SLOVAK UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering and Information Technology

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OPTICAL FIBER SENSORS WITH LONG FIBER BRAGG GRATING BASED ON OFDR

Dissertation thesis abstract

Bratislava 2019

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Dissertation thesis abstract

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Contents

1 | Introduction

There has always been a demand for increased capacity of transmission in communication systems. The technology has advanced since the invention of optical fibers. The idea of signal transmission through optical fibers was accelerated in 1966 [1] by Kao's invention of the technology for guiding light in optical fibers, for which he received the Nobel price. For high speed communication systems, one needs fast light sources. The invention of the semiconductor laser based on GaAs [2] and optical fiber technology have led to the first optical fiber communication systems. One of the crucial elements in the fiber optics revolution has been reduction in transmission attenuation. The most significant decline in attenuation occurred in 1970s when the attenuation of optical fibers was about 20 dB/km [3] at wavelength 0.8 μm and bandwidth about 50 Mbit/s to 100 Mbit/s. This was known as *the first generation of optical communication systems*. At that time the optical fiber communication revolution began.

Although a variety of optical fibers are available, nowadays, the singlemode optical fibers with the core diameter of about 9 μm and cladding diameter of about 125 μm prevail. Attenuation has steadied at 0.2 dB/km at the wavelength window near 1550 nm. There are many other properties, such as electromagnetic interference immunity, weight, size and availability, that have given an increase in developing new applications based on optical fibers.

In parallel with communication usage, optical fibers have been used as sensors in sensing systems. Optical fiber sensor, as an alternative to the *classic* electric sensor, can be defined as a means through which physical, chemical and biological quantity influences with the light propagating through an optical fiber to produce modulated optical signals with information about the measured quantity. There is no doubt that this technology can bring a large amount of applications, ranging from sensors for measuring biological functions in the medical industry [4], to measure the health of massive buildings and structures in civil engineering [5, 6, 7] and various measurements in space industry [8, 9, 10] and aircraft industry [11, 12].

A well-known optical fiber sensor is based on a periodic perturbation of the refractive index called fiber Bragg grating (FBG). This perturbation causes that a narrow band of the incident light is reflected. Since the perturbation properties can be affected by the measurand, the reflected light is modified according to the measurand magnitude. The main benefits of FBG sensors are implementation of multiple FBGs along an optical fiber and the capability to measure various physical, chemical and biological quantities. While temperature [13] and strain [14] influence the FBG physical properties without any attached external transducer; magnetic field [15], humidity [16], electric current [17], gases etc. influence the FBG properties through a measurand-sensitive material.

Distributed optical fiber sensors show great potential in many applications due to their capability of multiplexing several sensors along a single optical fiber. Therefore, compared to other sensing systems, optical frequency-domain reflectometry (OFDR) attracts many researchers and engineers [18, 19] due to its high spatial resolution in sub-millimeter domain. Even though OFDR was developed for the localization of the faults and components in optical fiber networks [20], the combination of OFDR and FBGs brings new approaches into the field of sensing systems.

2 | Objectives of the thesis

1. **Overview of the existing knowledge about optical fiber sensors with distributed parameters based on optical frequency-domain reflectometry and their sensing applications with long fiber Bragg gratings.**
2. **Analysis and description of fiber Bragg gratings in terms of their application in optical fiber sensors with distributed parameters.**
3. **Design and realization of an optical fiber sensor with fiber Bragg grating based on optical frequency-domain reflectometry for measurement of magnetic field spatial distribution.**
   (a) simulation and signal processing
   (b) technical realization of the sensing system
4. **Evaluation of the achieved results.**

3 | Achieved results

The main objective of the dissertation thesis is design and realization of FBG sensor based on OFDR for measurement of magnetic field. The thesis is separated into several parts which describe the particular issues separately.

