High-speed FBG interrogation system insensitive to fiber link attenuation for magnetic field sensing

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ABSTRACT

A high-speed FBG interrogation method for magnetic field sensing is proposed. A FBG attached to a magnetostrictive material (Terfenol-D) was used to show the output invariance when increasing the attenuation on the optical link. This was achieved by computing the ratio between the sensing and the reference signals, both generated using different DFB lasers properly tuned. The output remained invariant to attenuations up to 12 dB. Also, the system's interrogation speed was tested and compared to a commercial solution. While the commercial model was limited by its 6 kHz sampling frequency, this method provided responses up to 60 kHz.

Keywords: FBG, optical fiber sensor, interrogation method, magnetic field sensor, Terfenol-D

1. INTRODUCTION

Fiber Bragg Grating (FBG) is one of the most common type of optical fiber sensors due to its small size, reliability, simplicity and flexibility. It is well known that FBG is suitable for temperature and displacement transduction. They are often used together with other materials to transduce various physical quantities, finding numerous applications in engineering[1]. One of these applications is the monitoring of magnetic fields. One way to achieve this is attaching a FBG to a magnetostrictive material such as the rare earth alloy Terfenol-D. For instance, this material can be used as a composite that covers the FBG[2] or simply a solid piece with the FBG properly glued to it[3]. This type of sensor has important applications in the electric power industry, including the health monitoring of large power generators[2,3]. As important as the FBG sensor itself are the methods to extract the wavelength information provided by it. There are many techniques to interrogate the grating, such as the use of a Dispersion Compensation Fiber (DCF) to translate the wavelength shift to the time domain[4]. This method is very simple, but it requires high resolution instruments to detect small wavelength variations. One method employs an additional FBG to compensate the temperature[5], measuring the ratio between the amplitudes of the reference and sensing signals. However, this method does not provide a compensation for optical losses in the fiber, what can culminate in erroneous measurements if the attenuation is not known. This paper proposes a high-speed FBG interrogation method insensitive to optical losses with focus on magnetic field monitoring in power machines, which is an improvement of a previous work[3]. Two experiments were carried to demonstrate the insensibility to optical link attenuations and to compare the interrogation speed of the system with a commercial module available in our laboratory (Ibsen I-MON USB 256), which sampling frequency is 6 kHz.

2. EXPERIMENTAL SETUP

The experimental setup is composed of two main parts: the interrogation unit and the sensing unit as shown in Figure 1a. In the interrogation unit, the sensing signal from laser L1, centered at 1550.5 nm, and the reference signal from laser L2, centered at 1530 nm, are coupled into a single optical fiber by a 50/50 ratio coupler. Both signals pass by an optical circulator and are transferred to the sensing unit. An optical attenuator was employed to simulate losses in the optical fiber link. Once in the sensing unit, the two signals are separated by an add/drop filter A1. While the sensing signal goes through the FBG under test, the reference signal is reflected by a mirror. The wavelength of L1 is tuned on the FBG edge when no mechanical stress is applied (Figure 1b). When the FBG response is displaced due to mechanical deformation, it envelopes L1 and more optical power is reflected by the grating. Both signals return to A1 and they are once again in the same fiber. The reflected signals go through the circulator back to the interrogation unit, where they are separated by the add/drop filter A2 and are detected by its respective photodetectors. The signals are then amplified by logarithm

24th International Conference on Optical Fibre Sensors, edited by Hypolito José Kalinowski, José Luís Fabris, Wojtek J. Bock, Proc. of SPIE Vol. 9634, 96347Q · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2192674

amplifiers, optimized for low input amplitudes. Finally, the reference signal is subtracted from the sensing signal to compensate attenuations. Two experiments were carried out with the setup shown in Figure 1a: (i) to demonstrate the low sensitivity of the output signal with the optical attenuation and (ii) to measure the time response of the proposed system and to compare it with a commercial FBG interrogator based on array of photo detectors technology. These results are presented in the next subsections.

