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High-Sensitivity HydrophoneBased on Fiber Grating Laser And Acorrugated Diaphragm

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ABSTRACT: In this work, we present afiber optic hydrophones based on dual-frequency fiber grating lasers and a corrugated diaphragm. The laser is employed as sensing element and an elastic corrugated diaphragm is used to translate acoustic pressure P intolateral point loadNon the laser cavity. Experimental result shows the fiber laser hydrophone has a working bandwidth over 1 kHz with sub100 μPa/Hz$^{1/2}$minimum detectable pressure at 1 kHz.

Keywords: Fiber laser, fiber optic hydrophones, fibergrating

I. INTRODUCTION

Acoustic detection is a fundamental technique for engineering and defense applications.Compared to their piezoelectric counterparts, fiber optic hydrophones have presented advantages includingcompact sensor size, high sensitivity andlight weight [1].A number of sensor configurations based on interferometersor fiber lasers have been demonstrated and optimized for better detection capability [2-5]. As for fiber grating laser, it can simultaneously emit single-longitudinal mode output along the slow and fast axis. The intrinsic fiber birefringence produces a beat signal at radio frequency range, which can be utilized as sensing signal. The beat frequency shifts in accordance with applied perturbations due to the induced birefringence change [6,7].

Here we propose to develop high sensitivity hydrophones based on dual-frequency fiber grating lasers and corrugated diaphragm.In this scheme, the laser is employed as sensing element and a corrugated elastic diaphragm is used to translateacoustic pressure into lateral stress subjected on the fiber. As a result, the acoustic wave can be detected by reading out the frequency variation of the beating signal between the two orthogonal laser modes. Compared with the exiting methods,the fiber laser hydrophone can be frequency division multiplexed in a single fiber [8].In addition, radio-frequency demodulation is relatively mature and low-cost.In this work, we successfully pushed the detection limit of the hydrophone to sub 100 μPa/Hz$^{1/2}$ level detecting low frequency acoustic signal.

II. SENSING PRINCIPLE

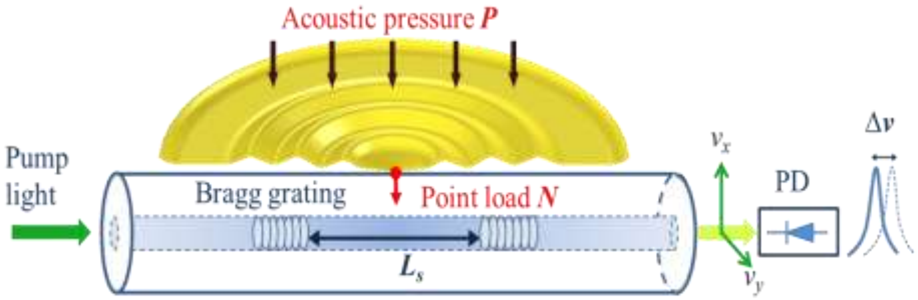

Fig. 1 Schematic of the present fiber laser hydrophone. Acoustic pressure is translated into concentrated lateral loadover the laser cavity, which induces detectable beat-frequency change.

Fig. 1 schematically shows the sensing element and transducer of thehydrophone. The sensing element is a dual-frequency fiber grating laser, fabricated by photowrittingtwowavelength matched Bragg gratingswith highly reflective in an Er-doped optical fiber. The grating separation is L_s. The grating-based Fabry-Perot cavity emits two polarization modes with lasing frequencies ν_x and ν_y, respectively, as a result of the intrinsic fiber birefringence [7,8]. The beat frequency can be expressed by$\Delta\nu = |\nu_x - \nu_y| = cB/n_0\lambda$,where$B$ represents fiber birefringence, c is the speed of light in vacuum, n_0 is the average mode index and λ denotes the lasing wavelength.A lateral load Ncan induce a birefringence variation to shift the beat frequency. The induced birefringence change in response to a transverse linear force simply writes as [9]:

$$\delta(\Delta\nu) = c\Gamma\eta \cdot \frac{N}{n_0\lambda} \quad (1)$$

where $c\Gamma/n_0\lambda\approx 10$ GHz/(N/mm) represents a coefficient associated with the elastic properties of silica glass[10] and $\eta$is the normalized intensity linear density [9].The radio-frequency beat signal can be demodulated I/Q data processing method, which has been widely used in software-defined radio systems.

