Review

Dynamic Gratings in Optical Fibers: Synthesis and Sensing Applications

Zuyuan HE and Kazuo HOTATE

Department of Electrical Engineering and Information Systems, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

*Corresponding author: Zuyuan HE   E-mail: ka@sagnac.t.u-tokyo.ac.jp

Abstract: We proposed two schemes of generating and localizing dynamic gratings in optical fibers: one is based on the gain saturation in erbium-doped fiber; the other is based on Brillouin scattering in the fiber. By using these dynamic gratings, fully distributed strain/temperature sensors have been demonstrated. In this presentation, we review the principles, basic schemes, and experimental demonstrations of the novel dynamic grating techniques.

Keywords: Dynamic grating, fiber-optic sensor, distributed, strain sensor, temperature sensor

1. Introduction

It is well known that fiber Bragg grating (FBG) can be used as a strain or temperature sensor since its Bragg wavelength is highly and promptly sensitive to the variation of measurand. FBG sensors can also be multiplexed for structure health monitoring applications. In past several years, we proposed two schemes of synthesizing dynamic gratings in optical fibers: one is based on the gain saturation in erbium-doped fiber [1−3]; the other is based on Brillouin scattering in the fiber [4−6]. By using these dynamic gratings, fully distributed stain/temperature sensors have been demonstrated. In this presentation, we review the principles, basic schemes, and experimental demonstrations of the novel dynamic grating techniques.

2. Distributed strain/temperature sensing based on dynamic grating in polarization-maintaining erbium-doped fiber [1−3]

When two counter-propagating coherent light beams (referred to as writing beams hereafter) are launched into a pumped erbium-doped fiber (EDF), they interfere to each other and form stationary interference fringes in the fiber. The interference fringes then create a periodical gain structure per the phenomenon of gain saturation and hence produce a dynamic grating in the EDF. The period of the grating is a half of the writing beam's wavelength in the fiber. When a third beam is launched into the fiber (referred to as reading beam hereafter), it is reflected by the dynamic grating when its optical frequency (wavelength) is the same as the writing beams'.

For strain/temperature sensing, we formed the dynamic grating in polarization maintaining erbium-doped fiber (PM-EDF). PM-EDF has different refractive indices along two primary polarization axes. We wrote the dynamic grating along one polarization axis and read the grating along the other polarization axis, thus the detected Bragg reflection optical frequency (wavelength) is different from that of writing beams. When a strain or temperature change is applied to the fiber, the refractive index changes,

which results in the change of birefringence. Therefore, the Bragg reflection frequency shifts in proportion to the strain or the temperature change. We measured the dependence of the Bragg frequency shift with respect to strain/temperature. The results are shown in Fig. 1. These results exhibit good linearity and demonstrate a strain-sensitivity of $1.4\,\mathrm{MHz}/\mu\varepsilon$ and temperature-sensitivity of $60\,\mathrm{MHz}/^{\circ}\mathrm{C}$.

By using the technique of synthesis of optical coherence function (SOCF) [7], we formed the dynamic grating in a localized region and controlled the position of the region to sweep along the fiber. If the dynamic grating is not formed at the part of the fiber where the strain is applied, the strain does not have any effect on the Bragg reflection frequency. In this way, we can determine the strain location by sweeping the localized dynamic grating along the PM-EDF.

The experimental setup of distributed strain sensing with the localized dynamic grating is shown in Fig. 2. The reflection from the dynamic grating is quite weak and buried under various noises. To get rid of the noises, we developed a dual-stage synchronous signal processing method. We designed
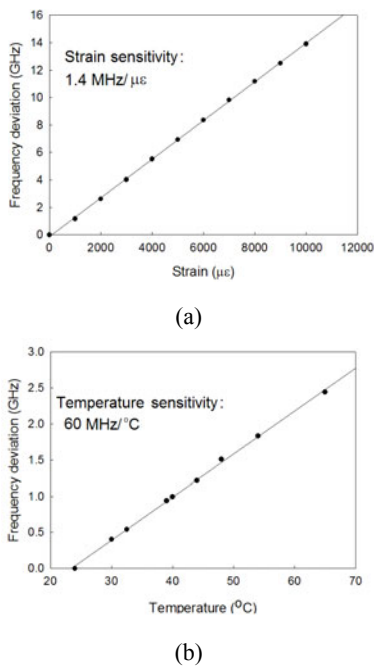
a scheme to switch the dynamic grating ON and OFF. In the ON-state, the dynamic grating is formed, and in the OFF-state is not. The ON-state is realized here by modulating the optical frequency of LD1 to localize the dynamic grating and sweep it along the fiber, while the OFF-state is realized by modulation to make the two writing beams not interfere inside the PM-EDF.

