	1	First	0.14pm
50MHz	3 FBGs at same center wavelength, no spacing in between	3	Last	16.7pm Average over Exp 2-4
50MHz	2 FBGs separated by 100m	2	First	0.36pm
50MHz	2 FBGs separated by 100m	2	Last	0.47pm
50MHz	3 FBGs separated by 100m	3	First	0.31pm
50MHz	3 FBGs separated by 100m	3	Middle	0.55pm
50MHz	3 FBGs separated by 100m	3	Last	0.68pm

Figure 5.1: Graph showing the measurement accuracy from the single FBG simulations with experimental results imposed on top (black bars on right side). The std. deviation from the 100 sweeps experiment from Chapter 2 is one added data point. The other two added data points are from the first FBG in the W-TDR Experiments in Chapter 4

Figure 5.2: Graph showing the measurement accuracy from the W-TDR 10 FBG simulations with experimental results imposed on top (black diamonds). The simulations have an ADC sample rate of 400MHz, FBG % ref. of 0.1%, and FWHM of 0.2nm. The experimental setup uses an ADC sampling rate of 50MHz, FBG % ref of 2%, and FWHM of 0.18nm

From Table 5.2, all of the measurement results except for Exp 2-4 are < 1pm accurate. The single FBG measurements and the measurements of the first FBG out of a series have similar accuracy results as the simulations in Table 5.1. The experimental results get even better if the measurement variance from jitter is added to the simulations. Because the simulations and experimental results support each other for single FBG measurement, it can be confidently said that the Insight laser is capable of <0.5pm measurement accuracy. Based on the simulation results for multi-FBG DUTs,

the $<0.5\text{pm}$ accuracy will still hold for even as much as 500 FBG sensors on a single fiber. This wasn't able to be tested in the lab due to equipment constraints.

5.2 Future Work

Because the simulations were so exhaustive, no more are really needed. The experimental work is where there is room for additional research. A new method would be to use custom laser sweeps and Wavelength-to-Time Domain Reflectometry to separate the FBG reflections into individual peaks that can easily be measured one-by-one. The goal of this would be to explore measurement accuracy in a wide variety of environments. The improved experiments need updates in three areas: custom laser sweeps, equipment, and new DUTs. The custom laser sweeps would be wavelength-chirped pulses that can be varied by the time-delay in between pulses, and by the wavelength sweep of the actual pulse. The laser in the lab is currently only capable of sweeping through identical pulses as a user-specified time-delay. New equipment that would be useful include optical fibers long enough to separate the individual FBGs so that the reflections are spread out in time enough to be individually measured, and a low-loss optical coupler to improve the signal-to-noise ratio over the 3dB one currently in use. A digitizer that can sample at 400MHz would also be an improvement over the current 50MHz one. New DUTs that could be experimented on are sensor networks with 100s of individual FBGs. This would emulate the real-world environment the laser can be especially useful in.

An important concept that should be added to any future work that deals with measuring the absolute value of the FBG center wavelength is shadowing. Shadowing

is when there are multiple FBGs in series, and the FBG's effect on the input signal affects the FBGs that receive the signal afterwards. For example, if two FBGs are at slightly different wavelengths, 1% reflectivity, and the same FWHM, then the reflected signal from the second FBG has two notches cut out of it, each at 1% of the total signal amplitude. If the FBGs are not at the same center wavelength, then this affect shifts the measured peak of the second FBG reflection off-center by a very small amount. This does not affect repeatability, and can be corrected using the de-embedding method discussed in Chapters 3 and 4.

The single-FBG measurement experiments completed so far can be used by future graduate students as a reference and a guide for doing experiments with larger numbers of FBGs. The simulations can be used as a reference of what to expect for the best-case scenario of experimentation results.