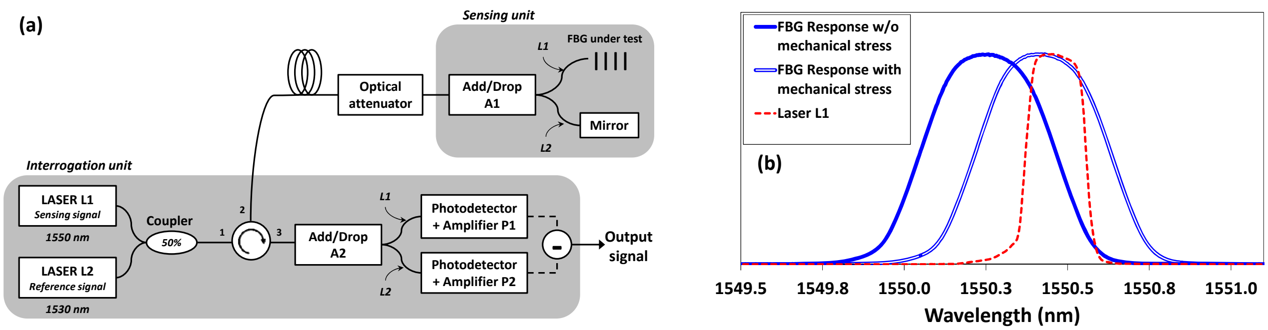

Figure 1. (a) Block diagram of the experimental setup. (b) FBG response along with the sensing laser position.

3. RESULTS AND DISCUSSION

For the first experiment, the FBG was attached to a Terfenol-D rod. This material suffers changes on its size when a magnetic field is applied to it, transferring this mechanical deformation to the grating and, therefore, constituting a magnetic field optical sensor. Using a rotating machine, a device was built to simulate the rotor of an electric generator. Four neodymium magnets were assembled on the machine's plate and the sensor was located on the fixed part of the machine, near the magnets. Figure 2a shows a photograph of the machine detailing the Terfenol-D rod and the FBG glued to it. With this scheme, the output signal was analyzed for different values of attenuation.

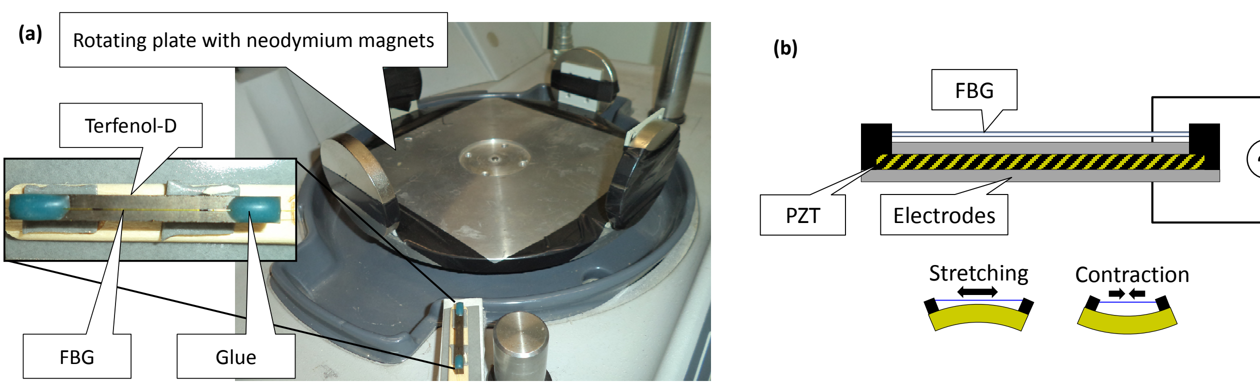

Figure 2. (a) Setup for testing the attenuation compensation. (b) PZT speaker and FBG used for the interrogation speed test.

Due to limited response time of Terfenol-D and the machine's maximum rotation speed of 70 rpm, for the second experiment an identical FBG was attached to a piezotransducer (PZT) speaker, as seen in Figure 2b, enabling high frequency measurements of the interrogation system. A sinusoidal signal was applied to the electrodes, with frequency varying from 10 Hz to 60 kHz and the output signal was monitored. This experiment was repeated using a commercial FBG interrogator (Ibsen I-MON USB 256) with maximum sampling rate of 6 kHz. The temporal responses of the PZT obtained with both systems were compared. The subsections below details the results obtained by each experiment.

3.1 Attenuation insensitivity experiment using a magnetic field sensor

Using the setup of Figure 1a with the sensing scheme of Figure 2a, the output signal was measured for different values of attenuation. Figure 3a shows the output signal when one of the neodymium magnets passes in front of the sensor. It can be noted that the amplitude of the signal is maintained independently of the attenuation applied. In Figure 3b, we can observe the variation of each signal (reference and sensing) as a function of the attenuation. The green line is the output signal (difference between the sensing signal and the reference).

