Ultrasonic Hydrophone Based on Distributed Bragg Reflector Fiber Laser

Bai-Ou Guan, Hwa-Yaw Tam, Sien-Ting Lau, and Helen L. W. Chan

***Abstract*—We demonstrate a novel fiber-optic hydrophone that uses a dual polarization distributed Bragg reflector (DBR) fiber laser as sensing element. The operation principle is based on the modulation of the birefringence of the fiber laser by high-frequency ultrasound. By measuring the amplitude and frequency of the sidebands as well as the polarization beat frequency of the output of the fiber laser using a photodetector and a radio-frequency spectrum analyzer, the amplitude and frequency of the acoustic pressure, and temperature can be determined simultaneously. The DBR fiber laser hydrophone has a linear response to acoustic pressure and can detect acoustic frequency up to at least 40 MHz.**

***Index Terms*—Acoustic sensor, Bragg grating, fiber laser, hydrophone, optical fiber transducers.**

I. INTRODUCTION

ULTRASONIC hydrophone has been attracting considerable interest due to the needs for characterization of medical ultrasonic equipment and safety assessment of patient exposure. Existing methods for measuring ultrasonic field is mostly based on the use of polyvinylidene fluoride (PVDF) hydrophone. However, this type of hydrophone is susceptible to electromagnetic interference and cannot withstand high ultrasonic power level. Furthermore, PVDF hydrophone with small active element, necessary for resolving narrowly focused ultrasonic beam, is not easy to fabricate. On the other hand, fiber-optic hydrophones are immune to electromagnetic interference and very small in size, and can withstand high ultrasound power. Several fiber-optic sensing schemes have been reported, including interferometric techniques [1]–[3], polarimetric techniques [4]–[6], and fiber grating techniques [7], [8]. Fiber grating hydrophone encodes acoustic pressure into the grating reflection wavelength and, therefore, allows many sensors to be wavelength-division multiplexing (WDM). Hitherto, the reported detection bandwidth of fiber grating hydrophones is less than 4 MHz [7].

In this letter, we demonstrate a novel fiber-optic hydrophone that uses a distributed Bragg reflector (DBR) fiber laser as the sensing element. Although acoustic sensors based on fiber grating laser were reported in [9] and [10], their operation principle is similar to that of the fiber grating hydrophone. Instead of modulating the relatively broad reflection signal (typically 0.2 nm) of the fiber gratings, acoustic pressure modulates the higher power and much narrower linewidth of the output of the fiber lasers. This offers much higher detection sensitivity and better resolution. The principle of the proposed hydrophone is based on the modulation of the birefringence of the laser cavity by acoustic pressure and consequently the beat frequency of the two orthogonal polarization modes of the fiber grating laser in response to the high-frequency ultrasound. It is capable of measuring ultrasound up to several tens of megahertz. This technique is much simpler and obviates the use of unbalanced interferometer and phase modulator that are required in pseudoheterodyning fiber grating (laser) hydrophones [8]–[10], and therefore, greatly simplify signal extraction. The frequency and amplitude of ultrasound as well as temperature can be determined simultaneously by measuring the amplitude and frequency of the sidebands, and polarization beat frequency of the laser output using a relatively inexpensive photodetector and a commercial radio-frequency (RF) spectrum analyzer. One of the advantages of this technique is that no expensive absolute wavelength measurement is needed.

II. PRINCIPLE

The DBR fiber laser consists of a pair of wavelength-matched Bragg gratings written in an active fiber with appropriate separation. It operates in two orthogonal eigen-polarization modes due to the fiber birefringence introduced during fiber fabrication and grating inscription. The frequency difference between the two modes is given by

$$\Delta\nu = \frac{B\nu}{n} \tag{1}$$

where ν is the lasing frequency, B and n are the birefringence and refractive index of the optical fiber, respectively. The polarization beat frequency $\Delta\nu$ of the laser can be measured with a photodetector and an RF spectrum analyzer. When the DBR fiber laser is subjected to an acoustic field, the acoustic pressure changes the fiber refractive index owing to the photoelastic effect. For an acoustic wavelength much larger than the fiber diameter, the induced index change is isotropic, whereas for an 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. In the case

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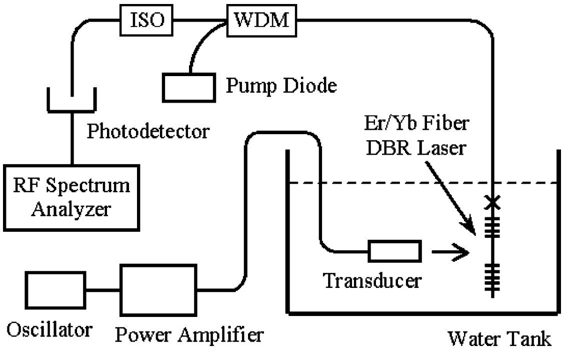

Fig. 1. Schematic diagram of the experimental setup. ISO: Optical isolator.