Fiber Bragg gratings

The first part describes wave propagation in optical fibers with inscribed FBG. The next section deals with coupling between the modes in the presence of a periodical perturbation in the core refractive index. We

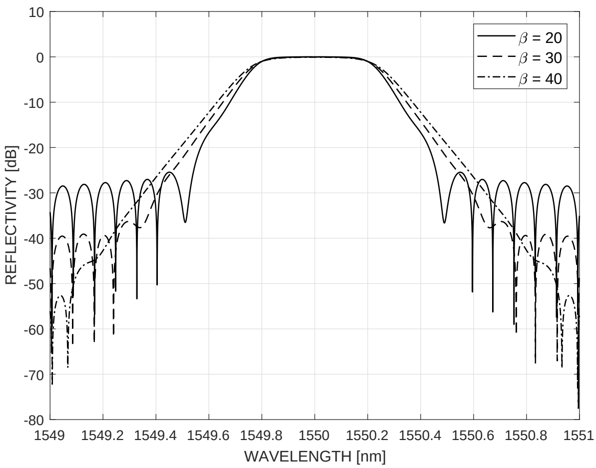


Figure 3.1: Reflectivity of apodised FBGs with gauss function δn(z) $\propto$ $e^{-\beta z^2}$; β = 20, 40, 60.

also describe a simulation model for simulating reflectivity of apodised

FBGs with parameters which are not constant over the FBG length. The simulation results are shown in Fig. 3.1. Moreover, this simulation model is also used for simulating OFDR with long FBGs.

FBG sensors

This part discusses existing FBG sensors and sensing systems for interrogating the reflected wavelengths and gives an overview about existing knowledge about optical fiber sensors based on FBG. In this part, we also describe the created and implemented FBG magnetic sensor.

The magnetic sensor includes a 10 mm long FBG attached to the magnetostrictive alloy Terfenol-D rod with size 3.5×3.5×35 mm^3. The rod was manufactured by TdVib company and has large magnetostriction 1000 μm/m according to the manufacturer's website. We glued the FBG on the rod with UV adhesive due to its great strength.

(a) **(b)**

Figure 3.2: (a) The experimental setup for measuring magnetic field with the made (b) FBG sensor glued on the Terfenol-D rod.

The experimental setup is shown in Fig. 3.2a and the Terfenol-D rod attached to the FBG is shown in Fig. 3.2b. Upon applying magnetic field to the FBG, the Terfenol-D lengthens, which causes structural changes in the

FBG resulting in the Bragg wavelength shift. From the experiment results,

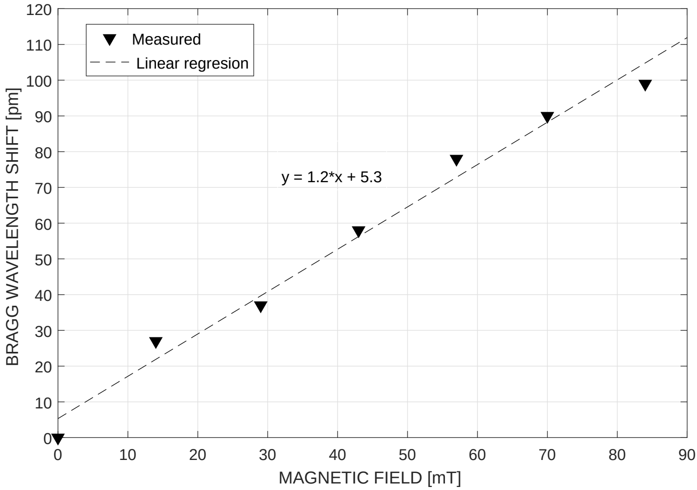


Figure 3.3: Bragg wavelength shift as a function of applied magnetic field.

shown in Fig. 3.3, it can be seen that the Bragg wavelength shift increases with increasing magnetic field intensity. Moreover, the wavelength shift can be approximate with a linear function with magnetic field intensity sensitivity 1.2 pm/mT.

Optical frequency-domain reflectometry

This part describes OFDR in detail, STFT signal processing method, simulation model, nonlinear optical frequency tuning and its impact on the detected signal. With the created simulation model, we simulate temperature influence on long FBGs using OFDR and the final spectrogram is shown in Fig. 3.4. The spectrogram shows that we can observe the Bragg wavelength shifts along the FBGs.

