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Study on the Characters of Phase-Shifted Fiber Bragg Grating in Asymmetric Perturbation and Its Application in Fiber Laser Acoustic Sensor

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Abstract: A π phase-shifted fiber Bragg grating theoretical model is established, and the effects of an asymmetric and symmetrical perturbation field on a phase-shifted fiber Bragg grating are investigated in this paper. The trends of wavelength shifting caused by effective refraction index of phase shift grating in symmetric and asymmetric acoustic field are investigated in detail. Then, the fiber laser acoustic sensors packaged in asymmetric and symmetrical structures are designed and tested, respectively. The results show that the acoustic response of the wavelength of the distributed feedback (DFB) fiber laser (FL) in an asymmetric packaging structure is much more sensitive than in that in the symmetrical structure. The sensor packaged in the asymmetrical structure has a better low frequency (0 Hz–500 Hz) performance and a higher sensitivity than that in the symmetrical structure, and the sensitivity is improved about 15 dB in average and 32.7 dB in maximum. It provides a new method to improve the sensitivity of the fiber acoustic sensor.

Keywords: Fiber acoustic sensor; phase-shifted fiber Bragg grating; asymmetric perturbation

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1. Introduction

Distributed feedback fiber lasers (DFB FLs) are used in the fiber laser acoustic sensor [1–4] and light source seeds [5–7] because of their high strain sensitivity, robust single frequency performance, low frequency noise, and multiplexing ability. It has attracted significant interest.

Some important properties of the DFB fiber laser have been researched recently, such as wavelength [6], linewidth [8], noise [5], and polarization [8, 9]. When it is used as a light seed to produce a high power and narrow linewidth laser, the wavelength stability is the most important aim. The wavelength character of the DFB fiber laser determines the quality of the light system. On the contrary, a fiber laser acoustic sensor requires the wavelength to be highly sensitive to external perturbations. The bare fiber laser has relatively low acoustic pressure sensitivity, so the enhancement of the sensitivity is the main topic by coating the bare fiber with some materials or structures designs [10–14]. Kersey *et al.* [15] and Koo *et al.* [16] reported that a narrow line-width fiber laser was selected as the sensing

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element, which was exposed to the acoustic environment in modulating its emission wavelength proportionally to its amplitude. Foster *et al.* [17] reported that poor resistance to bending capacity meant that the DFB fiber laser only required a small lateral force to cause a large degree of bending. Then in 2011, they reported a bender bar-based packaging scheme and pasted a DFB fiber laser on a flexible micro-machined beam, whose length was much less than that of the laser on silicon wafer, and demonstrated an excellent sensitivity in the order of 2 nm/MPa and the flat frequency response more than 5 kHz [18]. In 2013, Unnikrishnan *et al.* [19] reported that they utilized a thin large diaphragm-type package with novel engineering for pre-stress arrangement, and obtained a sensitivity of –160 dB ref rad/µPa and a flat response up to 5 kHz of operation. Launay *et al.* [20] demonstrated a wideband mechanical amplification design with high acoustic sensitivity. However, the complex nature of these packaging schemes made their fabrication and assembling difficult and expensive.

Most of coatings on the DFB fiber laser are implemented by using some material wrapped tightly. But those coatings generally may damage the laser due to the differential strain. Hence, its usefulness as an effective packaging for acoustic sensors is not much tested [21]. Another method is to enhance the strain of the DFB fiber laser by increasing the force bearing area. But the size of the sensor will increase and its high frequency response will lose.

All of those researches are under the premise that the DFB fiber laser device is in a symmetric perturbation field. The performance of a DFB fiber laser in an asymmetric perturbation field has not yet been reported to the extent of our knowledge.

In this paper, a π phase-shifted fiber Bragg grating theoretical model is established, and the effects of an asymmetric and symmetrical perturbation field on a distributed feedback fiber laser sensor are investigated. The trends of wavelength shifting caused by an effective refraction index of phase shift grating in symmetric and asymmetric acoustic field are investigated in detail. Then, DFB fiber acoustic sensors packaged in asymmetric and symmetrical structures are designed and tested, respectively.

