High-Frequency Ultrasonic Hydrophone Based on a Cladding-Etched DBR Fiber Laser

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***Abstract*—Distributed-Bragg-reflector (DBR) fiber-laser-based ultrasonic hydrophone has been found to possess increased detectable frequency range due to the improved sensitivity in the high-frequency region when the fiber cladding thickness was reduced. A wet etching technique is utilized to reduce the fiber diameter of the DBR laser. The peak response frequency moves from 21 to 40 MHz when the fiber diameter was reduced from 125 to 68 μm.**

***Index Terms*—Fiber Bragg grating, fiber laser, fiber-optic sensor, ultrasonic hydrophone.**

I. Introduction

ULTRASOUND has become indispensable in some applications, e.g., clinical imaging in cardiology, obstetrics, and gynecology. Medical imaging at frequencies higher than 15 MHz has become very important in clinical applications that require high resolution [1], [2]. In order to characterize the acoustic signal from a high-frequency transducer, hydrophones with high detection sensitivity and good lateral resolution are required.

In recent years, optical fiber sensors have attracted considerable interest for the detection of ultrasound as they have many advantages over conventional hydrophones based on piezoelectric effect [3], [4]. The merits of optical fiber sensors include small size, light weight, immunity from electromagnetic interference, and multiplexing capability. Chiang *et al.* [5] demonstrated a polarimetric ultrasonic sensor using a polarization-maintaining fiber. Lovseth *et al.* [6] reported a distributed feedback fiber laser for sensing ultrasound in air. Cox *et al.* [7] proposed an ultrasound sensing method based upon the detection of acoustically induced changes in the optical thickness of a Fabry–Pérot polymer film sensing interferometer.

Ultrasonic hydrophone based on a distributed Bragg reflector (DBR) fiber laser was demonstrated and patented by Guan *et al.* [8] and Tam *et al.* [9]. In that design, the DBR fiber laser formed by two Bragg gratings inscribed in an Er–Yb-codoped fiber operates in two orthogonal polarization modes because of the small fiber birefringence, introduced during grating fabrication by an ultraviolet side writing technique in the circularly symmetric structure of the fiber. Since the two polarization laser modes have a small wavelength difference corresponding to the fiber birefringence, polarization-mode beat (PMB) signal is generated. When a high-frequency ultrasonic pressure is applied to the surface of the fiber, the fiber birefringence is changed by the ultrasound-induced transverse pressure owing to the photoelastic effect. For an ultrasonic wavelength comparable with or smaller than the fiber diameter, the fiber becomes anisotropic and additional birefringence is introduced [5]. Consequently, the frequency of the PMB signal is modulated by the ultrasonic field, resulting in sideband frequency components with the frequency intervals and amplitudes related to the frequency and amplitude of the ultrasound, respectively. By measuring the sideband frequency components with a high-speed photodetector (PD) and a commercial radio-frequency (RF) spectrum analyzer, the ultrasonic signal can be determined. Compared to other optical detection approaches, the DBR fiber laser sensor is able to detect high-frequency ultrasonic field, up to about 50 MHz, with good sensitivity.

In this letter, we study the frequency response of the DBR fiber laser ultrasonic hydrophone and improve the sensitivity and frequency response by reducing the diameter of fiber cladding with a wet-etching technique. The experimental results show that the sensitivity in the high-frequency region is greatly enhanced and the peak response frequency of ultrasound is successfully extended from 21 to 40 MHz.

II. Fabrication and Etching of the DBR Fiber Laser

A pair of 1551-nm fiber Bragg gratings (FBGs) was fabricated in the Er–Yb-codoped fiber by using a 248-nm KrF excimer laser and a phase mask. The Er–Yb codoped fiber, with a diameter of 125 μm, was soaked in hydrogen gas at 100 atm, 70 °C for seven days before the grating inscription and annealed at 100 °C for one day after the grating inscription. One FBG is 3 mm long with reflectivity of ~90%, acting as the output coupling mirror. The other FBG with a length of 10 mm and reflectivity over 99% was fabricated close to the first one with a fiber spacing of 10 mm. Therefore, the effective cavity length