The simulation model was also used for measuring birefringence (Fig. 3.5). It shows spectrogram of four FBGs with different birefrin-

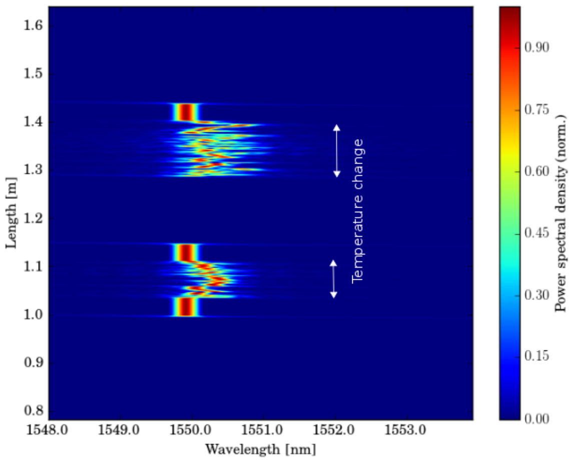


Figure 3.4: Spectrogram of two long FBGs with applied temperature change.

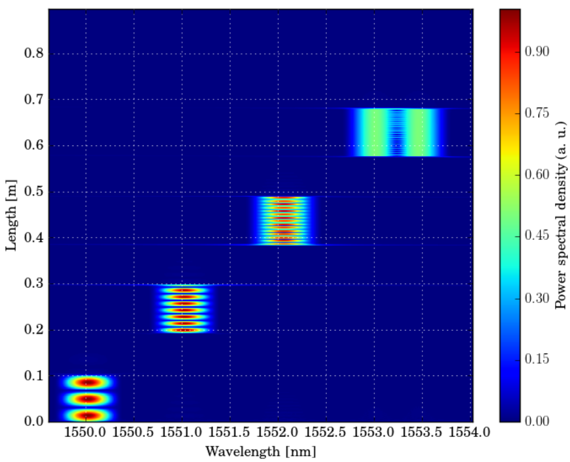


Figure 3.5: Spectrogram of four long FBGs with various birefringencies

gencies. Using this method, we can determine the resulting birefringence.

Subsequently, we simulated OFDR with two FBGs inscribed in a polarization-maintaining optical fiber. Due to these special optical fibers one can determine the influence of temperature and strain separately within a single FBG.

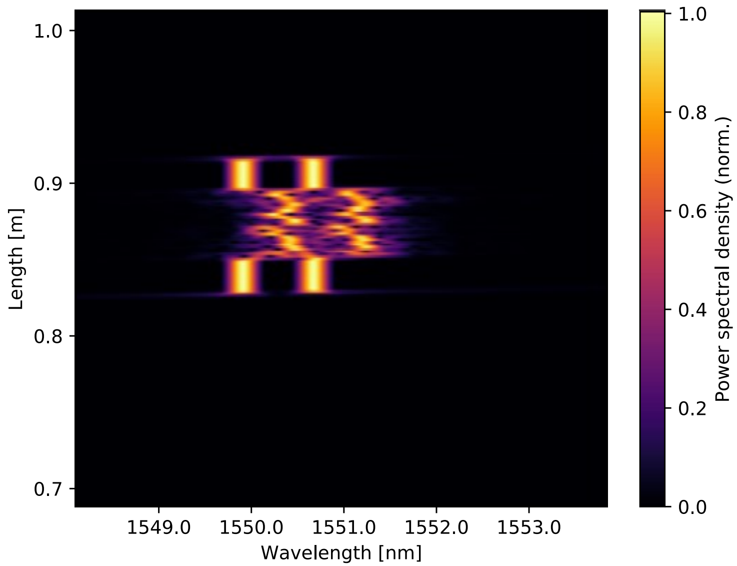


Figure 3.6: Spectrograms of power spectral density with applied temperature and strain distribution

OFDR experimental setup and measurements

This principal part describes our experimental measurement and OFDR sensing setup. First, we demonstrate the nonlinear frequency tuning of our tunable laser source and how the optical frequency is changing over time. The optical frequency deviation is measured with method introduced in [21] and the result is shown in Fig. 3.7. There is more than 15% deviation

