Dual polarization fiber grating laser hydrophone

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Abstract: A novel fiber optic hydrophone based on the integration of a dual polarization fiber grating laser and an elastic diaphragm is proposed and experimentally demonstrated. The diaphragm transforms the acoustic pressure into transversal force acting on the laser cavity which changes the fiber birefringence and therefore the beat frequency between the two polarization lines. The proposed hydrophone has advantages of ease of interrogation, absolute frequency encoding, and capability to multiplex a number of sensors on a single fiber by use of frequency division multiplexing technique.

OCIS codes: (060.2370) Fiber optics sensors; (060.2840) Heterodyne; (060.3510) Lasers, fiber; (060.3735) Fiber Bragg gratings

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1. Introduction

Over the last three decades, a considerable amount of research effort has been spent on the development of the fiber optic hydrophones. Fiber optic hydrophones have distinctive advantages over conventional hydrophones, including high sensitivity, electrical passive operation, immunity to electromagnetic interference, and multiplexing capability. Most of the reported fiber optic hydrophones are based on interferometric techniques, where acoustic signal is converted into a change in the phase of light traveling in one arm of an interferometer [1,2]. Fiber optic interferometric hydrophones have advantage of high sensitivity; however suffer from complexity in sensor multiplexing. Although large scale multiplexing of interferometric hydrophones using wavelength and time division multiplexing has been demonstrated and reported, the required techniques are relative complicated [3]. Various fiber optic hydrophones based on intensity modulation were also demonstrated, including those utilize the principle of microbending [4], the lateral misalignment between two fiber ends [5], the frustrated total internal reflection [6], and the change of coupling ratio of fiber coupler in response to acoustic signals [7]. Recently, fiber optic hydrophones based on fiber Bragg grating [8–10] or fiber grating laser [11–13] have attracted attention. Their working principle is based on the change of operation wavelength of fiber Bragg gratings or fiber grating lasers in response to acoustic pressure. This type of sensor in principle has distinctive advantage of ease of multiplexing a number of sensors on a single fiber by use of wavelength division multiplexing technique. However, they suffer from the low sensitivity. The pressure induced wavelength shift for a bare fiber Bragg grating is only -3×10^{-9} nm/Pa [14]. Although the pressure sensitivity can be significantly enhanced by coating fiber Bragg grating or fiber grating laser with elastomer material [10,11] or incorporating them into appropriate structure [12], the interferometric detection is required to read out the small wavelength shift induced by acoustic signal. This greatly complicates the sensor multiplexing.

In this paper, we propose a novel fiber optic hydrophone based on fiber grating laser. The principle of the proposed hydrophone is different in nature from the reported wavelength encoded fiber laser hydrophones. It uses dual polarization fiber grating laser as sensing element and converts acoustic signal into a change in the beat frequency between the two polarization modes from the laser. The author has previously demonstrated a high frequency ultrasonic sensor based on the same principle [15], where the ultrasonic field is directly applied to a bare fiber grating laser, the sensor is only capable of working in frequency range above MHz. Here we present a hydrophone based on the integration of dual polarization fiber grating laser and elastic diaphragm for detecting low frequency acoustic signal. The proposed hydrophone has advantages of ease of interrogation, absolute frequency encoding, and capability to multiplex a number of sensors on a single fiber.

2. Principle

Both distributed Bragg reflector (DBR) fiber laser and distributed feedback (DFB) fiber laser are applicable for acoustic detection in the proposed principle. The requirement is that the laser emits two polarization modes. When the laser output is monitored with a high speed photodetector, the two polarization modes generate a beat signal in the radio frequency (RF) domain. The beat frequency is given by

$$\Delta \nu = cB/n_0\lambda_0 \tag{1}$$

where c is the light speed in vacuum, λ_0 is the laser wavelength, n_0 and B are the average index and birefringence of the optical fiber, respectively.

When the fiber grating laser is subjected to an acoustic wave, the acoustic pressure changes the fiber refractive index due to the photoelastic effect. In the case of acoustic wavelength comparable to or smaller than the fiber diameter, the acoustic pressure changes fiber birefringence due to different index modulation along and perpendicular to the

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propagation direction of acoustic wave [16]. Therefore, the polarization mode beat frequency is inherently sensitive to high frequency ultrasonic wave [15]. For acoustic wavelength much larger than the fiber diameter, the acoustic pressure induces an isotropic change in the fiber refractive index. According to Eq. (1), parameters that change the refractive index will also modulate the beat frequency. However, the index-pressure coefficient of the silica fiber is too small, so the beat frequency is inherently insensitive to acoustic signal in frequency range below several hundreds of kHz.

