Implementation and characterization of polarimetric heterodyning fiber grating laser sensors

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Abstract: In this paper, we briefly review our recent work on polarimetric heterodyning fiber grating laser sensors, including the characterization, implementation, and multiplexing of the polarimetric sensors.

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1. Introduction

The polarimetric heterodyning fiber grating laser sensor converts the measurrand into a change in the beat frequency between the two orthogonal polarization modes from the fiber grating laser [1]. The polarimetric heterodyning fiber grating laser sensor possesses all the advantages of wavelength-encoded fiber grating laser sensor that responds to external perturbations in terms of shift in the operation wavelength of the laser, including small size, high accuracy, self-referencing and multiplexing capability. Because the beat frequency is in the radio frequency (RF) domain, the polarimetric heterodyning fiber grating laser sensor has a distinctive advantage of ease of interrogation. It does not require expensive wavelength measurement.

2. Response to temperature, axial strain, and lateral force

The polarimetric sensor requires the fiber grating laser to operate in two orthogonal polarization modes. When the laser output is monitored with a high speed photodetector, the two polarization modes generate a beat signal in the RF domain. The beat frequency is given by

$$\Delta \nu = \frac{cB}{2{n_0}^2\Lambda} \tag{1}$$

where c is the light speed in vacuum, n_0 and B are the average index and birefringence of the optical fiber, respectively, Λ is the grating pitch.

Deduced from Eq. (1), the temperature sensitivity can be expressed by

$$\frac{\delta(\Delta\nu)}{\delta T} = \Delta\nu\cdot\left[\frac{1}{B}\frac{\delta B}{\delta T} - (\alpha+2\beta)\right] \tag{2}$$

where α and β represent the thermal expansion coefficient and thermo-optic coefficient of silica glass, respectively. The item ($\alpha+2\beta$) depicts the effects of fiber elongation and the refractive-index change of silica glass. The item $\frac{1}{B}\frac{\delta B}{\delta T}$ denotes the normalized birefringence change induced by temperature variation. Theoretical analysis suggests that the temperature sensitivity can be a result of changes in both geometric and thermal-stress birefringence. Both the two kinds of birefringence decreases with temperature and therefore the beat frequency decreases with temperature. The temperature coefficient depends on the fiber dopant and fiber structure parameters, and so different fibers exhibit different temperature response. A polarimetric fiber grating laser sensor for simultaneous strain and temperature measurement was demonstrated [2]. The sensing head is formed by two concatenated ultra-short distributed Bragg reflector lasers inscribed in different active fibers. The total length of the sensing head is only 18 mm. The two lasers generate two beat notes which show different frequency response to strain and temperature. Simultaneous strain and temperature measurement was achieved by radio-frequency measurement.

The strain sensitivity can be derived from Eq. (1) as

$$\frac{\delta(\Delta\nu)}{\delta\varepsilon} = \Delta\nu\cdot\left[\frac{1}{B}\frac{\delta B}{\delta\varepsilon} - (1-2p_e)\right] \tag{3}$$

where p_e=0.22 is the effective elastic-optic coefficient to characterize the index change of silica glass and “1” represents the elongation. The item $\frac{1}{B}\frac{\delta B}{\delta \varepsilon}$ is the normalized birefringence change induced by the axial strain. Theoretical analysis shows that the effect of fiber elongation and material-index change expressed as (1-2p_e) in Eq. (3) can be compensated by the strain-induced birefringence change. As a result, zero strain sensitivity is possible. In the most recent experiment, strain-insensitive polarimetric fiber grating laser sensor has been demonstrated [3].

When a lateral force is applied to the laser cavity, an additional birefringence δB will be introduced into the active fiber and therefore the beat frequency will change. The lateral force introduced birefringence can be presented by [4]

$$\delta B = 2n_0^{\;3}(p_{11}-p_{12})(1+\nu_p)\,f\cos(2\theta)\big/\pi r E \tag{4}$$

where p_{11} and p_{12} are the components of strain-optical tensor of the fiber material, ν_p is Poisson's ratio, f denotes linear force (force per unit length), θ represents the angle of applied force direction with respect to the fast axis of the fiber, r is the fiber radius, and E is the Young's modulus of the silica fiber. Substituting Eq. (4) into Eq. (1), the lateral force induced beat frequency shift is given as

$$\delta(\Delta\nu) = \frac{2cn_0^{\;2}(p_{11}-p_{12})(1+\nu_p)\cos(2\theta)}{\lambda_0 \pi r E}f \tag{5}$$

Eq. (5) suggests that the beat frequency changes linearly with the lateral force. The maximum sensitivity as high as ~10 GHz/(N/mm) has been experimentally recorded [5].

3. Implementations of polarimetric fiber grating laser sensors

The polarimetric fiber grating laser sensors are very sensitive to lateral force when the loading direction is along the principle axes. Several photonic sensors based on the polarimetric fiber grating laser scheme have been demonstrated, in which the external perturbations are converted into birefringence change in the laser cavity by use of appropriate transducers.

Displacement sensor based on a fiber grating laser incorporated with a cantilever beam was demonstrated [6]. The laser cavity is positioned under the cantilever beam near the fixed end with the fiber axis perpendicular to the beam. When the free end of the cantilever beam is subjected to a vertical displacement, the fiber laser experiences a transversal force which changes the intra-cavity birefringence and therefore the beat frequency. The measured sensitivity coefficient was ~ 0.402 GHz/mm, which is close to the theoretical value, 0.424 GHz/mm. The result corresponds to a resolution of 2.5 nm, assuming the beat frequency measurement resolution is 1 kHz.