BIBLIOGRAPHY

1. Christian Martens. "Sweep Stability Characterization of a Vernier-Tuned Distributed Bragg Reflector (VT-DBR) All-Semiconductor Tunable Swept Laser System at 1550 nm for Sensing Applications," California Polytechnic State University, San Luis Obispo, Thesis 2015.
2. Greg Bergdoll. "Characterization of Two Vernier Tuned Distributed Bragg Reflector (VT-DBR) Lasers for Use in Swept Source Optical Coherence Tomography (SS-OCT)," California Polytechnic State University, San Luis Obispo, Thesis 2015.
3. Dennis Derickson et al., "SGDBR single-chip wavelength tunable lasers for swept source OCT," in SPIE Digital Library, San Jose, 2008.
4. Insight Photonics, "Atlas 3.7.0 User Manual".
5. Minneman, Hoover, Boschert, Ensher, Crawford, Derickson, Kersey. "Very High Sensor-Density Multiplexing using a Wavelength-to-Time Domain Reflectometry Approach based on a Rapidly Swept Akinetic-Laser," SPIE 24th International Conference on Optical Fibre Sensors. 2015.
6. Udoh, Njugma, Prabhu, "Modelling and Simulation of Fiber Bragg Grating Characterization for Oil and Gas Sensing Applications", 2014 First International Conference on Systems Informatics, Modelling and Simulation.
7. Werneck, Allil, Ribeiro, and Nazare, "A Guide to Fiber Bragg Grating Sensors", InTech, DOI: 10.5772/54682.
8. Joseph C. Palais "Fiber Optic Communications", 5th Ed. Pearson Publishing.
9. (2015, May) Multimode Vs Singlemode Fibre for Distributed Sensing. [Online] <http://www.sensornet.co.uk/download-news/faqs/71-multimode-vs-singlemode-fibre-for-distributed-sensing>
10. Luis Orozco, "Optimizing Precision Photodiode Sensor Circuit Design". January 2014. [Online] <http://www.analog-eetimes.com/content/optimizing-precision-photodiode-sensor-circuit-design>

11. ThorLabs Instrumentation, "PDB100 Series Balanced Amplified Photodetectors".
Version 1.3, 2007
12. ThorLabs, "InGaAs High Speed Photodiode with FC/PC Bulkhead", 24112-S01,
Rev E, 2015
13. Agilent Technologies, "Agilent AN 154 S-Parameter Design", Application Note.
June, 2006.
14. Bonesi, Minneman, Ensher, Zabihian, Sattman, Boschert, Hoover, Leitgeb,
Crawford, and Drexler. "Akinetic All-Semiconductor Programmable Swept-Source
at 1550nm and 1310nm with Centimeters Coherence Length". 2014 Optical
Society of America
15. Mathworks, "Designing Low Pass FIR Filters".
<http://www.mathworks.com/help/dsp/examples/designing-low-pass-fir-filters.html>

Appendix A: MATLAB Code

```
% This code models three FBGs, then plots the reflections. An appropriate  
% amount of noise is added, then the signal is filtered. The system  
% parameters are: Laser output power = 7mW, ADC sampling rate = 400MHZ,  
% FBG FWHM = 0.2nm, FBG reflectivity = 2%. System losses and the  
% photodetector transimpedance amplifier are taken into account.
```

```
% Simulation of a Fiber Bragg Grating Sensor
```

```
%=====
```

```
=
```

```
clear all  
close all  
clc
```

```
%=====
```

```
=====
```

```
% fibre simulation parameters
```

```
%=====
```

```
=====
```

```
% FBG FWHM = 0.2nm, % ref = 2%  
L = 0.0037; % Grating Length  
dn = 0.64e-4; % Induced index change
```

```
% FBG Center Wavelengths  
design_lambda = 1545.83e-9; % Center WL 1  
design_lambda2 = 1541.72e-9; % Center WL 2  
design_lambda3 = 1549.62e-9; % Center WL 3
```

```
neff=1.4455; % Effective refractive index of FBG
```

```
A=design_lambda/(2*neff); % Grating period 1  
A2=design_lambda2/(2*neff); % Grating period 2  
A3=design_lambda3/(2*neff); % Grating period 3
```

```
a1 = 0.007; % Amplitude of input signal to FBGs  
tl1 = 3/3.23;
```

```

tl2 = 1/3.23;
i = 1;
lambda= 1540e-9; % Wavelength range is 1540nm - 1551nm
for lambda=1540e-9:0.0007222e-9:1551e-9
%=====
=====
% Coupled-mode Theory
%=====
=====

v=0.138; % visibility, v assumed to be 1

k=(pi./lambda)*v*dn; % AC coupling coefficient

sigma_dc =0; %(2*pi./lambda).*dn;

% general DC coupling coefficient
sigma = 2*pi*neff.*(1./lambda - 1/(2*neff*A)) + sigma_dc;
sigma2 = 2*pi*neff.*(1./lambda - 1/(2*neff*A2)) + sigma_dc;
sigma3 = 2*pi*neff.*(1./lambda - 1/(2*neff*A3)) + sigma_dc;

%=====
=====
% Power Reflection coefficients(R)
%=====
=====

K2 = k.*k;
sigmas = sigma.*sigma;
difference = K2-sigmas;
numerator = sinh(L*sqrt(difference)).^2;
denominator = cosh(L*sqrt(difference)).^2 - sigmas./K2;
R = numerator./denominator;

sigmas2 = sigma2.*sigma2;
difference2 = K2-sigmas2;
numerator2 = sinh(L*sqrt(difference2)).^2;
denominator2 = cosh(L*sqrt(difference2)).^2 - sigmas2./K2;
R2 = numerator2./denominator2;

sigmas3 = sigma3.*sigma3;
difference3 = K2-sigmas3;
numerator3 = sinh(L*sqrt(difference3)).^2;
denominator3 = cosh(L*sqrt(difference3)).^2 - sigmas3./K2;