Figure 3 shows the reflection spectrum when the dynamic grating is swept along the fiber and we can see clearly the Bragg frequency shift through the strained section.
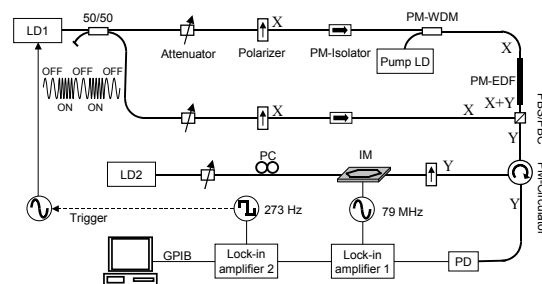

Fig. 2 Experimental setup: LD, laser diode; PC, polarizer controller; IM, intensity modulator; PD, photo-detector; PM-WDM, polarization-maintaining wavelength division multiplexer; PBS/PBC, polarization beam splitter / polarization beam combiner.
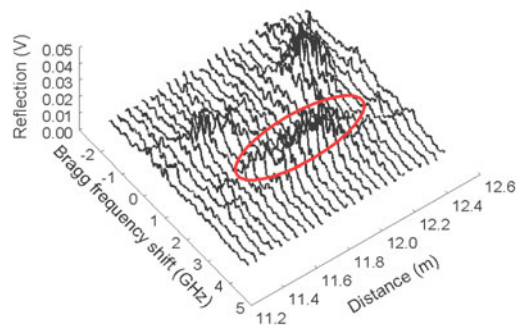

Fig. 3 Reflection spectrum when the dynamic grating is localized at different positions.

3. Distributed discriminative sensing of strain and temperature by using birefringence and Brillouin scattering in PMF [4−6]

Brillouin fiber-optic sensors have been investigated for decades and they show great

(a)

(b)

Fig. 1 Strain (a) and temperature (b) -dependence of Bragg frequency shift of the dynamic grating.

potentials in applications of smart materials and smart structures. The sensing mechanism is based on the linear dependences of Brillouin frequency shift (BFS) on strain or temperature. This common mechanism results in a trouble in discriminating the response to strain from that to temperature by using a single fiber.

We have demonstrated a novel method to discriminate the response to strain and that to temperature by simultaneously measuring the BFS and the birefringence in a PANDA-type polarization-maintaining fiber (PANDA-PMF). We have proved recently that, in the process of stimulated Brillouin scattering (SBS) in a PANDA-PMF, the acoustic wave generated by the counter-propagating pump-probe light waves along each principal polarization (*x*-polarization, slow axis; *y*-polarization, fast axis) has exactly the same displacement distribution in the fiber's cross section. This fact indicates a feasibility to generate a dynamic acoustic grating (DAG) via SBS processing. In our proposed novel method, at first, the changes of BFS along *x*-polarization are measured by pump-probe detection in order to provide a group of contributions from strain and temperature. Secondly, the DAG is maintained to its maximum by fixing the frequency of *x*-polarized probe light at the measured BFS. Then, a *y*-polarized readout light with ramp-swept frequency is launched into the fiber to detect the changes of the birefringence, which gives the second group of contributions from strain and temperature.
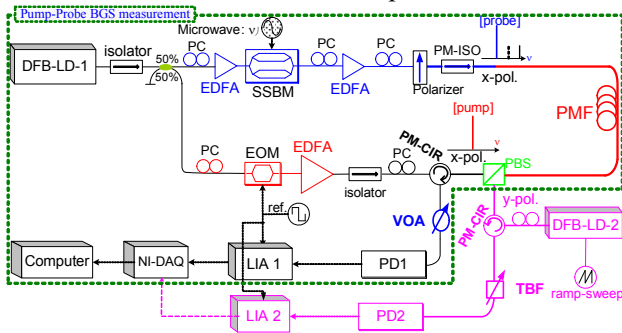