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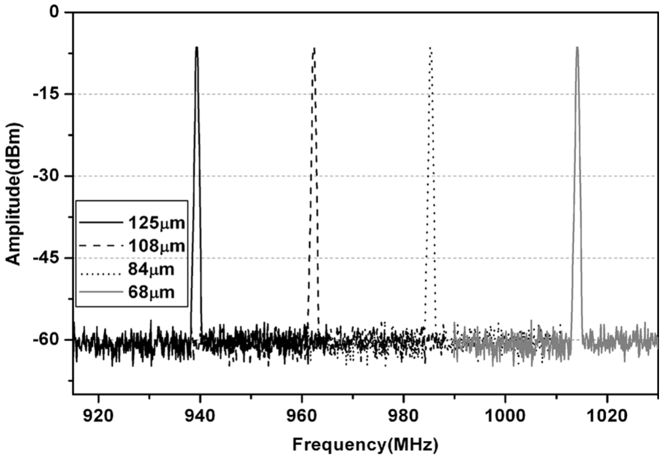

Fig. 1. Measured PMB spectra of fiber lasers with different cladding diameters.

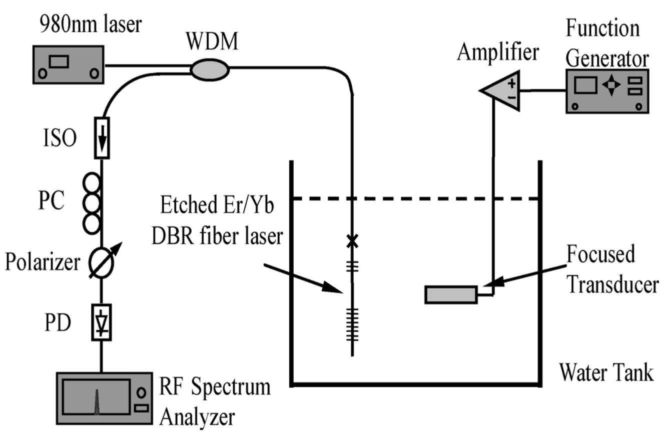

Fig. 2. Schematic diagram of experimental setup. WDM: wavelength-division multiplexer; ISO: isolator.

of the DBR fiber laser is 16.5 mm. The PMB frequency of the unetched DBR fiber laser was measured to be 939 MHz.

To reduce the cladding diameter of the DBR fiber laser, it was fixed on a Teflon frame and then immersed in a hydrofluoric (HF) acid solution with a concentration of 24%. The temperature of the HF solution was maintained at 30 °C. The cladding diameter of the etched DBR fiber laser was measured by using a 50 × microscope. The etching rate for the fiber cladding is $\sim 1\ \mu\mathrm{m/min}$. The PMB frequency of the DBR laser is found to increase with reduction of the fiber diameter. Fig. 1 shows the measured PMB spectra as a function of the diameter of the etched DBR fiber laser. The PMB frequency increases linearly at a rate of 1.24 MHz/μm with reducing fiber cladding diameter. This provides a precise approach to control the frequency of the PMB, and has the potential to be used in the frequency generation of microwave photonics.

III. Characterization of the Ultrasonic Hydrophone

The performance of the cladding-etched DBR fiber laser ultrasonic hydrophone was tested in a water tank. Fig. 2 shows the schematic diagram of the experimental setup. Both the DBR fiber laser hydrophone and a commercial transducer were immersed in a plastic tank filled with distilled water. The fiber laser was pumped with a 980-nm laser diode through a wavelength-division multiplexer. An optical isolator was used to eliminate any unwanted reflection back to the laser cavity. An optical polarizer was inserted after a polarization controller (PC). The polarization state of the laser output was adjusted by the PC to produce maximum PMB signal. The PMB signal detected by a PD was recorded by using an RF spectrum analyzer. In order to achieve maximum PMB signal, the angles of the polarizer should be 45° from the two orthogonal polarization modes.

The ultrasonic wave was generated by a focused broadband transducer with a center frequency of 30 MHz and a focal length of 14 mm in continuous mode. The transducer was driven by a function generator with an amplifier. The maximum frequency of the function generator was 50 MHz. The cladding-etched DBR fiber laser hydrophone was placed at the focus plane of the transducer.