By attaching a mass at the free end of the cantilever beam, the same structure can be used as an acceleration sensor [7]. When the structure is subjected to acceleration or vibration, the mass causes a vertical displacement variation of the free end of the beam. As a result, a varying beat frequency signal will be detected.

Polarimetric fiber grating laser based current sensor was demonstrated by using a permanent magnet as transducer [8]. The magnet applies a lateral force onto the laser cavity due to the action of the magnetic field from an electric current. The beat frequency changes linearly in response to the electric current. The sensor is capable of measuring both dc and ac current. Although the sensor was tested in the laboratory by applying small current, the sensor is expected to be applicable for the measurement of large current passing through a single current line.

Polarimetric fiber grating laser hydrophones has also been developed. When an optical fiber is subjected to an acoustic field, its refractive index is modulated by the acoustic wave due to the photoelastic effect. For acoustic wavelength comparable with or much smaller than the fiber diameter, the acoustic pressure induces different index changes along and perpendicular to the direction of the acoustic wave and therefore changes the fiber birefringence. Therefore, the beat frequency is inherently sensitive to high frequency ultrasound (> 1 MHz) [9]. However, the acoustically induced birefringence at low acoustic frequencies is much smaller. To detect low frequency acoustic signal, appropriate transducer is required. A fiber optic low frequency acoustic sensor has been developed based on the integration of a polarimetric fiber grating laser and an elastic diaphragm [10]. The diaphragm transforms the acoustic pressure into transversal force acting on the laser cavity which changes the fiber birefringence and therefore the beat frequency.

4. Multiplexing of polarimetric fiber grating laser sensors

Multiplexing capability is an attractive feature of fiber grating laser sensors. To realize the multiplexing of polarimetric fiber grating laser sensors, each laser in the array is required to has not only a given wavelength but also a given beat frequency. One can easily write fiber grating lasers with different wavelength by using phase masks with different period. The difficulty lies in how to fabricate dual-polarization fiber grating lasers with different beat frequency.

A method to trim the beat frequency of the polarimetric fiber grating laser sensor is demonstrated by an additional exposure with the UV laser [11]. The UV-side-illumination can introduce an additional birefringence into the cavity fiber and therefore permanently changes the beat frequency. Three DBR fiber lasers were tested with three different exposing directions: exposing along slow axis, exposing along fast axis, and exposing at 45°. As a result, the beat frequency increased by 700 MHz after 1400 impulse by exposing to UV beam along the slow axis, decreases by about 450 MHz for along the fast axis. For the 45° exposure orientation, the beat frequency changes by only ~150MHz. Based on the above method, a sensor array has been demonstrated by cascading six DBR polarimetric fiber grating laser sensors in a single fiber.

5. Conclusion

In summary, we have reviewed the responses, implementation, and multiplexing of polarimetric fiber grating laser sensors. The responses of the sensors to temperature, axial stress, and lateral force have been characterized. The beat frequency is highly sensitive to lateral force, and several different sensors have been developed by using appropriate transducers to convert measurrands into lateral acting onto the laser cavity. A sensors array containing six polarimetric DBR fiber laser sensors has been demonstrated. Compared to wavelength-encoded fiber grating sensors or fiber grating laser sensors, a distinctive advantage of the polarimetric fiber grating laser sensors is its ease of interrogation. It does not require expensive wavelength measurement and can be treated with mature and cheap RF techniques.

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7. References

[1] G. A. Ball. G. Meltz, and W. W. Morey, "Polarimetric heterodyning Bragg-grating fiber-laser sensor," Opt. Lett., **18**, 1976-1978 (1993).

[2] Y. N. Tan, Y. Zhang, L. Jin, B. O. Guan, "Simultaneous strain and temperature fiber grating laser sensor based on radio-frequency measurement," Opt. Express, **19**, 20650-20656 (2011).

[3] L. Jin, Y. N. Tan, Z. Quan, M. P. Li, and B. O. Guan, "Strain-insensitive temperature sensing with a dual polarization fiber grating laser," Opt. Express, **20**, 6021-6028 (2012).

[4] S. C. Rashleigh, "Origins and control of polarization effects in single-mode fibers", J. Lightwave Technol., **1**, 312-331 (1983).

[5] Y. Zhang, B. O. Guan, and H. Y. Tam, "Characteristics of the distributed Bragg reflector fiber laser sensor for lateral force measurement," Opt. Commun., **281**, 4619-4622 (2008).

[6] Y. Zhang and B. O. Guan, "High-sensitivity distributed Bragg reflector fiber laser displacement sensor," IEEE Photon. Technol. Lett., **21**, 280-282 (2009).

[7] B. O. Guan, X. S. Sun, Y. N. Tan, "Dual Polarization fiber grating laser accelerometer," 4th European Workshop on Optical Fibre Sensors, Proc. SPIE, vol. 7653, Article Number: 76530Z, 2010.

[8] B. O. Guan and S. N. Wang, "Fiber grating laser current sensor based on magnetic force," IEEE Photon. Technol. Lett., **22**, 230-232 (2010).

[9] B. O. Guan, H. Y. Tam, S. T. Lau, and H. L. W. Chan, "Ultrasonic hydrophone based on distributed Bragg reflector fiber laser," IEEE Photon. Technol. Lett., **17**, 169-171 (2005).

[10] B. O. Guan, Y. N. Tan, and H. Y. Tam, "Dual polarization fiber grating laser hydrophone," Opt. Express, **17**, 19544-19550 (2009).

[11] Y. Zhang, Y. N. Tan, T. Guo, and B. O. Guan, "Beat frequency trimming of dual-polarization fiber grating lasers for multiplexed sensor applications," Opt. Express, **19**, 218-223 (2011).