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A MICRO TOTAL REFLECTIVE EXTRINSIC FABRY-PAROT INTERFEROMETRIC FIBER OPTIC PRESSURE SENSOR FOR MEDICAL APPLICATION

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This paper presents the newly designed fiber optic pressure sensor using the TR-EFPI fiber optic sensor with a single mode fiber (SMF), and a micro fabricated diaphragm. The output signal of TR-EFPI fiber optic pressure sensor can be easily analyzed based on the spliced loss based model and large deflection theory. Then, we can design the optimal length between the thin film of diaphragm and the end of single mode fiber. From these analyses, the relation between the applied pressure and the output signal of TR-EFPI fiber optic sensor can be simulated. Based on these processes, we can design the TR-EFPI fiber optic pressure sensor measuring various conditions by changing the size of thin film. As the newly designed TR-EFPI fiber optic pressure sensor can be fabricated in small size and has good sensitivity, it can be applied to medical instrument like pressure sensor and force sensor for catheter and minimally invasive surgery robot for safer surgery.

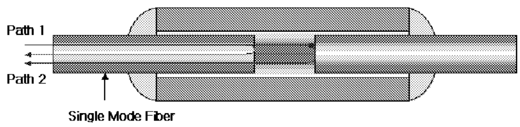
1. Introduction

Many researchers pay attention to the development of micro fiber optic pressure sensors which can overcome the drawbacks of conventional pressure sensor because of its advantages such as excellent sensitivity and resolution, immunity from electromagnetic interference, and dimensional compactness. Kim suggested a EFPI fiber optic pressure sensor with well-designed diaphragm, and the FISO Technologies Inc. developed fiber optic pressure sensor using a white light interferometric system. Though these fiber optic pressure sensors are small and have high performance, they have some disadvantages. For examples, they need complex micro fabricating process and expansive data processing systems, even if these sensors are very compact and cheap. These EFPI fiber optic pressure sensors cannot detect the change of pressure direction. Thus, many researchers proposed some ways of measuring the direction of physical properties using

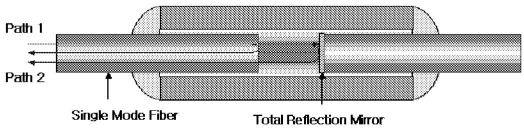
EFPI fiber optic sensor [1-2]. Among these various methods, we can choose one method without adding other signal processing systems such as spectrum analyzer, and with very simple structure. That is the Total Reflective type EFPI (TR-EFPI) fiber optic sensor [2]. In this paper, newly designed TR-EFPI fiber optic pressure sensor is presented.

2. *Principle of TR-EFPI Fiber Optic Pressure Sensor*

Figure 1 shows the structures of the EFPI and the TR-EFPI fiber optic sensor. Conventional EFPI fiber optic sensors have two single-mode fibers for transmitting incident and reflected light. From left fiber, the light is transmitted. 3% of incident light is reflected at the end surface of left fiber (path 1), 97% of incident light is transmitted and travels the air gap. 3% of second incident light reflected at the end surface of right fiber (path 2).



(a) EFPI Fiber Optic Sensor



(b) TR-EFPI Fiber Optic Sensor

Fig.1 Structure of EFPI / TR-EFPI fiber optic sensors

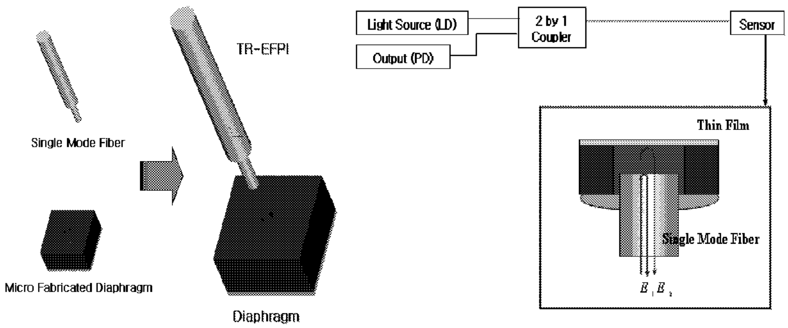


Fig. 2 TR-EFPI fiber optic pressure sensor

The light path of a TR-EFPI fiber optic sensor is the same to that of a conventional EFPI fiber optic sensor. However, a TR-EFPI fiber optic sensor has a total-reflected surface which increases the light intensity of path 2. Figure 2 shows how the TR-EFPI fiber optic sensor can be utilized as a pressure sensor. A TR-EFPI fiber optic pressure sensor consists of SMF and micro fabricated diaphragm. The light is introduced to the single mode fiber and transmits 2×1 coupler. The 3% of incident light of end of single mode fiber is reflected (path 1), and the rest of light propagates and the whole of incident light is reflected from the thin film and gets back to the single mode fiber. That is, a total reflected surface of Fig.1 is replaced with the total reflected thin film of Fig.2. The phase difference of theses two light paths causes interference in the optical receiver (output). Thus, the change of gap length by the applied pressure results in the interferometric fringes as the output signal. Then, we can obtain the applied pressure information measuring the air gap length between the end of single mode fiber and the total reflected thin film.