A bare fiber laser can hardly respond to low frequency acoustic waves due to the circular symmetry of the fiber. An elastic corrugated diaphragm, which has been applied as a basic elastic element in engineering applications, is employed for the translation of acoustic pressure into optical response. The diaphragm is characterized by radius *r*, corrugation depth *H*, and the diaphragm thickness *h*. With the assumption of small deflection,for anedge-clamped diaphragm, the relation between the deflection at the rigid center and the amplitude of the applied pressure *p* can be simply expressed by [11]:

$$y(P) = P\frac{r^4}{AEh^3} \quad (2)$$

where $A = 2(3+q)(1+q)/[3(1-\mu^2/q^2)]$, E and μ represent Young's modulus and Poisson's ratio of the metal, respectively.$q$is a shape factor defined as $q^2 = 1 + 1.5(H^2/h^2)$ [11].For anedge-clamped diaphragm, a concentrated load*N*normally applied at the rigid center can induce adeflection [11], which can be written as:

$$y(N) = N\frac{r^2}{A'\pi Eh^3}, \quad (3)$$

where$A' = (1+q)^2/[3(1-\mu^2/q^2)]$.As shown in Fig. 1, the fiber laser is beneath the diaphragm and in pointcontact with the rigid center of the diaphragm. The deflection at the rigid center for such a center-supported diaphragm can be considered nearly zero, due to the reacting force which should equals *N*. As a result, the acoustic pressure *P* is translated to a point load*N* onto the laser cavity, yielding an optical response in terms of beat-frequency variation.Combining Eqs. (2) with (3), we can assume the deflection induced by a uniform pressure *P*be equivalent to the effect of a concentratedpoint load*N*at the rigid center, which can be expressed as:

$$N = P \cdot A_e \quad (4)$$

where $A_e = \pi r^2\,(1+q)/(2(3+q))$ denotes the effective area of corrugated diaphragm and affect the transduction efficiency between *P* and *N*.Eqs. (1) and (4) denotes the sensing principle of the hydrophone.

III. SIMULATION ANALYSIS

We numerically calculated 10 Pa static pressure induced deformation of the corrugated diaphragm with finite-element-method software. Fig. 2 shows radial profile of its deformations, zeroradiusdenotes the rigid center of the diaphragm. As shown in Fig. 2(a), the deflection at its rigid center has a maximum deflectionfor the edge-clamped and center-free diaphragm. Fig. 2(b)showsthe edge-clamped/center-supported one exhibits zero deflection as a result of the reacting force from the fiber, which is consistent with the present hydrophone.

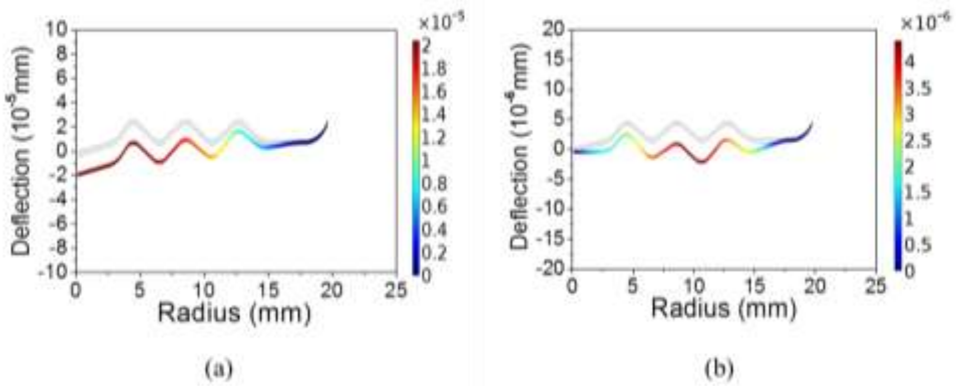

Fig. 2 Radial profile of FEM calculated deformations of
(a)an edge-clamped and **(b)** an edge-clamped/center-supportedelastic corrugated diaphragms in response to 10 Pastaticpressure.

IV. EXPERIMENT

Fig. 3 shows experiment devices and the acoustic detection system. The fiber laser is pumped with a 980 nm laser diode via a wavelength-division multiplexer (WDM). The diaphragm and the fiber laser are encapsulated into the transducer structure as the hydrophone. A waterproof speaker (UWS-045, KHZ Corporation)is placed at the bottom of a water tank as an acoustic source.The amplitude and frequency of the acoustic wave can be adjusted by a digital signal generator.The amplitude and frequency of the acoustic wave can be adjusted. A commercial hydrophone (8104, Brüel&Kjær) with a voltage sensitivity 10 mV/Pa is used for calibration. The beat-frequency variation is measured by use of a vector signal analyzer (MS2692A, Anritsu).

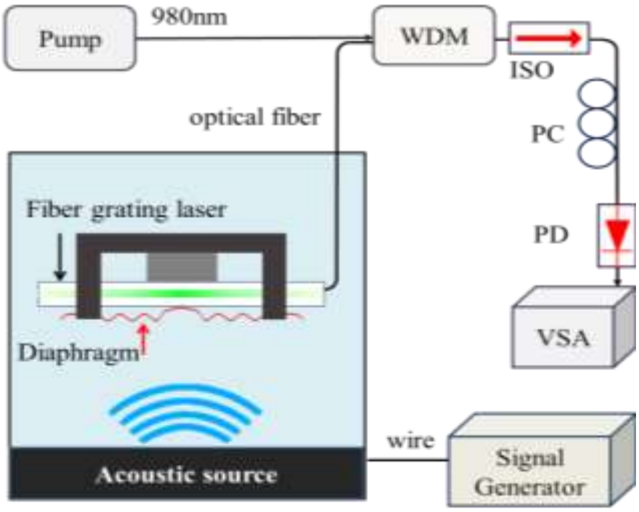

Fig. 3 Schematic of underwater acoustic detection system with the fiber grating laser hydrophone. WDM: Wavelength-division multiplexer. ISO: Optical isolator; PD: Photodetector; PC: Polarization controller; VSA: Vector signal analyzer.