Fig. 4 Experimental setup of the proposed scheme to discriminate strain and temperature. The parts enclosed in the dotted box denote the pump-probe BGS measurement.
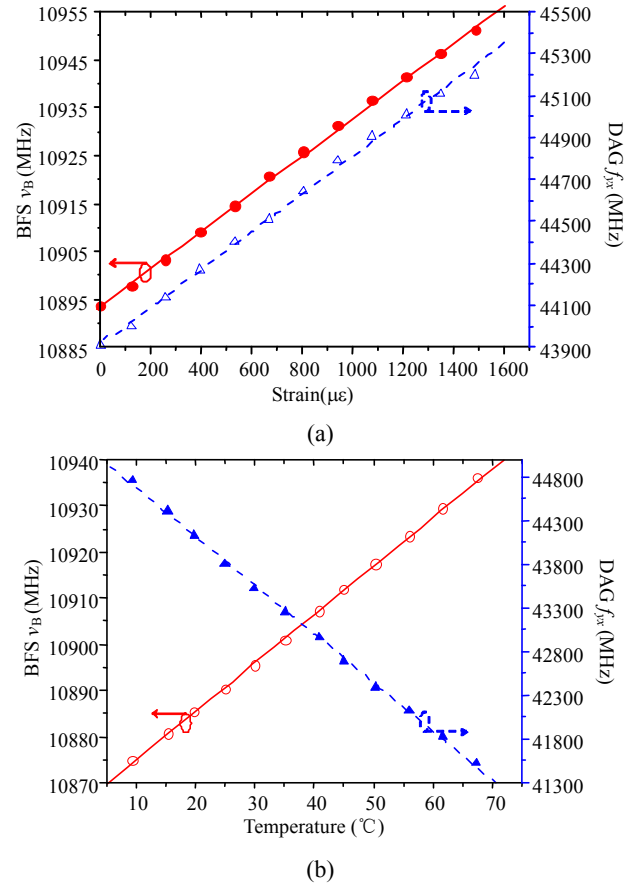

(a)

(b)

Fig. 5 Measured dependence of BFS and DGS frequency deviation on strain (a) and temperature (b).

The experimental setup to simultaneously measure BFS and DAG in a PANDA-PMF is depicted in Fig. 4. Within the dotted box the parts for *x*-polarization BGS measurement and DAG generation via SBS-based pump-probe scheme are shown. The PMF components are introduced to maintain the pump and probe lights propagating along *x*-polarization axis in the fiber under test (FUT). The PANDA-PMF is placed under controlled strain and temperature.

Figure 5 shows the measured dependence of BFS and DAG frequency deviation on strain (a) and temperature (b). The least-squares linear fitting to the detected strain dependence of the BFS v_B or the DAG f_{yx} gives the strain coefficient of the BFS ($C_v^\varepsilon =$ 0.03938 MHz/με) or that of the DAG f_{yx} ($C_f^\varepsilon =$ 0.8995 MHz/με). Similarly, we obtained the temperature coefficient of the BFS ($C_v^T =$

1.0580 MHz/℃) and that of the DAG f_{yx} ($C_f^T =$ −55.8134 MHz/℃). It is notable that the strain coefficient C_f^ε is positive while the temperature coefficient C_f^T is negative. This feature provides the possibility of high-precision discrimination. Our experiment demonstrated a reproducible accuracy of 3 με – 4 με and 0.02 ℃ – 0.03 ℃.