2. Theory and methods

The configuration of a DFB fiber laser is shown in Fig. 1. It consists of a phase-shifted grating written on a short section of Er^{3+} doped fiber. Normally, the optical phase shift is $\pi/2$ and located at the center of the grating. When the DFB fiber laser is optically pumped with a light of shorter wavelength, it will emit stimulated emission with a narrow bandwidth at the wavelength of the band pass peak. Due to having short effective cavity length, most DFB fiber lasers can readily achieve single mode operation and stable output. The specific wavelength and line width are determined by the transfer function of the gratings and get narrowed due to the emission bandwidth of the active fiber.

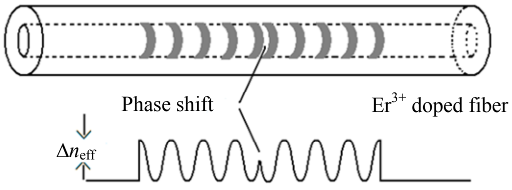


Fig. 1 DFB fiber laser configuration.

The transfer matrix method (TMM) is a commonly used tool for analyzing the reflection spectrum of fiber Bragg grating (FBG) and fiber phase-shifted grating [22, 23]. TMM can be used to represent the solutions of the coupled-mode theory, e.g. to construct the solutions of multi-sectional (separated into M sections in this paper) DFB structures within a phase-shifted regime between and facet reflectivity regimes at both ends [24]. By dividing the fiber grating into a large number of uniform pieces, the mode coupling of each piece can be expressed in a matrix form as

$$\mathbf{F}_i=\begin{bmatrix}\cosh(\gamma l)+i\dfrac{\hat{\sigma}}{\gamma}\sinh(\gamma l) & i\dfrac{k}{\gamma}\sinh(\gamma l)\\ -i\dfrac{k}{\gamma}\sinh(\gamma l) & \cosh(\gamma l)-i\dfrac{\hat{\sigma}}{\gamma}\sinh(\gamma l)\end{bmatrix} \quad (1)$$

where i is the number of each section, $0\leqslant i\leqslant M$. $\gamma=\sqrt{k^2-\hat{\sigma}^2}$, $\hat{\sigma}$ is the direct current (DC) coupling efficiency, and k is the alternating current (AC) coupling efficient, both of which are functions of effective refraction index n_{eff} and grating pitch $\varLambda$. For a phase-shifted grating, a phase shift matrix is inserted at the location of the phase shift as

$$\mathbf{F}_{\mathrm{shift}}=\begin{bmatrix}\exp(-i\varphi_i/2) & 0\\ 0 & \exp(i\varphi_i/2)\end{bmatrix} \quad (2)$$

where φ_i is the phase shift value.

To simulate the spectrum of the DFB fiber laser, we set the number of sections as $n=150$, phase shift as $\varphi_i=\pi/2$, and its position in the center as $n/2=75$. The final transfer matrix can be determined as follows:

$$\mathbf{F}_{\mathrm{shift}}=\prod_{j=0}^{j=n/2-1}\mathbf{F}_j\cdot\mathbf{F}_{\mathrm{shift}}\cdot\prod_{j=n/2+1}^{j=n}\mathbf{F}_j\,. \quad (3)$$

The final result can be got by imposing the boundary conditions [24]. As Fig. 2 shows, the lasing window will be located at the center of the grating. The effective refraction index increment is expressed as δ_n caused by external disturbing. The wavelength of the DFB fiber laser λ_{FL} is equal to the Bragg wavelength of the grating λ_{Bragg} and also equal to the wavelength of the lasing window.

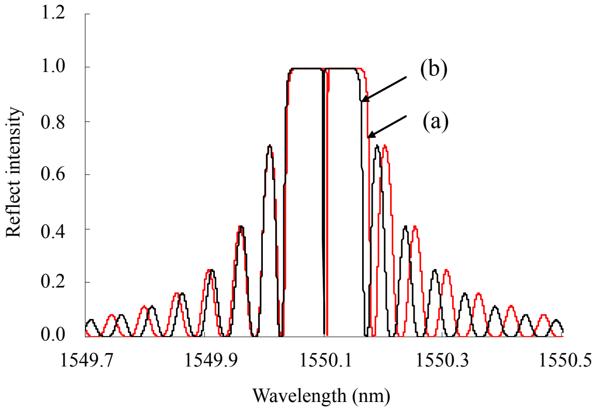


Fig. 2 Phase shift grating spectrum of the DFB fiber laser in a symmetric perturbation field n_{eff} = 1.449: (a) δ_n =0 and (b) δ_n =0.2.