```

```
R3 = numerator3./denominator3;
```

```
%=====
=====
% Scattering Parameters
%=====
=====
```

```
s(1,1) = R;
s(2,2) = R;
s(1,2) = 1-R;
s(2,1) = 1-R;
```

```
T(1,1) = -(s(1,1).*s(2,2)-s(1,2).*s(2,1))./s(2,1);
T(2,2) = 1./s(2,1);
T(1,2) = s(1,1)./s(2,1);
T(2,1) = -s(2,2)./s(2,1);
```

```
s2(1,1) = R2;
s2(2,2) = R2;
s2(1,2) = 1-R2;
s2(2,1) = 1-R2;
```

```
T2(1,1) = -(s2(1,1).*s2(2,2)-s2(1,2).*s2(2,1))./s2(2,1);
T2(2,2) = 1./s2(2,1);
T2(1,2) = s2(1,1)./s2(2,1);
T2(2,1) = -s2(2,2)./s2(2,1);
```

```
s3(1,1) = R3;
s3(2,2) = R3;
s3(1,2) = 1-R3;
s3(2,1) = 1-R3;
```

```
T3(1,1) = -(s3(1,1).*s3(2,2)-s3(1,2).*s3(2,1))./s3(2,1);
T3(2,2) = 1./s3(2,1);
T3(1,2) = s3(1,1)./s3(2,1);
T3(2,1) = -s3(2,2)./s3(2,1);
```

```
Tm = T2*T*T3;
Sm(1,1) = Tm(1,2)/Tm(2,2);
Sm(1,2) = (Tm(1,1)*Tm(2,2)-Tm(1,2)*Tm(2,1))/Tm(2,2);
Sm(2,1) = 1/Tm(2,2);
Sm(2,2) = -Tm(2,1)/Tm(2,2);
```

```
% Solve for reflected signal - losses
```

```

b1(i) = 0.25*0.9*Sm(1,1)*a1;

%-----
% Calculates Noise for a Given Signal Amplitude and Bandwidth

Ip = b1(i);    % Signal Current Amplitude
bw = 1*10^-6;  % System Bandwidth

Ins2 = 2*(1.6*10^-19)*bw*Ip;    % Squared value of shot noise

Int2 = bw*3.2916*10^-27;        % Squared value of thermal noise

lex = (7.4*10^-12)*sqrt(bw);    % Excess noise

RIN = 0.0019*Ip;                % Relative intensity noise

Itotal = sqrt((RIN^2) + (lex^2) + Ins2 + Int2)*rand(); % Total Noise
noise = Itotal;
%-----
b1(i) = 5000*(b1(i) + noise); % signal + noise, then converted to voltage

i = i + 1;

end

%%-----FIR Filter
N = 10;    % FIR filter order
1.*10^6;   % passband-edge frequency
Fp = 1.*10^6;
Fs = 400e6;    % 400 MHz sampling frequency
Rp = 0.00057565; % Corresponds to 0.01 dB peak-to-peak ripple 0.00057565
Rst = 1e-6;    % Stopband attenuation

NUM = firceqrip(N,Fp/(Fs/2),[Rp Rst],'passedge'); % NUM = vector of coeffs
%fvtool(NUM,'Fs',Fs,'Color','White') % Visualize filter
LP_FIR = dsp.FIRFilter('Numerator',NUM); % Or use NUM200 or NUM_MI

for i = 1:length(b1)
    output(i) = step(LP_FIR,b1(i));
end

[c,lag]=xcorr(b1,output); % Correct Filter Shift
[maxC,l]=max(c);

```

```

lag = lag(I);
shift = -lag;
output2 = output((shift+1):length(output));
output2(end+shift)=0;
filter_out = output2;

% Set wavelength for each data point (400MS/s)
lambda=(1540e-9:0.0007222e-9:1551e-9);
% Plots Data
plot((10^9).*lambda,b1,'b')
hold on
plot((10^9).*lambda,filter_out,'r')
title('FBG Reflection Spectra with Filtering at 2% Ref');
xlabel('Wavelength (nm)');
ylabel('Reflection (V)');
legend('Unfiltered Data','Filtered Data')

%-----

```