that a high-frequency (>1 MHz) plane ultrasonic wave is incident normally upon a fiber, the induced change in birefringence is given by [5]

$$\Delta B = kp_a \sin \omega_a t \cos 2\theta \tag{2}$$

where k is a constant depending on the acoustic frequency, and the photoelastic coefficients and refractive index (seen by the ultrasonic wave) of the optical fiber. p_a and ω_a are the amplitude and angular frequency of the acoustic pressure, respectively. θ is the angle between the polarization axis of the fiber and the propagation direction of the acoustic wave. Hence, ultrasound results in frequency modulation of the beat carrier produced by the fiber laser. By measurement of the frequency and the amplitudes, relative to the carrier of the upper and lower sideband components, the angular frequency and the amplitude of the acoustic pressure can be determined simultaneously. In most practical situations, the acoustic pressure along the fiber is not uniform. Provided that the fiber is parallel to the acoustic wavefront (i.e., the line of constant phase), the induced beat frequency change is given by

$$\delta\Delta\nu = \Delta\nu \frac{k\int_0^L p_a dl}{BL} \cos 2\theta \sin \omega_a t \tag{3}$$

where L is the cavity length of the DBR fiber laser. Therefore, the readout of the sensor is the line integral of the acoustic pressure amplitude across the laser cavity.

The DBR fiber laser hydrophone is capable of simultaneous temperature and ultrasound measurement. From (1), the polarization splitting $\Delta\nu$ is a function of the lasing frequency ν, fiber birefringence B, and fiber refractive index n, all of which are temperature-dependent. Consequently, $\Delta\nu$ changes with temperature [11]. In contrast to ultrasound pressure, temperature is a very slow changing parameter. It induces a shift in the frequency of the carrier. Therefore, simultaneous measurement of these two parameters can be easily achieved.

III. EXPERIMENT AND RESULTS

The experimental setup is shown in Fig. 1. The DBR fiber laser was constructed with an Er–Yb codoped fiber. Two 1550-nm gratings were written into the doped fiber with a separation of 10 mm. The length of one grating was 10 mm long and had a reflectivity of larger than 99%, while another grating was 3 mm long and had a reflectivity of around 90%. The 980-nm pump light was launched from the 3-mm-long grating side through a WDM. An optical isolator was placed at the laser output to eliminate any unwanted reflection. The laser operated robustly in single longitudinal mode and dual polarizations with frequency difference of 854 MHz. The optical components (isolator, WDM, and fibers) connecting the fiber laser to the detector introduce some transformations to the polarization state of the orthogonal eigenmodes generated by the fiber laser and, thus, beating between these eigenmodes occurs at the detector. When the fiber laser was pumped with about 46 mW, a beat signal with a carrier-to-noise ratio of 58 dB was recorded, as shown Fig. 2(a). The output power of the DBR fiber laser was 2.5 mW.

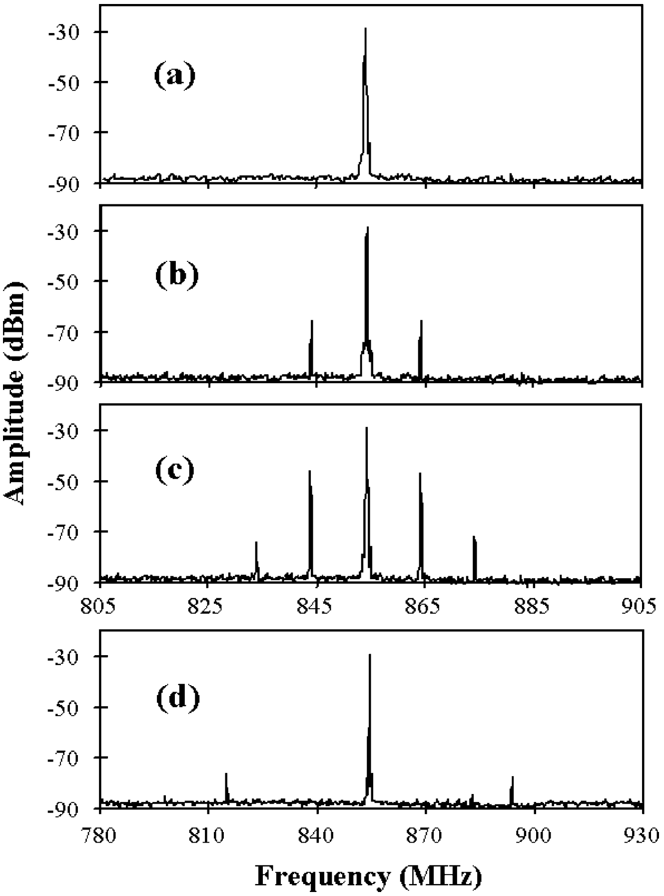

Fig. 2. Beat signal spectra of the DBR fiber laser as the acoustic transducer was driven at different voltages and frequencies. (a) No (0 V) driving voltage. (b) 0.1-V driving voltage at 10 MHz. (c) 1.0-V driving voltage at 10 MHz. (d) 8.5-V driving voltage at 40 MHz.