Fig. 4(a) shows measured amplitudes of acoustically induced beat-frequency variations as a function of applied acoustic pressure. The applied acoustic wave has a frequency of 800 Hz. Theamplitudeschanges in proportion with applied acoustic pressure. The slope of the linear fittingreflectssensitivity, which is estimated to 181 kHz/Pa. Fig. 4(b) shows the detected output sinusoidal waveforms for acoustic signal of 800 Hz, 25 Pa.

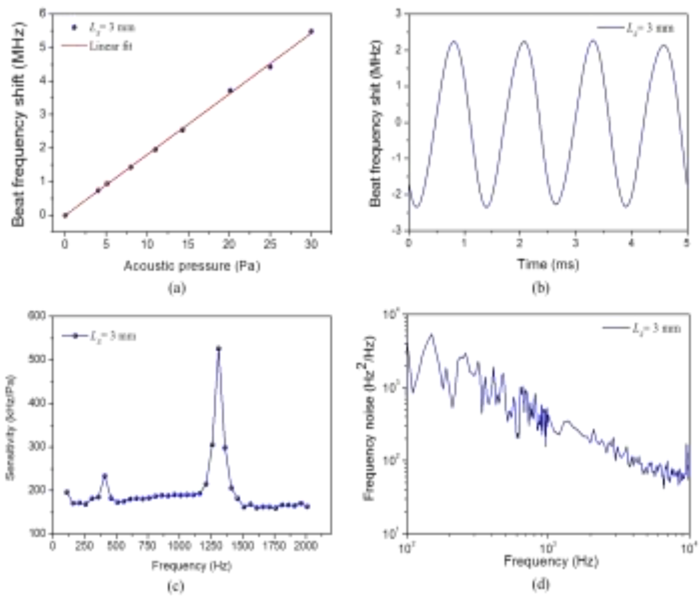

Fig. 4(a) Measured beat-frequency variations as a function of applied acoustic pressure at 800 Hz. **(b)** Output waveforms of the fiber laser hydrophones at 800 Hz, 25 Pa.**(c)**Measured frequency responses of fiber laser hydrophones with 3 mm cavity length.**(d)**Measured frequency noise spectra of fiber lasers with L_s = 3 mm. The noise level is characterized with a parameter C are about 2×10^5.

As shown in Fig. 4(c),there are two peaks on the frequency response curve at about 410 Hz and 1310 Hz, respectively. The peak at 410 Hz is obviously much lower than another one, it probably come from resonance of other objects in our experiment.The resonant frequency of the transducer should be1310 Hz, determined by the elastic property of the corrugated diaphragm. The average beat-frequency sensitivity $S_b$over the working bandwidth from 110 to 1210 Hz is 186 kHz/Pa. Fig. 4(d)shows the measured noise spectra for lasers with L_s is 3 mm.The noise of the beat signal at the low-frequency range mainly arises from intracavity thermal fluctuation [12]. The frequency noise spectral density can be simply expressed by $S(f) = C/f$., where C is used to characterize the noise level. The noise levels are $C = 2\times10^5$. The corresponding minimum detectable acoustic pressure P_{min} can be simply estimated with $P_{min} = \sqrt{S(f)}/S_b$, where S_b is the beat-frequency sensitivity. As a result, the minimum detectable acoustic pressures are estimated as 74μPa/Hz$^{1/2}$ at1kHz.According to the average sensitivity and the minimum detectable sound pressure, the SNR at 1 kHz is estimated to be 81 dB. In order to avoid acoustic signal distortion, we can only obtain 30 Pa the maximum acoustic pressure in working frequency range. The dynamic range of the hydrophone is around 112 dB in our experiment, the practical dynamic range of the hydrophone should be better than it.

V. CONCLUSION

In this paper, we have demonstrated a high acoustic pressure sensitivity fiber laser hydrophone based on an elastic corrugated diaphragm as the transducer. The sensing element is the dual-frequency fiber grating laser working in beat-frequency encoding manner. An elastic corrugated diaphragm cantranslate acoustic pressure P into lateral point load N on the laser cavity.The load creates alocal optical phase change and inducesan optical response in beat-frequency shift.Experimental result shows that the working bandwidth of the hydrophone is about 1.1 kHz and the resolution canachievesub 100 μPa/Hz$^{1/2}$level at 1 kHz.The SNR at 1 kHz can reach 81 dB.The dynamic range of the hydrophone is around 112 dB.The performance of the fiber laser hydrophone can be further improved by transducer optimization and forming lasers with highly confined mode.

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