It has been demonstrated that the polarization mode beat frequency is highly sensitive to transversal force [17]. This provides a way to measure parameters that the beat frequency is inherently insensitive to by using appropriate transducers to convert the measurands into transversal force acting on the fiber grating laser. The proposed hydrophone employs an elastic diaphragm as transducer to induce transversal force on the laser cavity. Figure 1 shows the schematic diagram of the proposed hydrophone.

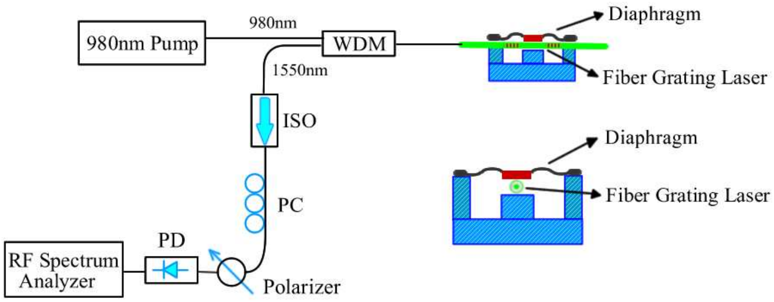

Fig. 1. Schematic diagram of the proposed fiber grating laser hydrophone.

The strength analysis of the corrugated diaphragm yields the acoustic pressure p induced transverse force F acting on the laser cavity to be

$$F = \frac{K_F A_F}{K_p A_p} \pi R^2 p \tag{2}$$

where A_p and K_p are the dimensionless stiffness coefficient of stretching non-linear item and bending stiffness coefficient caused by the hard core when uniform pressure acts on the diaphragm, A_F and K_F are the dimensionless stiffness coefficient of stretching non-linear item and bending stiffness coefficient caused by the hard core when concentrated force acts on the hard core, and R is the radius of the diaphragm.

The transversal force F induced shift in the beat frequency is given by [17]

$$\delta(\Delta \nu) = KF \tag{3}$$

where K is a constant related to the mechanical and geometrical parameters of the optical fiber. In our design, a DBR fiber laser is used and the transversal force F covers a length L_f less than the effective cavity length L_eff of the fiber laser. In this case, K can be expressed by

$$K = \frac{1}{L_\mathrm{eff}} \frac{2cn_0{}^2(p_{11} - p_{12})(1+\nu_\mathrm{p})\cos(2\theta)}{\lambda_0 \pi r E_\mathrm{f}} \tag{4}$$

where p_{11} and p_{12} are the stress-optical coefficients of the optical fiber, ν_p, E_f, and r are the Poisson's ratio, Young's modulus, and radius of the optical fiber, and θ is the angle of the force direction relative to the fiber polarization axis.

Using Eq. (2) in Eq. (3), we obtain that the relationship between the acoustic pressure and the shift in beat frequency is given by

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$$\delta\left(\Delta\nu\right) = K\frac{K_F A_F}{K_p A_p}\pi R^2 p \tag{5}$$

It is clear from Eq. (5) that the shift in beat frequency is a linear function of acoustic pressure.

3. Experiment and results

A dual polarization DBR fiber laser was fabricated by inscribing a pair of fiber Bragg gratings in Er-doped fiber with 193 nm excimer laser and phase mask. The Er-doped fiber has peak absorption of 11 dB/m at 980 nm. The fiber laser consisted of 3.8-mm-long low reflectivity grating, 6.5-mm-long high reflectivity grating, and 10 mm grating spacing. The total length of the fiber laser was 20.3 mm. The threshold for dual polarization lasing was about 5 mW. A corrugated diaphragm made from beryllium bronze was used as transducer. The radius of the diaphragm was $R = 15.7$ mm. A silicon slice with diameter of 6.7 mm was mounted to the center of the diaphragm to apply uniform press to the fiber laser cavity. According to Eq. (4), the sensor sensitivity depends on the angle θ between the force direction and the fiber polarization axis. To enhance the sensor sensitivity, the laser was positioned with the fiber polarization axis aligned to the force direction. The 980nm pump light was launched into the laser cavity from the low reflectivity grating side through a wavelength division multiplexer (WDM). The backward laser output was launched into a high speed photodetector (PD) through a polarization controller (PC) and an in-line polarizer. Figure 2 shows the output spectrum of the DBR fiber laser with pump power setting to 187 mW. The laser operated around 1536.8 nm with signal-to-noise ratio of ~65 dB. Figure 3 shows the beat signal spectrum of the DBR fiber laser measured with a radio frequency (RF) spectrum analyzer. The beat signal centered around 1755 MHz with signal-to-noise ratio better than 70 dB.