In the experiment, the DBR fiber laser was fixed on a metal frame and placed inside a water tank. A plane ultrasound field generated by a transducer (Panametrics V312) with diameter of 6.35 mm and center frequency of 10 MHz, was driven in continuous mode. The water tank was lined with sonic absorbent rubber to avoid reflection of the ultrasound. The fiber laser was positioned in the near field of the transducer perpendicular to the ultrasound propagation direction. Fig. 2(b) and (c) shows the beat signal spectrum recorded by the spectrum analyzer when the acoustic transducer was driven at 10 MHz with different driving voltage. As expected, sidebands appeared as the DBR fiber laser was subjected to the ultrasound, and the sideband

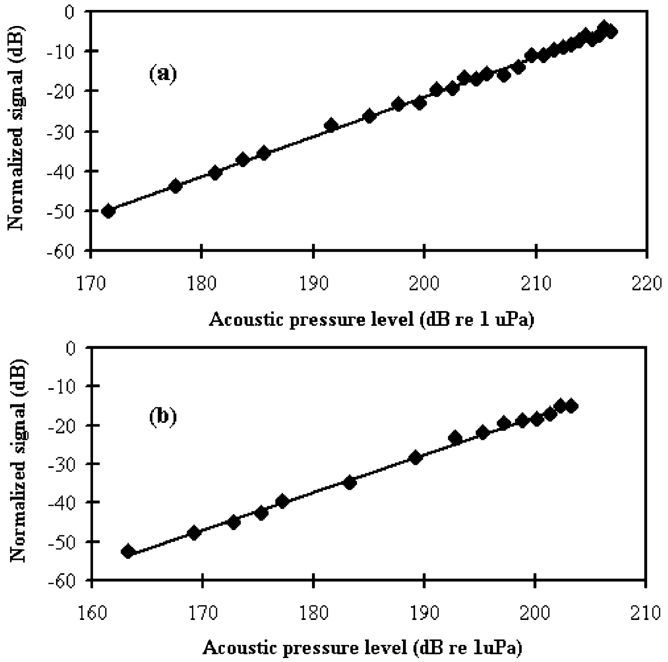

Fig. 3. Magnitude (normalized with the carrier magnitude) of the first-order sideband versus ultrasound pressure level at (a) 10 and (b) 20 MHz.

signal increases with the amplitude of the ultrasound. Fig. 3(a) and (b) shows the responses of the DBR laser hydrophone at 10 and 20 MHz, respectively. A linear relationship between the measured magnitude (normalized with the carrier magnitude) of the first-order sideband and the ultrasound pressure was obtained. Using the measured carrier-to-noise ratio in Fig. 2 and the curve in Fig. 3, the minimum detectable pressure level was calculated to be 164 dB re 1 μPa and 158 dB re 1 μPa at 10 and 20 MHz, respectively. It is expected that the fiber laser hydrophone is capable of detecting ultrasound of much higher frequency. Fig. 2(d) shows a beat signal spectrum when the acoustic transducer was driven at 40 MHz. The specified operating frequency of the Panametrics V312 transducer is 10 MHz and, therefore, the acoustic pressure generated at 40 MHz is very small. Our experimental setup was, thus, limited to investigate ultrasound frequencies up to about 40 MHz.

Fig. 4 shows the measured carrier frequency dependence with temperature. Since the fiber refractive index increases while both the lasing frequency and the fiber birefringence decrease with increasing temperature, the carrier frequency is inversely proportional to temperature. Linear regression fit to the data yields a temperature coefficient of -1.38 MHz/°C.

IV. CONCLUSION

We have demonstrated a dual polarization DBR fiber laser-based ultrasonic hydrophone. The operation principle is based on the modulation of the birefringence of the fiber laser by ultrasound pressure. The frequency and amplitude of ultrasound as well as temperature can be determined simultaneously by measuring the amplitude and frequency of the sidebands, and polarization beat frequency of the laser output using a photodetector and a commercial RF spectrum analyzer. We have also demonstrated that DBR fiber laser sensor can detect ultrasound with frequency up to 40 MHz. The advantages of this sensor include ease of interrogation, multiplexibility using WDM technique, and the avoidance of expensive absolute wavelength measurement.

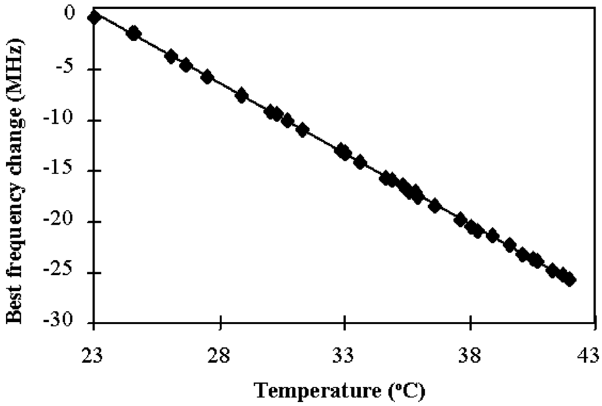

Fig. 4. Carrier frequency change versus temperature.

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