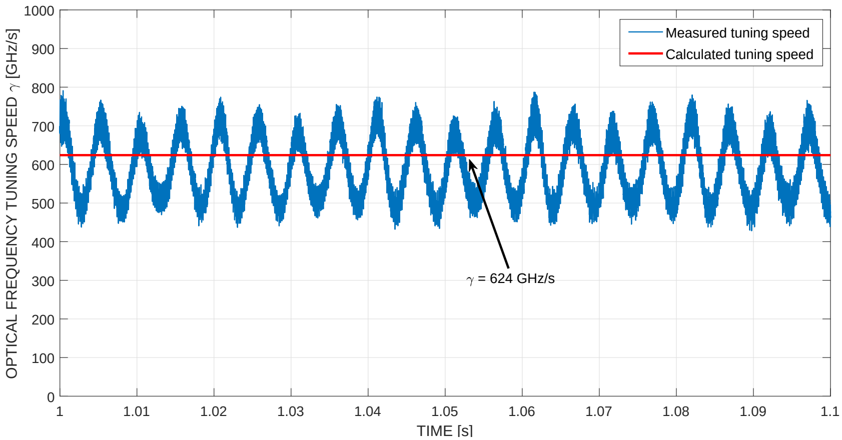


Figure 3.7: Measured time-varying optical frequency tuning speed as a function of time, where the blue line represents the measured tuning speed and the red line shows the calculated tuning speed for our measuring setup.

in the optical frequency tuning speed beacuse the tuning speed varies from 480 to 780 GHz/s. The repetition of the fluctuations is approximately 200 Hz which is probably caused by the feedback control in the TLS used during optical frequency tuning.

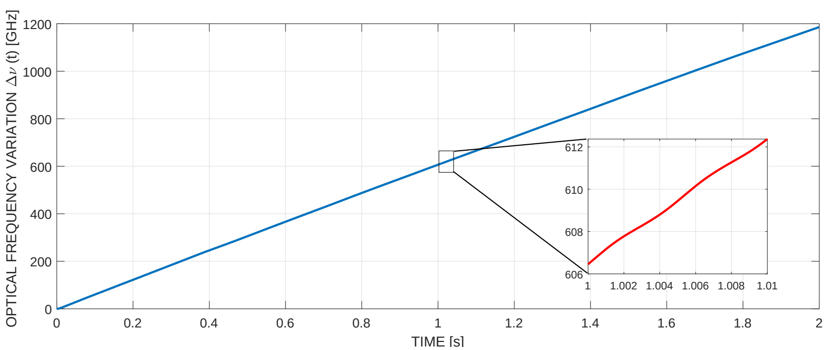


Figure 3.8: Optical frequency variation along the whole scanning process. The zoom shows small fluctuations in optical frequency.

Figure 3.8 shows the integration of our measured tuning speed. Although it looks linear within the whole range, there are some fluctuations. As shown in the zoomed figure around 1 s, we can observe that the optical frequency slightly varies.

Following these results, there is a need to reduce the effect of the nonlinearities in order to increase spatial resolution. This leads to the experimental OFDR setup with an auxiliary interferometer with equidistant optical frequency sampling.

Since the tunable laser source has fluctuations in the optical frequency tuning, we implemented an auxiliary interferometer functioning as an external clock generator for the DAQ card. Our experimental setup is shown in Fig. 3.9.

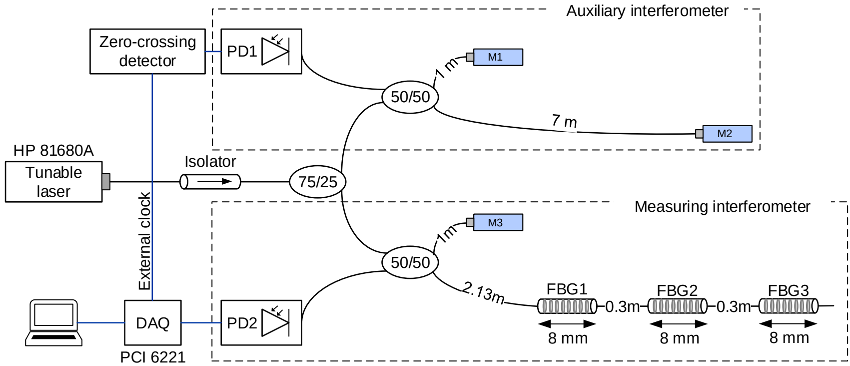
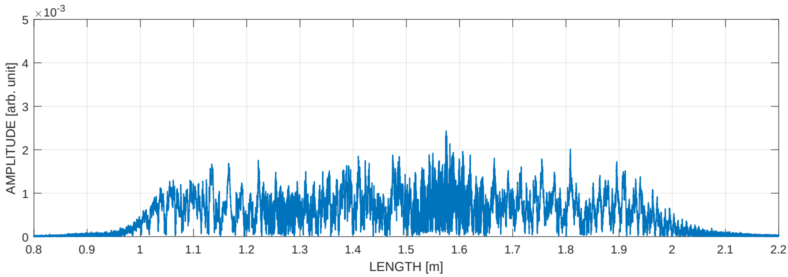