3. Results and discussion

3.1 Simulation results

External perturbation will cause the DFB fiber laser to undergo dimensional and refractive index changing, which leads to a shift of lasing wavelength λ_{FL} [25]. In the presence of acoustic fields, due to the elastic-optic effect and acoustic-optical effect, the effective refraction index of the grating will be changed by external perturbation, thereby the reflection spectrum of the grating will be changed together. In a homogeneous field (as Fig. 3 shows), two sides of the DFB fiber laser (separated by a $\pi/2$ phase shift) are affected synchronously, which will make the effective refraction change synchronously. But in an asymmetric field (as Fig. 4 shows), two sides of the DFB fiber laser are affected asymmetrically. The results are completely different in these two conditions.

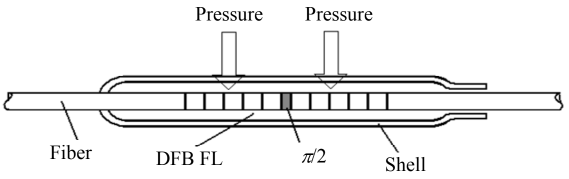


Fig. 3 Symmetrical structure of DFB fiber laser acoustic sensor.

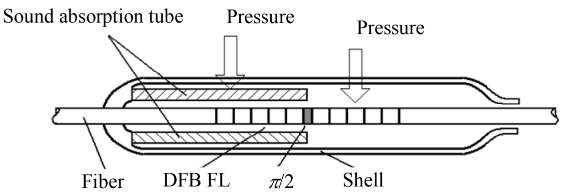


Fig. 4 Asymmetrical structure of DFB fiber laser acoustic sensor.

From Fig. 5 we can see that by increasing the effective refraction index increment δ_n from 0 to 0.2, the wavelength of the fiber laser λ_{FL} in a symmetrical field is changed from 1550.107 nm to 1550.094 nm, which decreases about 13 pm. A linear relation between λ_{FL} and δ_n is found, and the slope of the curve is –0.065. In the asymmetrical field, by increasing δ_n from 0 to 0.0005, λ_{FL} is changed from 1550.107 nm to 1550.0375 nm, which decreases nearly 70 pm. And a nonlinear relation between λ_{FL} and δ_n is found (as Fig. 6 shows).

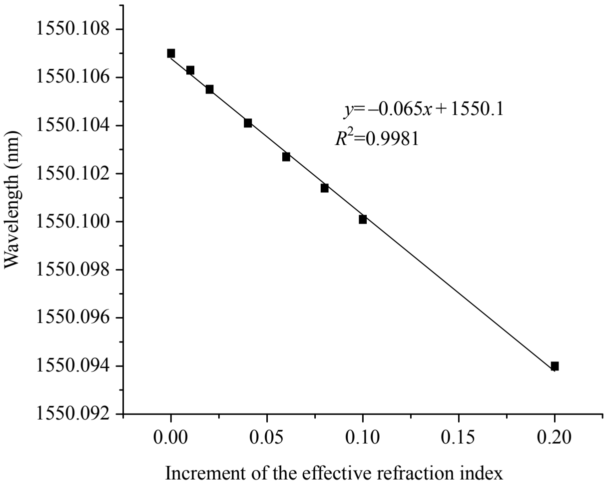


Fig. 5 Wavelength response curve in a symmetrical perturbation.