We also demonstrated the fully-distributed measurement by using the technique of SOCF as shown in Fig. 6. Four heated segments cascaded along the PMF sample are prepared and the detected distribution of BGS and the dynamic grating spectrum (DGS) from 2 m to 9 m are illustrated in Fig. 6(b). For the distributed measurement, the FM frequency for the light sources is scanned while the microwave frequency to SSBM or the *y*-polarized carrier frequency is ramp-swept for BGS or DGS characterization, respectively. Figure 6(c) concludes the characterized distribution of the temperature-induced different changes of the BFS ν_B and frequency deviation f_{yx} along the fiber. Repeatability test shows an accuracy as high as ± 0.7 MHz of the BFS ν_B and ± 11 MHz of the frequency deviation f_{yx}.
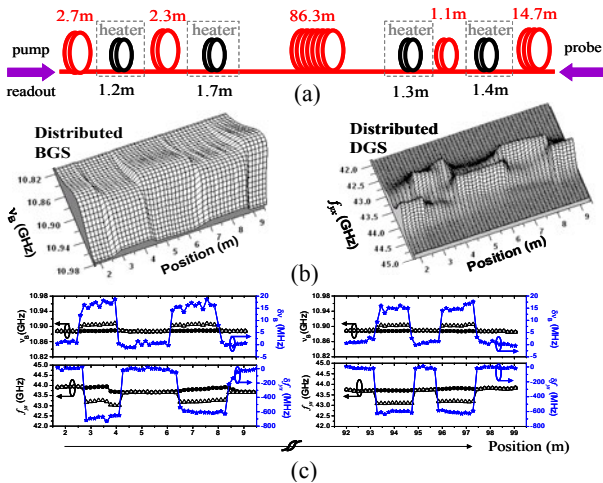

Fig. 6 Fully-distributed measurement results: (a) the prepared PMF sample, (b) 3D distribution of measured BGS and DGS, and (c) distribution of BFS ν_B (upper) or frequency deviation f_{yx} (lower) and their temperature-induced changes near the heated segments.

4. Conclusions

The principles, basic schemes, and experimental demonstrations of novel distributed sensing techniques based on synthesis of dynamic grating in optical fiber are reviewed.

We demonstrated experimentally a novel distributed fiber-optic strain sensor by localizing a dynamic grating in PM-EDF using the technique of SOCF with a spatial resolution of 20 cm. The performance of strain-sensitivity is 1.4 MHz/με, which is 28 times higher than SBS-based technology. We believe that the spatial resolution can be even improved.

We also demonstrated fully-distributed sensing by generating and localizing the SBS-induced dynamic grating. 1.2 m spatial resolution and 110 m measurement range have been successfully realized with system accuracy as high as ± 0.7 MHz for the BFS measurement and ± 11 MHz for the frequency deviation measurement.

Acknowledgment

References

[1] X. Fan, Z. He, and K. Hotate, "Novel distributed fiber-optic strain sensor by localizing dynamic grating in polarization maintaining erbium-doped fiber: proposal and theoretical analysis," *Jpn. J. App. Phys.*, vol. 44, no. 2, pp. 1101−1106, 2005.

[2] X. Fan, Z. He, and K. Hotate, "Novel strain-and-temperature-sensing mechanism based on dynamic grating in polarization-maintaining erbium-doped fiber," *Opt. Express*, vol. 14, no. 2, pp. 556−561, 2006.

[3] X. Fan, Z. He, and K. Hotate, "Distributed strain sensor based on dynamic grating in polarization-maintaining erbium-doped fiber," *Opt. Lett.*, vol. 33, no. 15, pp. 1647−1649, 2008.

[4] W. Zou, Z. He, and K. Hotate, "Complete discrimination of strain and temperature using

Brillouin frequency shift and birefringence in a polarization-maintaining fiber," *Opt. Express*, vol. 17, no. 3, pp. 1248−1255, 2009.

[5] W. Zou, Z. He, K. Y. Song, and K. Hotate, "Correlation-based distributed measurement of dynamic grating spectrum generated in stimulated Brillouin scattering in a polarization-maintaining optical fiber," *Opt. Lett.*, vol. 34, no. 7, pp. 1126−1128, 2009.

[6] K. Y. Song, W. Zou, Z. He, and K. Hotate, "All-optical dynamic grating generation based on Brillouin scattering in Polarization-maintaining fiber," Opt. Lett., vol. 33, no. 9, pp. 926-938, 2008.

[7] K. Hotate and Z. He, "Synthesis of optical coherence function and its applications in distributed and multiplexed optical sensing," *J. Lightwave Technol.*, vol. 24, no. 7, pp. 2541−2557, 2006 (Invited).