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Laser self-mixing interference fibre sensor*

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Fibre sensors exhibit a number of advantages over other sensors such as high sensitivity, electric insulation, corrosion resistance, interference rejection and so on. And laser self-mixing interference can accurately detect the phase difference of feedback light. In this paper, a novel laser self-mixing interference fibre sensor that combines the advantages of fibre sensors with those of laser self-mixing interference is presented. Experimental configurations are set up to study the relationship between laser power output and phase of laser feedback light when the fibre trembles or when the fibre is stretched or pressed. The theoretical analysis of pressure sensors based on laser self-mixing interference is indicated to accord with the experimental results.

Keywords: laser self-mixing interference, fibre sensor
PACC: 4255P, 4281P

1. Introduction

Fibre sensors are fibre-based instruments for sensing some physical quantities.[1] The physical quantities can be measured by changing the fibre's optical parameters such as optical length and light polarization when light travels through an optical fibre. Fibre sensors have been extensively applied in measurement for their advantages such as high sensitivity, electric insulation, corrosion resistance, interference rejection and so on.

Fibre sensors with interference metric technique are considered to be the most accurate fibre interference sensors at present. As shown in Fig.1, in the process of interference measurement, the output light from laser is split into two beams: each of them is coupled with an optical fibre. One fibre transmits reference light and the other transmits measuring light which is affected by an external force. The interference occurs when these two waves join together. In this way, the external force can be accurately detected by measuring the interference intensity.[1,2]

Self-mixing interference occurs in a laser cavity when the laser is subjected to an external optical feedback from a surface.[3−7] Due to the interference between the feedback light and the original light in the laser cavity, both the power output and the oscillation frequency of laser are modulated. The laser power will oscillate from peak to valley as the phase of feedback light changes by π.

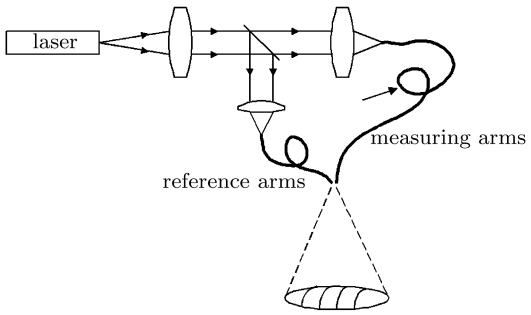


Fig.1. Fibre sensors with interference metric technique.

In this paper, a novel laser self-mixing interference fibre sensor which combines the advantages of fibre sensors with those of the laser self-mixing interference is presented. Different from fibre sensors with the interference metric technique, laser self-mixing interference fibre sensors introduced in this paper have no reference arms, but only measuring arms used to transmit the feedback light. They combine the advantages of laser self-mixing interference with those of fibre sensors. Though they are simple in structure, they are as accurate as interferometers in measurement. Its basic working theory is briefly reviewed also. The experiments report on the variation in power output when the fibre sensor is stretched or pressed.

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2. Theory of fibre sensor based on laser self-mixing interference

A simple laser self-mixing interferometer is composed of a laser and an external mirror. The power output of the laser can be modulated by moving the external mirror. The variation of the power output ΔI can be defined as

$$\Delta I = \beta \cos(2kL_{\mathrm{E}}), \tag{1}$$

where k is the magnitude of wave vector, β is the scale factor and L_{E} is the distance between laser mirror and external mirror.

It can be concluded from Eq.(1) that ΔI changes from peak value to valley value as the distance L_{E} changes by $\lambda/4$. Therefore, the movement of external mirror can be calculated accurately by measuring the variation in power output ΔI.

A fibre sensor based on laser self-mixing interference is composed of a semiconductor laser, a photoelectric detector and a fibre whose end surface is coated with a reflective film as shown in Fig.2. The output laser is coupled to the optical fibre and reflected by the fibre reflective end surface of fibre. The laser self-mixing interference occurs as the reflected light is fed back into the laser cavity. The laser power output will change with phase variation of the feedback light that is affected by the environment around the fibre such as pressure, pull, rotation, temperature, etc. For example, a pressure on the fibre will result in the variations in the optical length of the feedback light as well as the laser power output. These indicate that the physical quantities can be detected by measuring the laser power output. Compared with the fibre sensors with interference metric technique, this sensor has no reference fibre, but only one fibre used to transmit the feedback light.