3. *Design: Estimation of Output Signal*

3.1. *Analysis of output signal of TR-EFPI based on the spliced loss based model*

The propagation of light can generally be explained by the harmonic wave equation, which is the solution of the wave equation based on the Maxwell's equation. The wave equations of the optical path 1 and path 2 of TR-EFPI fiber optic pressure sensor is described as such

$$\begin{aligned} E_1(x_1) &= E_0 r_1 \cos(k \cdot x_1 - \omega \cdot t) \\ E_2(x_2) &= E_0 t_1 t_2 r_2 L(s) \cos(k \cdot x_2 - \omega \cdot t) \end{aligned} \tag{1}$$

The optical fiber/air reflection factor is r_1, the optical air/fiber reflection factor is r_2, the optical fiber/air transmission factor is t_1 and the air/optical fiber transmission factor is t_2. ω is the angular frequency and k is the propagation constant. s is the length of the air gap $(x_2 - x_1)$ between single mode fiber and the total reflected thin film, and $L(s)$ is amplitude loss equivalent to the intensity loss from the spreading of light in the two paths. Because the optical intensity is proportional to the square of the electric field amplitude E_0, the transmittance $T(s)$ of the normalized intensity is described by:

$$T(s) = \frac{E^2(s)}{E_0^{\ 2}} = \left\{ r_1^{\ 2} + t_1^{\ 2} t_2^{\ 2} r_2^{\ 2} L^2(s) + 4 t_1 t_2 r_1 r_2 L(s) \cos(2ks) \right\} \tag{2}$$

To calculate the amplitude loss $L(s)$, we can use the spliced loss based model analysis. For TR-EFPI optical fiber pressure sensor, the formula for the intensity loss by spreading of light is expressed as follows [3]:

$$\eta(s) = L^2(s) = \frac{1}{1 + (0.5 s / x_R)^2} \tag{3}$$

Finally, we can estimate the output signal of TR-EFPI fiber optic pressure sensor versus the air gap length between the single mode fiber and thin film. Figure 3 shows the transmittance of TR-EFPI fiber optic pressure sensor for the change of air gap length. From this figure, we can obtain the optimal ranges which have the change of the intensity level and interferomtric signal. The optimal range is 0~200μm on the condition that the diameter of single mode optical fiber is 7.9μm, Numerical Aperture of single mode fiber is 0.1, and the wave length of light source (LD) is 1315nm.

$$T(s) = \frac{E^2(s)}{E_0^{\ 2}} = r_1^{\ 2} + \frac{t_1^{\ 2} t_2^{\ 2} r_2^{\ 2}}{1 + (0.5 \cdot 2s / x_R)^2} + \frac{4 t_1 t_2 r_1 r_2 \cos(2ks)}{\sqrt{1 + (0.5 \cdot 2s / x_R)^2}} \tag{4}$$

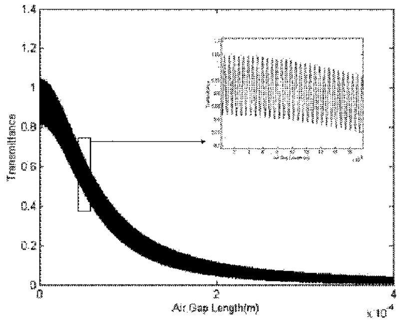


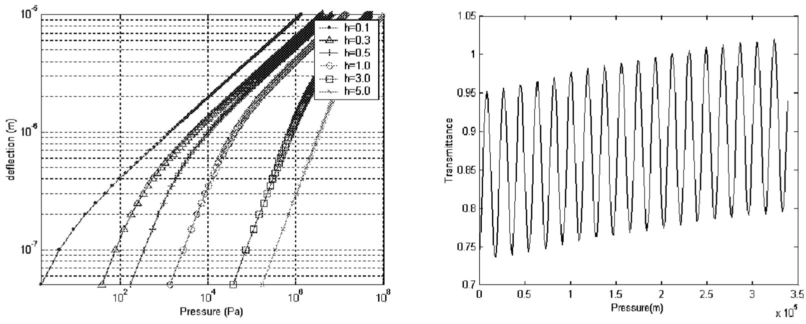
Fig. 3 Transmittance of TR-EFPI for the change of air gap length