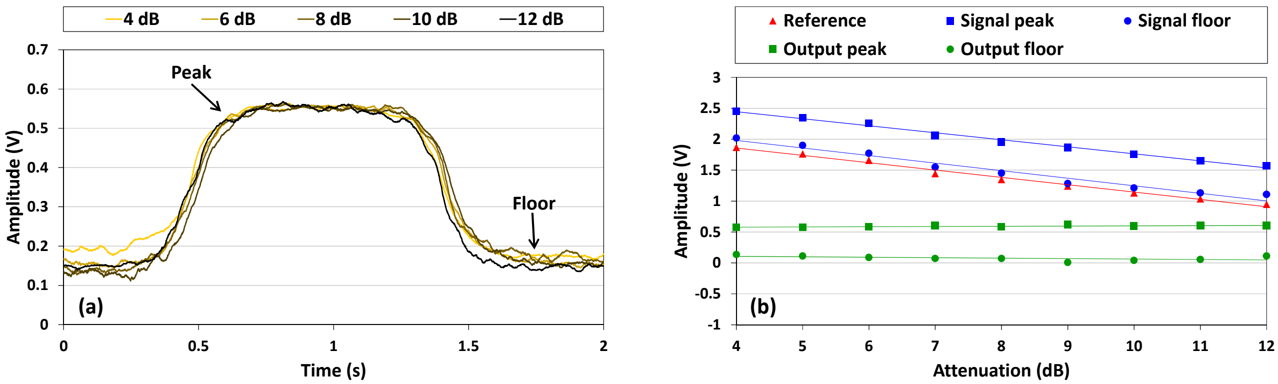

Figure 3. (a) Detection of one neodymium magnet with different attenuation levels. (b) Values of the peak and floor levels of the sensing, reference and output signals as a function of the attenuation.

To achieve these results, some improvements were made in the electronics concerning the photodetectors and the logarithm amplifiers from results previously reported[3]. Better quality components were used to reduce the noisy response of the amplifiers when low signals are applied to their inputs. Figure 4a shows the response of the set photodetector + amplifier as a function of the input optical power for the two channels used (sensing and reference channels). Along with the data, the error bars indicates the noise measured for each input power. Figure 4b shows a comparison between the prior[3] and present results. While in the previous work the output floor increased with greater attenuations, the present results shows that both the peak and floor amplitudes remained constant.

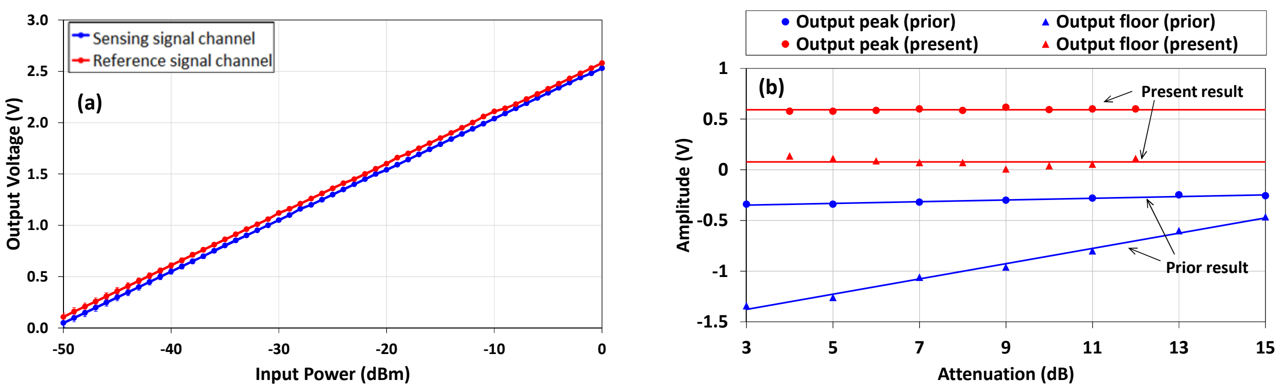

Figure 4. (a) Response of the set photodetector + amplifier. (b) Comparison between previous and current results

3.2 Interrogation speed measurement and comparison using a PZT as a vibration source

Besides improved response and insensitivity to fiber attenuations in the link, we also carried out response-time measurements of the proposed system and compared it to the response-time of a commercial interrogator available in our laboratory (Ibsen I-MON 256 USB). This was accomplished by applying a sinusoidal signal to the PZT speaker, with frequency varying from 10 Hz to 60 kHz. Differences between these methods can be observed when we analyze the output signal in time domain (Figure 5). Notice that when driving the PZT with 1 kHz, the commercial interrogator already shows a low resolution output (6 points per period) when compared to the signal obtained using the proposed system (Figure 5b).

