A PDMS Film Structured Optical fiber Ultrasonic Sensor with high Sensitivity and Wide Response Range characteristics

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Abstract. This paper proposes an implementation method of the optical fiber FP pressure ultrasonic sensor with a controllable cavity length and a variable membrane, in order to effectively improve the sensitivity and response range of the optical fiber Fabry-Perot (FP) ultrasonic sensor. The optical fiber FP ultrasonic sensor with PDMS film structure proposed in this paper has obvious advantages in improving sensitivity and response range.

1. Introduction
Optical fiber ultrasonic sensors have the advantages of high sensitivity, small size, light weight, anti-electromagnetic interference, corrosion resistance and long-range detection. They have broad applications in marine safety, ultrasonic communication, industry, disaster prevention and other fields.

In recent years, thin-film structured optical fiber FP ultrasonic sensors have been extensively studied [1-5]. In general, there are two main ways to achieve ultrasonic sensing in optical fiber FP sensors: one is by changing the refractive index of the medium in the FP interference cavity, and the other is by changing the length of the FP cavity. Many schemes have been proposed to optimize the performance of the system. Tingting Gang et al. proposed an ultrasonic sensor structure containing an optical fiber microcavity that successfully achieved high-sensitivity fiber-optic ultrasonic sensing [1]. Xingjie Ni et al. proposed a new optical fiber underwater acoustic sensor (hydrophone) consisting of two fiber Bragg Grating (FBG) self-demodulation methods. This FBG hydrophone has only one structure with a pair of matched FBGs for sensing and demodulation [2]. F. Guo et al. proposed a high-frequency external cavity FP optical fiber ultrasonic sensor based on a thin silver film, but its high-frequency responses is poor, the film production process is quite complicated, and the cost of instrumentation is high [3]. D.H. Wang, P.G. et al. proposed a probe-type high-sensitivity all-silicon optical fiber FP ultrasonic hydrophone for characterizing high-intensity focused ultrasound fields. However, the preparation of large-diameter monolayer graphene films and their transfer to the end of the sensor are often difficult to manipulate [4]. Xiaobo Liu et al. proposed a miniature optical fiber ultrasonic sensor based on FP interference. As one of the two interfaces of the FP cavity, the NOA68 film-air interface is sensitive to ultrasound due to its low Young's modulus. The ultrasonic response band is wide, but only ultrasonic waves above 300kHz can be received, and the sensor has a low signal-to-noise ratio and low sensitivity [5].
In summary, the study of optical fiber FP ultrasonic sensors with high-sensitivity and wide-response range is still not comprehensive. To this end, this article proposes an optical fiber FP ultrasonic sensor based on PDMS film structure to enhance sensitivity and response range. The sensor sensitivity performance is superior in the frequency range of 70kHz-280kHz. The proposed optical fiber FP ultrasonic sensor is easy to prepare, low cost, and highly reproducible.

2. Sensor working principle

When ultrasonic waves act on the film structure of the optical fiber FP cavity, the film position and cavity length will change. The FP reflection spectrum will change accordingly with the change of the film position, and the ultrasonic detection can be realized by demodulating the wavelength of the reflection spectrum. In this article, the demodulation method was a single-wavelength method, in which a narrow linewidth tunable laser was injected into the fiber FP cavity through a circulator, and the interference light signal reflected by the FP cavity was output again through the circulator and then transformed into an electrical signal associated with ultrasound by a photo-detector (PD), which can be analyzed by a spectrometer or acquisition card to invert the ultrasound characteristics.