3.2. Analysis of deflection of thin film

We use gold (Au 99.9%) as the material of thin film, because of its good reflectance and ductility. And we must determine the diameter of thin film that guarantee the alignment between the total reflective thin film and the end of optical fiber, and that can be made as a minimum size sensor. If the alignment is not guaranteed, TR-EFPI sensor cannot detect the reflective light because of the great light loss [3]. Next, we determine the thickness of thin film. The deflection of the diaphragm by the applied pressure can be described mathematically. Timoshenko and Woinowsky-Krieger have described the detailed derivation for a deflected circular plate such as Eq. (5), the maximum deflection of circular plate can be derived [4]:

$$w_0 = \frac{Pa^4}{64D} \frac{1}{1 + 0.488 \frac{w_0^{\ 2}}{h^2}} \tag{5}$$

Figure 4(a) shows the maximum deflection of thin film by applied pressure for several thicknesses: the material of thin film is gold, and the diameter of thin film is 130 μm. From theses two analyses, we can derive the output signal of TR-EFPI sensor for applied pressure. We choose the initial air gap length, 20 μm for the highest gradient of output signal. It means that we can easily detect the change of light intensity level. And we can determine the thickness of thin film of diaphragm in 0.5 μm with respect that the range of sensor is 0 ~ 1MPa.



(a) Deflection of thin film by applied pressure (b) Light intensity analysis of TR-EFPI

Fig. 4 Analysis of TR-EFPI fiber optic pressure sensor (h=0.5μm, a=65 μm)

4. *Verification of TR-EFPI Fiber Optic Pressure Sensor*

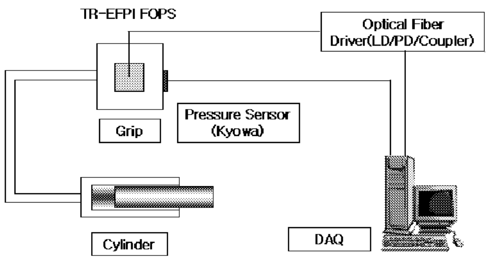
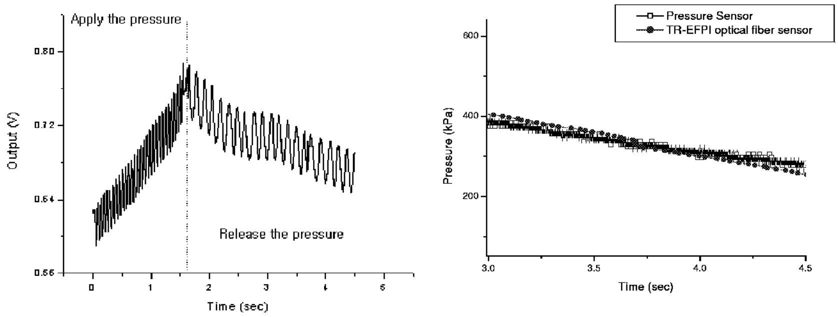


Fig. 5 Verification equipment



(a) Output signal of TR-EFPI (b) Pressure signal from TR-EFPI

Fig. 6 Output signal of TR-EFPI fiber optic pressure sensor

We fabricated the diaphragm which is the same size designed by above processes. And then we verified the output signal of TR-EFPI fiber optic pressure sensor. Figure 5 shows the TR-EFPI fiber optic pressure sensor test equipment. Test equipment is composed of cylinder, pressure sensor gripper, reference pressure sensor and DAQ system. Pressure is applied by the cylinder and is released by the valve attached to cylinder. And TR-EFPI fiber optic sensor signal and reference pressure sensor signal experienced the pressure change is sent to the DAQ system. Figure 6(a) shows the output fringe light intensity signal of TR-EFPI fiber optic pressure sensor and Fig. 6(b) shows the pressure information from the TR-EFPI fiber optic pressure sensor compared with reference pressure sensor signal. As shown in Fig. 6 showed, TR-EFPI fiber optic pressure sensor follows the reference pressure sensor with resolution of 4kPa.

5. *Summary*

In this paper, a newly designed TR-EFPI fiber optic pressure sensor was suggested to compensate the drawbacks of conventional EFPI fiber optic pressure sensor, which have difficulty in distinguish pressure direction. Considering components of sensing system, fabrication and signal processing, this TR-EFPI fiber optic pressure sensor is simpler and more effective measurement compared with the EFPI fiber optic pressure sensor. We designed the optimal air gap length between the single mode fiber and thin film using the output signal analysis based on the spliced loss based model. And we analyzed the output signal of TR-EFPI fiber optic pressure sensor for applied pressure using the large deflection theory of circular plate. Finally, we verified the TR-EFPI fiber optic pressure sensor with a very sufficient resolution. This TR-EFPI fiber optic pressure sensor can be easily applied to the medical sensors for theses advantages.

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