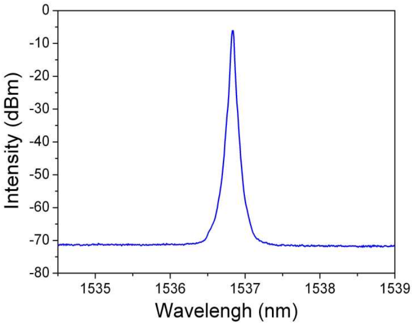


Fig. 2. Output spectrum of the DBR fiber laser.

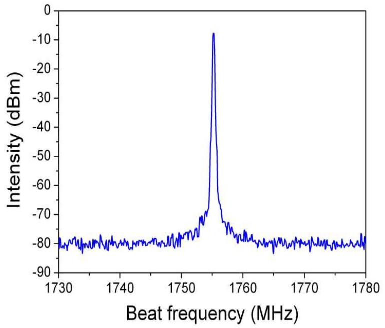


Fig. 3. Beat signal spectrum of the DBR fiber laser.

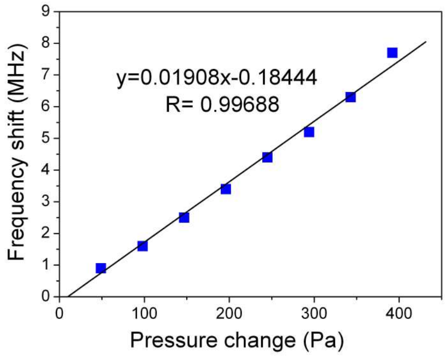
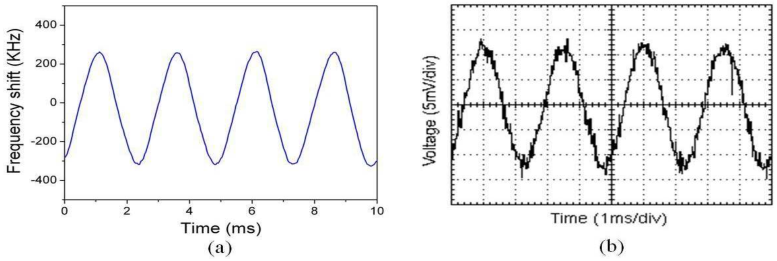


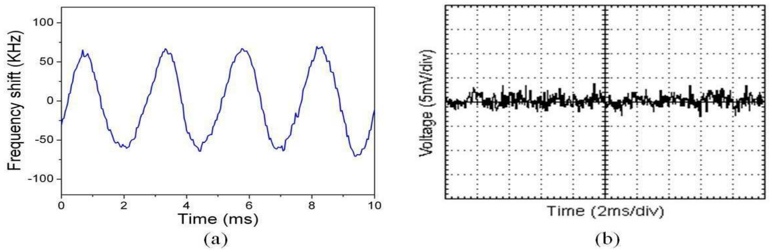
Fig. 4. Static pressure response of the fiber grating hydrophone.

The response of the fiber laser hydrophone to static pressure was investigated by installing the sensor in the bottom of a water tank. The static pressure was changed by varying the height of the water, while the beat frequency was monitored with the RF spectrum analyzer. The experimental results are plotted in Fig. 4. As expected, the beat frequency changes linearly in response to the applied pressure. The sensitivity coefficient was estimated, by linearly fitting the experimental data in Fig. 4, to be 0.019 MHz/Pa. From Eq. (5), the sensitivity coefficient was theoretically calculated to be 0.133 MHz/Pa, which is 7 times higher than the experimental result. A possible cause of the discrepancy may be that bonding the diaphragm with epoxy results in a change in mechanical properties of the diaphragm.