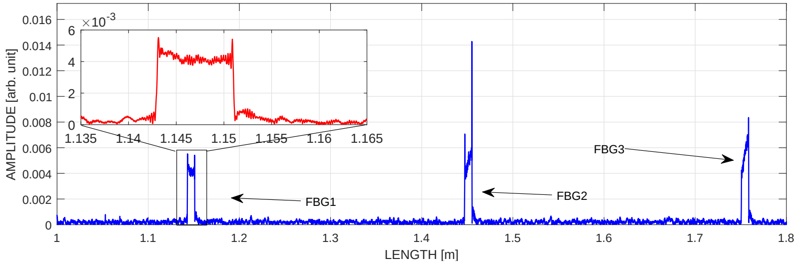
Figure 3.9: Experimental OFDR setup with NI PCI-6221 DAQ card and zero-crossing detector.

The results are shown in Fig. 3.10. For comparison, we also plotted spectrum of the detected signal without equidistant optical frequency sampling shown in Fig. 3.10a. It can be seen that without the equidistant frequency sampling, we can not observe any separated FBGs, although the measuring interferometer contains three FBGs. Because we want to interrogate the individual FBGs in the optical fiber, measuring without the auxiliary interferometer is inapplicable.

On the other hand, application of equidistant optical frequency sam-



(a) Detected signal without external clock signal from the auxiliary interferometer.



(b) Detected signal with external clock signal from the auxiliary interferometer.

Figure 3.10: Fourier transform of the detected signals (a) without and (b) with the external clock signal.

pling gives us better results. Figure 3.10b shows the reflected signal as a function of position along the optical fiber. There are three easily distinguished peaks which represent reflectivity of the FBGs. It can be seen that FBG1 is located at 1.14 m from the reference point. The next FBG is located at around 1.44 m and the last FBG is at 1.74 m. If we look at the measuring setup shown in Fig. 3.9, one can see that the distances correspond with the fiber lengths of the setup. Moreover, Fig. 3.10b also shows a detailed look of FBG1, where we can determine the length of the FBG. Note that the length of FBG1 is 8 mm according to the manufacturer's datasheet and this length also matches our measurement results.

It is important to note that this part also describes the developed and implemented a postprocessing technique to resample the measured data according to the instantaneous optical frequency obtained from the signal at PD1 in order to maintain high spatial resolution. The resampling process is as follows: first, we run the measurement with triggering the TLS and data acquisition from both PDs. The synchronization between the data acquisition and the output optical signal from the TLS was similar to the previous measurement. Then we adjust the detected signal at PD1. The adjustment consists of changing the samples to unity or zero in compliance with the instantaneous optical frequency. When the signal crosses zero values, we adjust that sample to unity and other samples are set to zero. This basically means that the signal at PD1 was transformed into a clock signal. Subsequently, this signal is multiplied with the measuring signal at PD2. This will lead to a sampled signal, where the samples have nonzero values only at time when the auxiliary signal crosses zero values. This can also be understood as software external sampling from the previous method with zero-crossing detector. The last step is to remove the zero-valued samples from this signal. This process rearranges the detected sensing signal according to the nonlinear tuning. Figure 3.11 shows the reflected power distribution of the detected signal with and without the nonlinear compensation with the proposed resampling technique. In Fig. 3.11, the reflected power distribution of the reflected signal was sampled at equidistant time intervals without using the auxiliary interferometer. Therefore, the power of the signal is spread over 70 cm. When we use the auxiliary interferometer and our resampling method, there is a certain peak at position ~2.97 m within the fiber as shown in Fig. 3.11b. The length spectrum of the FBG is around 1 cm which corresponds to the length of the used FBG.