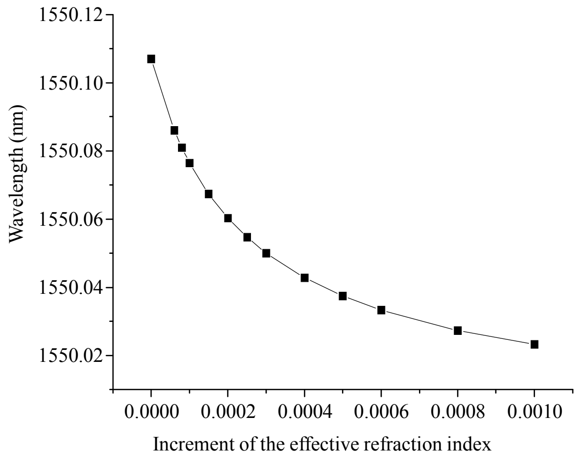
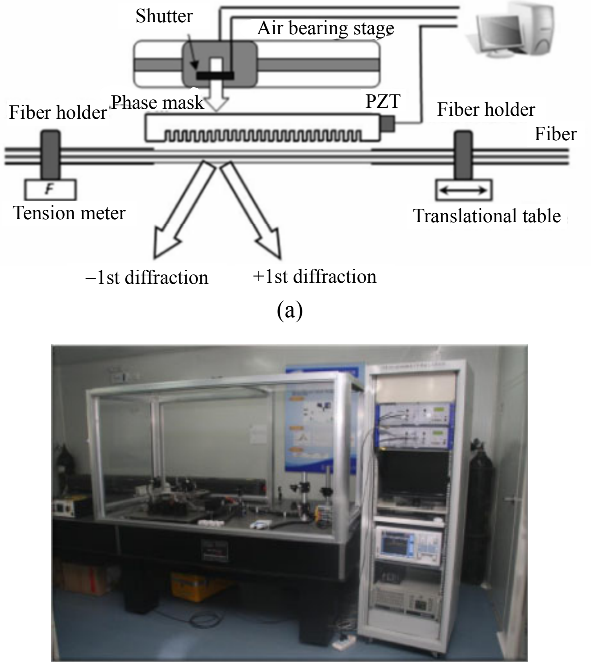


Fig. 6 Wavelength response curve in an asymmetrical perturbation.

It is well known that the wavelength of DFB fiber laser is sensitive to the axial strain (ε), and the slope of $\lambda_{FL} / \varepsilon$ is positive, which is opposite to λ_{FL} / δ_n. And axial strain is regarded as the main factors because it is obviously more effect. In general, δ_n can be neglected for its relatively smaller wavelength response than the axial strain in a uniform perturbation. But it can't be ignored in a non-uniform field such as asymmetrical perturbation discussed in this paper, because wavelength changes largely when the refractive index changes. Especially, when it is disturbed by an asymmetric horizontal force, the DFB fiber laser axial strain will become the secondary factor, while effective refraction index will be the leading factor in this case.

3.2 Application in fiber laser acoustic sensor

A polarization-dependent grating is generated by a vertically polarized ultraviolet (UV) scanning laser [26]. In the fabrication process, the phase shift is introduced by a movement of the phase mask to the fiber during beam scanning [27]. In this paper, we employ a UV laser (244 nm frequency-doubled harmonic Argon ion continuous wave laser) to write phase-shifted grating in the photosensitive Er^{3+} doped fiber (Nufern, the peak absorption at 1530 nm is 8 dB/m) by scanning UV beam across the phase mask (as Fig. 7 shows). The scanning speed of the UV laser is electrically controlled to obtain the desiring UV-induced index modulation amplitude. The phase mask is put on a piezoelectric transducer (PZT) moving stage with the nm-grade resolution and accuracy. The phase shift is introduced by an instantaneous movement of the phase mask to the fiber at the center of the phase-shifted grating, and the movement is $\Lambda/4$ for a $\pi/2$ phase shift.