(a) (b)

Fig. 5. Output waveform of (a) the fiber laser hydrophone and (b) PZT hydrophone at 400 Hz, 2.7 Pa.



(a) (b)

Fig. 6. Output waveform of (a) the fiber laser hydrophone and (b) PZT hydrophone at 400Hz, ~0.2 Pa.

The dynamic response of the fiber laser hydrophone was investigated by applying acoustic pressure to the sensor head in water. A commercial piezoelectricity (PZT) hydrophone with sensitivity of −167 dB re V/μPa and unflatness of less than 0.4 dB in the range from 10 Hz to 1000 Hz was used as a calibration reference. The acoustic wave was generated by a speaker which was driven by sinusoidal signals. The output waveform of the fiber laser hydrophone was monitored with the FM-demodulated waveform display function of the RF spectrum analyzer. The output of the PZT hydrophone was monitored with an oscilloscope. Figure 5 and Fig. 6 show the output waveform of the fiber laser hydrophone and the PZT hydrophone at 400 Hz with different driven voltage applied to the speaker. The acoustic pressure was estimated, from the PZT hydrophone, to be 2.7 Pa and ~0.2 Pa, respectively, for Fig. 5 and Fig. 6. It is clear that, the fiber laser hydrophone provides ideal sine waveform without distortion, and the fiber grating laser hydrophone exhibits much higher sensitivity than the PZT hydrophone. The RF spectrum analyzer used in the experiments is capable of displaying FM-demodulated waveform with a minimum frequency offset of 10 kHz, corresponding to a minimum detectable signal of 0.03 Pa (at 400 Hz). Figure 7 shows the frequency response of the fiber laser hydrophone calibrated with the PZT hydrophone. The response exhibits a ± 7 dB variation across the measurement bandwidth.

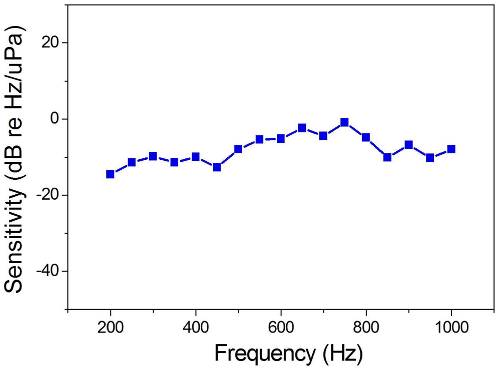


Fig. 7. Frequency response of the fiber laser hydrophone

The minimum detectable signal relies on both response sensitivity of the sensor head and readout capability of the demodulation system. The detection ability of the fiber laser hydrophone here was limited in part by the readout resolution of the built-in FM-demodulation function of the RF spectrum analyzer. We are now developing high resolution beat frequency measurement system. The sensor head sensitivity is dependent on both the transducer design and the fiber grating laser itself. According to Eq. (4), the sensor sensitivity can be increased by reducing the fiber cladding diameter. Much lower acoustic pressure is expected to be detectable by optimizing the sensor head and employing high resolution interrogation system.

The beat frequency is sensitive to temperature with coefficient of −1.38 MHz/°C [15]. In contrast to acoustic signal, temperature is a slow changing parameter. Therefore, temperature effect is not an issue for practical applications. The small size of the fiber laser hydrophone makes it a potential candidate for towed hydrophone arrays. For this application, cross-sensitivity to acceleration is an important consideration. Further works are to characterize the acceleration response, and to optimize the sensor head design to improve the sensitivity and frequency response.

Although fiber grating laser sensors are ideally suited to wavelength division multiplexing, there are some issues arising from the active nature of the device that limit the number of sensors, such as cross talk between lasers, pump depletion, and sensor power equalization, need to be addressed for applications requiring large-scale multiplexing of sensors.

4. Conclusion

A novel fiber optic hydrophone based on the integration of a dual polarization fiber grating laser and a diaphragm has been demonstrated. The principle is based on the change of the beat frequency generated by the two polarization lines from the fiber laser in response to acoustic pressure. Because the beat frequency is in RF frequency range, the hydrophone can be

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interrogated with the well-developed FM demodulation technique that is commonly used in RF test and measurement. The distinctive advantages of the proposed hydrophone include ease of interrogation, absolute frequency encoding, and capability to multiplex a number of sensors on a single fiber.

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