The main objective was the technical realization of the OFDR sensing system with measurement of magnetic field. Figure 3.12 shows the configuration of OFDR setup to measure magnetic field. The results obtained from the experimental OFDR setup are shown in Fig. 3.13. The spectrograms show the wavelength shifts of FBG2 with the increasing magnetic field. As the magnetic field was increasing, the reflected wavelengths were shifting to the longer wavelengths. This was caused by elongation of the Terfenol-D rod with the applied magnetic field which leads to the modi-

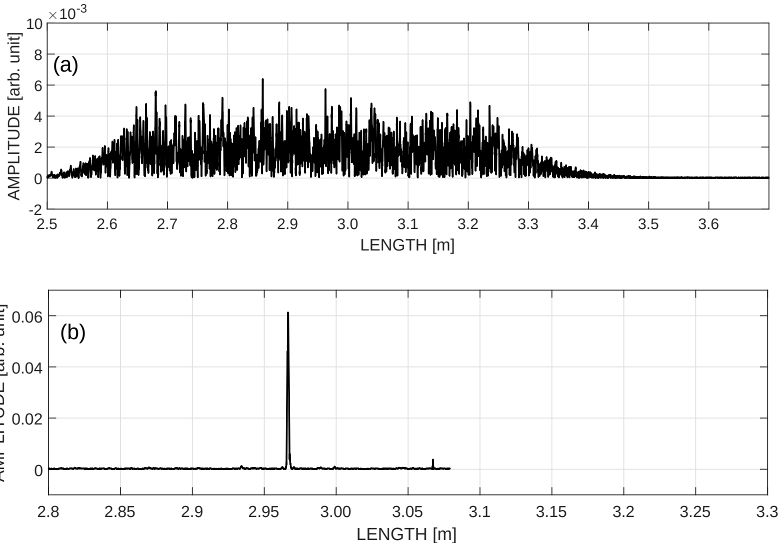


Figure 3.11: Reflected power distribution of the signal at PD2 (a) without resampling and (b) with resampling method.

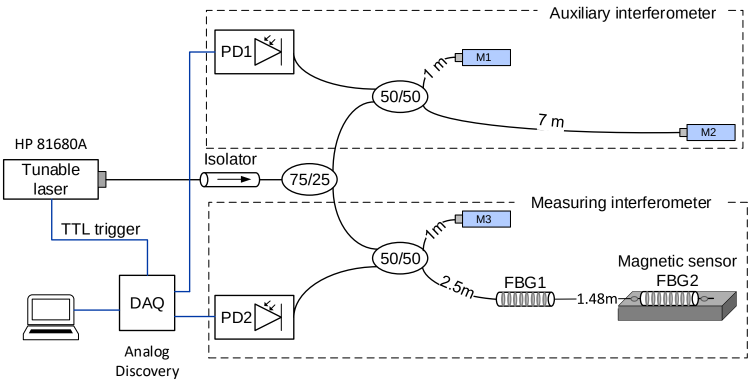


Figure 3.12: OFDR setup for measuring magnetic field with included temperature compensation FBG1.

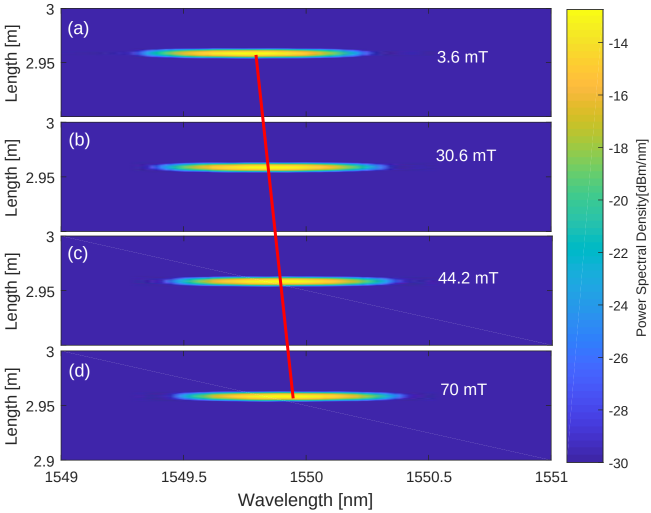


Figure 3.13: Spectrograms of FBG2 with applied magnetic field (a) 3.6 mT (b) 30.6 mT (c) 44.2 mT and (d) 70 mT. The red line shows the wavelength shift as a function of the magnetic field with sensitivity around 2.2 pm/mT.

fication of the effective refractive index and mainly by the spatial period. The spectrograms not only show the wavelength shift but also the position at which the reflection occurs. Based on this fact, we are able to determine not only the magnetic field magnitude but the position along the fiber as well.