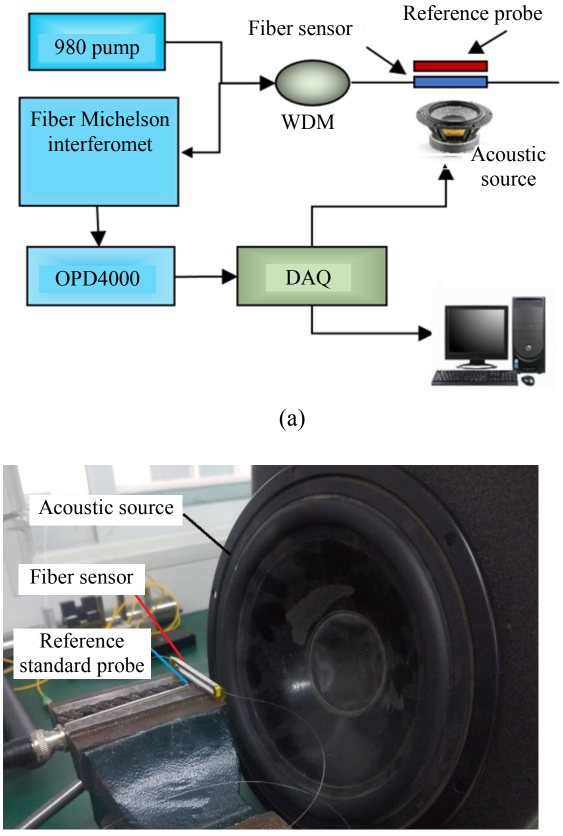


(a)

(b)

Fig. 7 Fabrication system of phase-shift grating using the phase mask: (a) structure diagram and (b) picture.

As Fig. 8 shows, we design a test system for the DFB fiber laser acoustic sensors. The DFB fiber laser sensor is pumped by a 980 nm semiconductor laser. The interferometric interrogation method is adopted to realize a high resolution wavelength shift demodulation. The wavelength shift of the fiber laser is converted into a phase shift by using an unbalanced interferometer. The interferometer is well packaged because the isolation of the interferometer is very important to prevent environmental perturbations such as temperature, noise and vibration. Phase-generated carrier (PGC) and 3-by-3 coupler is employed in the system [28]. Optical phase demodulator (OPD4000, supplied by Optiphase Inc.) can demodulate sensor's response. And a reference probe is put near the fiber laser acoustic sensor to revise deviation of the acoustic source.



(a)

(b)

Fig. 8 Test system of DFB fiber laser acoustic sensor: (a) structure diagram and (b) picture.

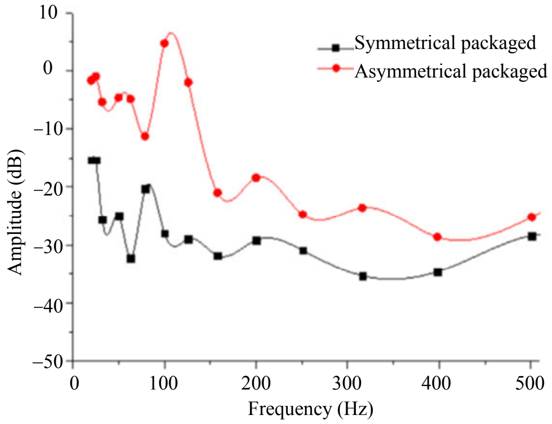


Fig. 9 Acoustic response of the DFB fiber laser acoustic sensor.

The DFB fiber laser acoustic sensors are packaged in the structures of Fig. 3 and Fig. 4, respectively. The test results are presented in Fig. 9. The test results show that the acoustic response of the acoustic sensor packaged in the asymmetrical structure has a better low frequency (0 Hz–500 Hz) performance and a higher sensitivity than that in the symmetrical structure. The sensitivity is improved about 15 dB in average and 32.7 dB in maximum. The resonance peak of the asymmetrical structure sensor is about 110 Hz, while symmetrical structure sensor is about 80 Hz.

4. Conclusions

We establish a π phase-shifted fiber Bragg grating theoretical model and investigate the effects of an asymmetric and symmetrical perturbation field on a phase-shifted fiber Bragg grating in this paper, and found that the asymmetric acoustic field would bring a greater effect to wavelength shifting. It can be utilized to improve the sensitivity of the fiber laser acoustic sensor. To verify it, we design two fiber laser acoustic sensor package structures, which are in asymmetric and symmetrical, respectively. The test results show that the acoustic response of the acoustic sensor packaged in the asymmetrical structure has a better low frequency (0 Hz–00 Hz) performance and a higher sensitivity than that in the symmetrical structure. The sensitivity of the acoustic sensor is improved about 15 dB on average and 32.7 dB in maximum in the asymmetric packaging structure.

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