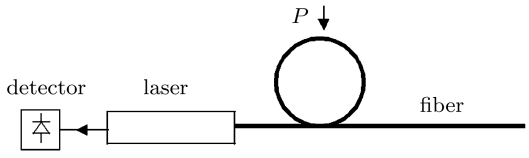


Fig.2. Laser self-mixing interference fibre sensor.

In this system, the laser power oscillates while the external force P on the fibre increases gradually. With the theory of elastic mechanics, the phase difference of feedback light, $\Delta\phi$, can be written as[8]

$$\Delta\varphi = 2\left[nk_0\varepsilon_3 + k_{\mathrm{o}}n^3(P_{11}\varepsilon_1 + P_{12}\varepsilon_2 + P_{12}\varepsilon_3)/2\right]L, \tag{2}$$

where k_0 is the magnitude of wave vector in vacuum, L is the length of fibre on which an external force is exerted, n is the refractive index of the fibre, ε_1 and ε_2 represent the lateral strains of the fibre, ε_3 is the longitudinal strain, and P_{11} and P_{12} are the elasto-optical coefficients.

According to elastic mechanics, the relationship between stress σ and strain ε can be described as

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1/E & -\mu/E & -\mu/E & 0 & 0 & 0 \\ -\mu/E & 1/E & -\mu/E & 0 & 0 & 0 \\ -\mu/E & -\mu/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix}, \tag{3}$$

where E is the Young's modulus of elasticity and μ is the Poisson coefficient.

If the fibre is stretched by an external force P, the stress σ can be written as

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -P \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{4}$$

where σ_1 and $\sigma_2$represent the lateral stresses of the fibre, σ_3 is the longitudinal stress.

By substituting Eq.(4) into Eq.(3), the relationship between stress σ and strain ε is given as

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} P\mu/E \\ P\mu/E \\ -P/E \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{5}$$

Therefore, the external force P can be expressed as

$$P = \Delta\varphi/2L[-nk_0/E + k_o n^3(-P_{11}\mu + P_{12}\mu - P_{12})/2E]. \tag{6}$$

If the fibre is pressed by one-dimensional transverse external force P, the stress σ can be written as

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} -P \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{7}$$

By substituting Eq.(7) into Eq.(3), the relationship between stress σ and strain ε is expressed as

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -P/E \\ P\mu/E \\ P\mu/E \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{8}$$

Therefore, the external force can be written as

$$P = \Delta\varphi/2L[nk_0\mu/E + k_o n^3(-P_{11} + 2P_{12}\mu)/2E]. \tag{9}$$

3. Experiments and analysis

The fibre sensor system used in the following experiments is composed of an LD, a fibre and a photoelectric detector as shown in Fig.2. A detector is sealed in the LD to measure the power output, and the output signal is input into a computer data collection system.

The first experiment is to study the variation in laser power output while the optical fibre end trembles. The fibre is a single-mode fibre with a 300 mm length. No obvious variation in power output can be detected while the fibre trembles if no reflective film is coated on the end surface. Otherwise, the power output has a notable oscillation while the end surface of the fibre is coated by a reflective film with a reflectivity of 70%. The detected result is shown in Fig.3, where the vertical axis represents the laser power output. The oscillation frequency of power output is similar to the trembling frequency of the fibre.

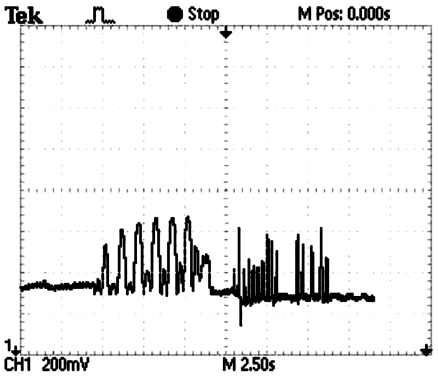


Fig.3. The laser power output while the fibre trembles.

The second experiment is to study the power output while the fibre is stretched. The wavelength of the LD is 1310 nm. The fibre is a single-mode fibre with a 1000 mm length, and the reflectivity of the film on the end surface of fibre is 70%. The fibre is circled around a 20 mm-diameter piezoelectric ceramic to make 8 fibre rings. The piezoelectric ceramic is driven by a periodic triangular voltage whose peak value is 50 V and whose frequency is 20 Hz. The experimental system is illustrated in Fig.4.