In order to establish the relation between the wavelength shift and the applied magnetic field, we outlined the linear regression with a red line. The line reveals that the sensitivity is around 2.2 pm/mT.

Figure 3.14 shows the reflected Bragg wavelength peaks of FBG1 and FBG2. As mentioned above and indicated in Fig. 3.14a, FBG2 needed a temperature compensation by another FBG due to its temperature dependency. The wavelength shifts of FBG1 shown in Fig. 3.14b have small fluctuations due to the constant temperature, although there is a certain leap around 15 mT. This results in a leap of the reflected wavelength of FBG2. Thus, the impact of temperature change on the reflected wavelength can

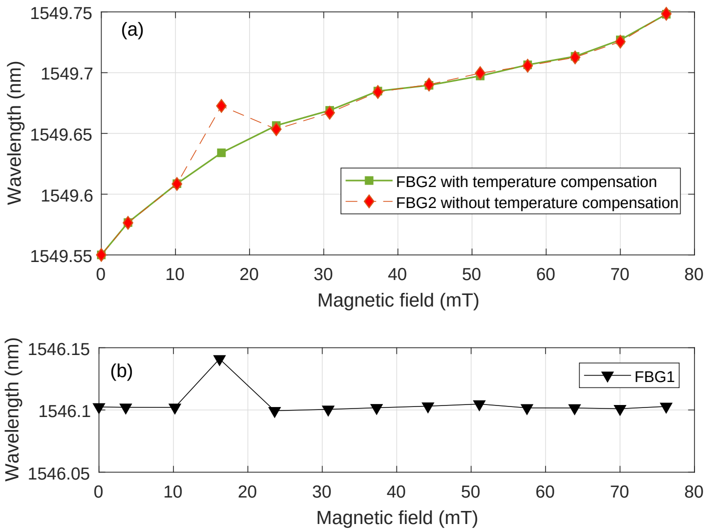


Figure 3.14: Reflected wavelength peaks from (a) FBG2 with and without the temperature compensation; and (b) the reflected wavelength peaks from FBG1 with a small wavelength peak leap around 15 mT.

be substantially reduced by using another FBG.

4 | Contribution

The contributions of the thesis are enumerated in the following list:

1. Design, development and technical realization of the OFDR sensing system using FBGs as sensors. We experimentally tested and measured magnetic FBG sensors with attached magnetostrictive material Terfenol-D as a transducer using the assembled OFDR setup.

2. Analysis, description and simulation of FBGs and their applications in sensing systems for measuring various physical quantities. We mainly focused on FBG magnetic sensors based on Terfenol-D and ferrofluids.

3. Analysis and description of the OFDR simulation model with STFT signal processing method. Simulations of OFDR for measuring temperature and strain along optical fiber.

4. Simulation of OFDR for measuring birefringence and its impact on the detected signal.

5. Description and implementation of signal processing method based on STFT in our simulations as well as in our experimental measurements.

6. Analysis, design and implementation of two methods for reducing the impact of nonlinear optical frequency tuning on the detected signal. One method uses an auxiliary interferometer for equidistant optical frequency sampling. We designed and implemented the second method which is based on resampling the detected signal considering the instantaneous optical frequency during the tuning process.

7. Analysis and measurement of nonlinear optical frequency tuning and its influence on the spatial resolution of OFDR.

5 | Author's publications

[1] **KAPLAN, Norbert** - JASENEK, Jozef - KORENKO, Branislav - ČERVEŇOVÁ, Jozefa. "Optical fiber strain sensors with long FBG using OFDR". In *International interdisciplinary PhD workshop 2016* : Brno, Czech Republic. September 12-15, 2016. Brno : University of Technology, 2016, S. 16-20. ISBN 978-80-214-5387-6. In database: **WOS**.

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[1] "ELITECH'16: 18th Conference of Doctoral Students", Faculty of Electrical Engineering and Information Technology, Bratislava, Slovakia, June 6 2016.

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