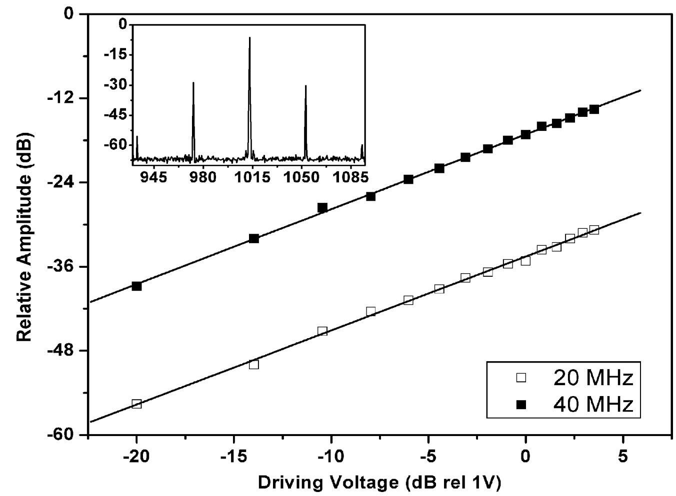

Fig. 3. Measured amplitude as a function of driving voltage. The inset is an example of the observed PMB signal spectrum of 68-μm fiber laser hydrophone at 40 MHz.

IV. Results and Discussion

The inset of Fig. 3 shows an example of the observed PMB signal spectrum. The sidebands of the PMB signal appeared when the fiber laser was subjected to an ultrasonic field. There are two main sidebands with a frequency difference from the main peak which is the same as that of the ultrasonic frequency, and other high-order sidebands also appear when the ultrasound is strong. The amplitude difference between the PMB signal and its first-order sidebands can be used to determine the amplitude of the ultrasonic signal. The diameter of the fiber laser hydrophone is 68 μm, while the ultrasonic transducer was driven at 40 MHz. Fig. 3 shows the response of the cladding-etched DBR fiber laser hydrophone as a function of the input voltages to the transducer driven at 20 and 40 MHz. A good linearity of response was observed. Fig. 4 illustrates the results of frequency response of the cladding-etched DBR fiber laser with four different diameters of 125, 108, 84, and 68 μm. One can see that the frequency responses of the sensor become flatter since both the first resonant peak (at 21 MHz for the case of 125-μm diameter) and the second resonant peak (very sharp at 40 MHz) moved to the higher frequency as the diameter of fiber cladding was decreased, and the sensitivity in the

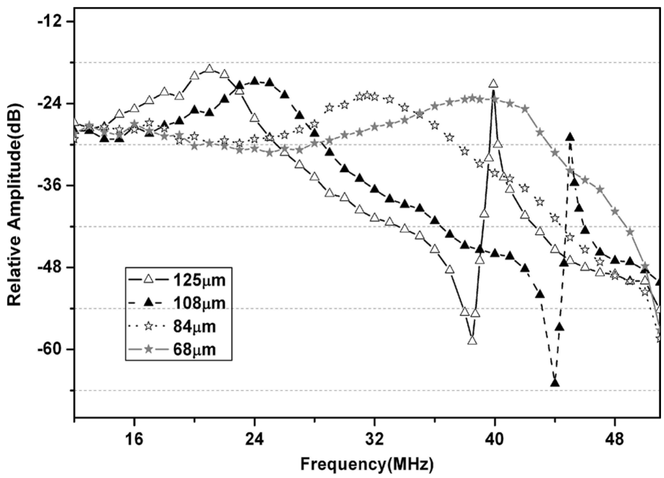

Fig. 4. Signal amplitude against ultrasonic frequency for fiber lasers with different cladding diameters.

high-frequency region, neglecting the influence of the second resonant peak, was improved significantly. Compared with the 125-μm diameter DBR laser hydrophone, the 68-μm diameter laser hydrophone showed a higher sensitivity improved by 10–35 dB in the frequency range of 30–44 MHz, and the peak response frequency shifted from 21 to 40 MHz.

V. Conclusion

We have demonstrated a cladding-etched DBR fiber laser hydrophone for high-frequency ultrasound sensing applications. With decreasing diameter of the fiber cladding, the frequency response of the sensor becomes flatter and the peak response frequency increases so that the sensitivity in the high-frequency region is improved. Owning to its small diameter, the cladding-etched DBR fiber laser hydrophone can provide good spatial resolution. It is a potential candidate for beam profile measurement in the characterization of high-frequency ultrasonic transducer in bio-medical applications.

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