In Figure 5c, the driving frequency is 6 kHz, the same value of the sampling frequency of the commercial interrogator. Therefore, the interrogator can sample only one point in each period of the output signal. As can be noticed, while the signal obtained by the proposed method is clearly visible, the signal obtained by the commercial interrogator is nearly a straight line. Figure 5d shows the response to a driving signal of 60 kHz. In this case, the sampling frequency is lower than the driving frequency, so the output signal from the commercial interrogator is not displayed correctly. However, the output signal from the proposed method can still be recovered.

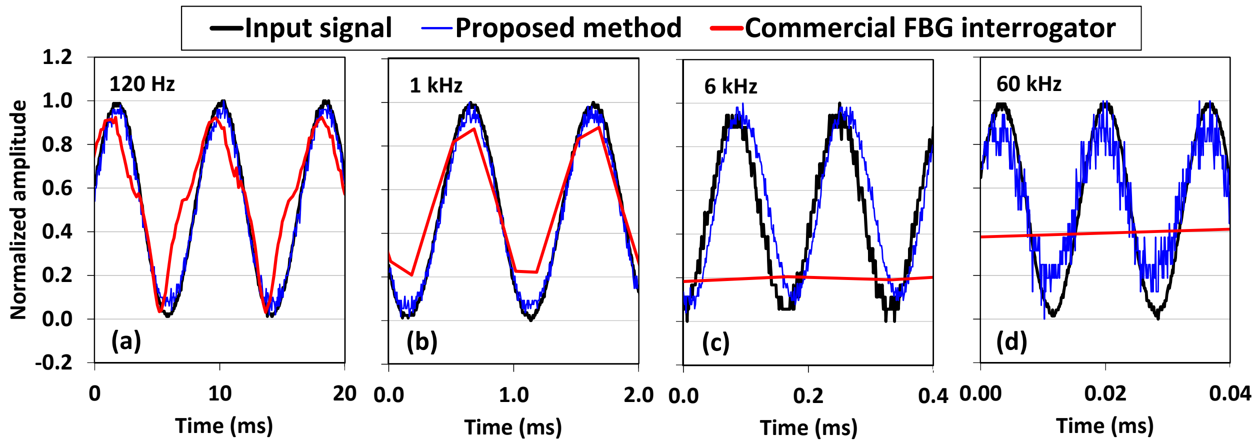

Figure 5. Comparison of the output signal obtained by the proposed method and by a commercial FBG interrogator with different driving frequencies. (a) 120Hz (b) 1kHz (c) 6kHz (d) 60kHz.

Although we measured output signals up to 60 kHz, the system is expected to respond to higher frequencies. This could be demonstrated by employing another technique to drive the mechanical deformation on the FBG, since the PZT speaker's response affects the bandwidth of this experiment. Furthermore, the maximum frequency of the proposed system is mainly dependent of the bandwidth of the logarithm amplifiers, which can be adjusted by controlling its gain.

4. CONCLUSION

We presented a high-speed FBG interrogation method insensitive to attenuations in the optical fiber that connects the sensor to the interrogator. Although the system was developed to monitor the magnetic field of power machines, it can be used in various other applications that employ FBG based sensing, such as vibration or temperature monitoring. It was demonstrated invariance to attenuations up to 12 dB and it was also shown that the proposed system is capable of detect frequencies up to 60 kHz. It is expected that the proposed system could properly respond even to higher frequencies by simply reducing the gain of the logarithm amplifiers. However to test system to higher frequencies, it is necessary to drive the mechanical deformation on the FBG using a different method, due to the bandwidth limitations of the PZT speaker.

ACKNOWLEDGEMENTS

This project was developed under the R&D program of Tractebel Energia and Itá Energética regulated by ANEEL (Brazilian Electricity Regulatory Agency), under number PD-0403-0038-2013.

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