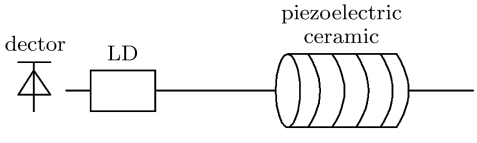


Fig.4. Experiment system while the fibre is stretched by piezoelectric ceramic.

Owing to the influence of the periodic triangular voltage, the length of the optical fibre as well as the external diameter of the piezoelectric ceramic will be altered periodically, which will cause the variation in laser power output. Figure 5 shows the variation in laser power and periodic triangular voltage observed in an oscilloscope. It is apparent that the laser power has the same period as that of the triangular voltage.

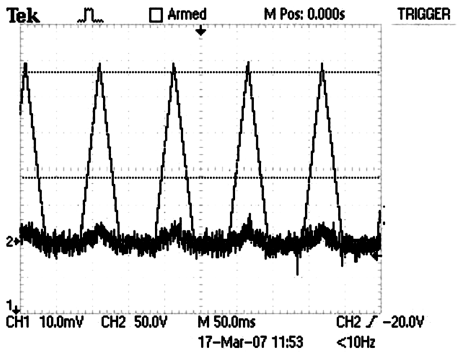


Fig.5. The laser power output while the piezoelectric is driven by a periodical triangular voltage.

The third experiment is to study the power output while the fibre is pressed. The fibre is a single-mode fibre with a 300 mm length, and the reflectivity of the film on the end surface of fibre is 70%. Pressure P is added gradually by a micrometer. The pressed length of the fibre is 8 mm as we can see in Fig.6. The pressure will change the length and refractive index of the fibre. Consequently, the phase of the feedback light will be changed by the pressure, which finally results in the periodic variation in laser power output.

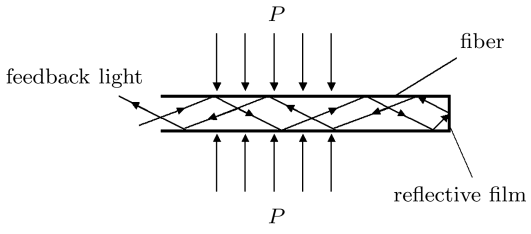


Fig.6. The laser feedback light when one-dimensional external force P is exerted on the fibre.

During the test, the pressure on the fibre is strengthened gradually until the fibre breaks. The laser power output can be observed from peak to valley, then from valley to peak and so on as shown in Fig.7.

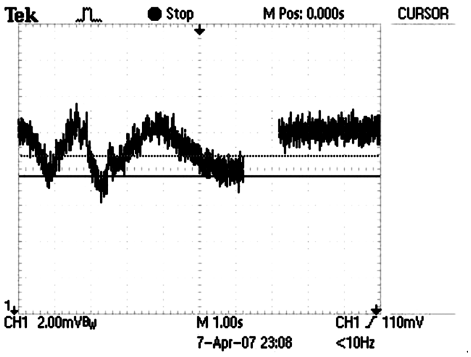


Fig.7. Oscillation of power output while the fibre is pressed.

In the experimental system the elasto-optical coefficients P_{11} and P_{12} are 0.126 and 0.27 respectively, the Passion coefficient μ is 0.17, the refractive index of the fibre, n, is 1.458 and the forced length of the fibre, L, is 8 mm. When the laser power varies from peak to valley the feedback light phase difference $\Delta\phi$ is 180°C. By substituting these data into Eqs.(8) and (9), the distortion of the fibre is obtained to be 0.016 mm. In our experiment, the reading difference of the micrometer is 0.015 mm as the laser power output varies from peak to valley. Therefore, the difference between the experiment result and the theoretical data is very small, which mainly comes from the error in reading of the micrometer. The accuracy and sensitivity will be enhanced if more fibre rings are used to increase the length of forced fibre in the system. This experiment demonstrates that the fibre sensor based on laser self-mixing interference is feasible.

4. Conclusion

In this paper, a novel fibre sensor based on laser self-mixing interference is presented and its basic theory is also discussed. The fibre sensor is simple in structure but high in accuracy. It combines the advantages of the laser self-mixing interference with those of a fibre sensor. The experimental results obtained reveal that the variation in feedback light phase nearly accords with the theoretical data. In conclusion, this type of fibre sensor opens up new prospects for fibre sensors and is hopeful to be substituted for the interference fibre sensor under some conditions.

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