According to the theory of elastic deformation, when acoustic pressure is applied to the film structure, it causes its deformation, which consequently changes the FP cavity length X. For a rigidly clamped circular film structure, the center deformation can be determined by the equation (1).

\[
X = \frac{3(1-\mu^2)p r^4}{16Er^3} = \frac{f_1^2}{\sqrt{(f_1^2 - f^2) + 4f^2\sigma^2}}
\]

(1)

Where E and \(\mu\) are the Young's modulus and Poisson's ratio of the film material, \(p\) is the acoustic pressure, \(t\) and \(r\) represent the thickness and radius of the film layer, \(f\) is the frequency of the acoustic wave, \(f_1\) is the intrinsic frequency of the film structure, and \(\sigma\) is damping coefficient. According to equation (1), the pressure sensitivity of the optical fiber FP ultrasonic sensor can be significantly enhanced using a lower Young's modulus and reducing the thickness-to-diameter ratio of the film structure. Because PDMS has excellent physical properties such as low Young's modulus, simple curing process, very high flexibility and high reflectivity, PDMS was chosen to prepare pressure sensitive films for low-frequency acoustic sensing.
3. Temperature sensitivity analysis

3.1. Ultrasonic response at different film layers and cavity lengths
In order to analyze the influence of different film thickness and cavity length on the ultrasonic characteristics of the structure, the ultrasonic response characteristics of the sensor was and the test results and its transformed waveform is shown in Fig. 1.

As shown in Fig. 2, the optical fiber FP ultrasonic sensor FP prepared in this article had a good sine wave shape and no obvious distortion when the signal was received in the 180kHz ultrasonic environment. After FFT transformation, there was a signal with a very high amplitude pulse at 180kHz that had a signal-to-noise ratio of 54.45dB, therefore, the sensor had a good spectral response to the 180kHz ultrasonic signal generated by the ultrasonic transmitter.

Next, the ultrasonic frequency response characteristics of senor was tested with the starting frequency of 10kHz and a test step length of 10kHz, and the specific ultrasonic frequency response characteristics are shown in Fig. 3.

![Fig. 2 180KHz ultrasonic response (top right) and FFT transform (bottom left)](image)
According to Fig. 3, when the ultrasonic frequency exceeded 430kHz, the response of sensor was abnormal, and no effective waveform could be detected. This was due to the fact that the ultrasonic signal frequency was too large for the film layer structure to produce a normal deformation response. As a result, the correlation between the received signal and the emitted signal was significantly reduced, and no valid data could be extracted after 430kHz.

3.2. The relationship between ultrasonic response and distance

In the distance (the distance mentioned here is the distance from the end of the optical fiber to the ultrasonic source, hereinafter) measurement experiment, the ultrasonic response characteristics of the sensor at different distances was tested in this article, where the range of the distance was 0.5cm~4cm with each incremental step of 0.5cm, as shown in Fig. 3, depicted the characteristic curve of ultrasonic response versus distance.

As shown in equation (2), the exponential function with higher degree of fitting and simple fitting expression was chosen as the fitting method in this article.

\[ y = ae^{bx} \]
Where the unit of $x$ is cm, and the data is substituted into the fitting image to find $a$ and $b$ (as shown in Fig. 10), and $a \approx 3.75$, $b \approx -1.54$, so the fitted expression is shown in equation (3) below.

$$y = 3.75e^{-1.54x}$$ (3)

This corresponds to the attenuation characteristics of ultrasonic waves in the air, and $R^2 \approx 0.985$.

To facilitate analysis, we changed the vertical coordinate to decibel (dB) and redrew the curve (as shown in Fig. 4) to evaluate more easily the variation characteristics of Vpp. The redrawn characteristic curve is basically linear with a slope of about 6.2dB/cm.

4. Conclusion

In this article, an optical fiber FP pressure ultrasonic sensor with controllable cavity length and variable film layer is proposed for detecting ultrasonic frequencies below 430kHz. According to the experimental results, the highest frequency response in ultrasonic detection could reach 430kHz, the system signal-to-noise ratio could reach more than 50dB in the range of 70kHz-280kHz, and the signal-to-noise ratio could reach up to 70dB. The experimental results showed that the proposed PDMS film structured optical fiber FP ultrasonic sensor has promising application value in the optical fiber ultrasonic sensor system with high sensitivity and wide response range.

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