Research on sensing characteristics of low-finesse fiber-optic Fabry-Perot cavity

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ABSTRACT

The Low-Finesse Fabry-Perot(F-P) cavity, as a kind of fiber-optic sensor probe frequently used, can be applied to detect physical parameters of strain, temperature, acoustic wave, pressure, and so on, and is an important optical sensing component. In this paper, sensing properties of low-finesse F-P cavity is deeply and systemically analyzed. At first, the interference principle of F-P cavity is illuminated from three aspects which include the distribution of light power, the characteristic of interference fringe and the sensitivity. Considering the spectrum of incident beam obeys a Gaussian distribution, the intensity distribution of reflected beam is approximate to a cosine function within a Gaussian envelope and the visibility of interference fringes follows a Gaussian distribution also. Moreover, the operating point of low finesse F-P cavity must be held near the quadrature-point for the maximum sensitivity. The operating characteristic of F-P cavity is analyzed from three aspects including linearity, property of temperature and contrast of fringe. Analyzing results show that the F-P cavity can offer the linearity of 2.2%, and the fringe contrast drops as the length of F-P cavity increases. In addition, the F-P cavity is insensitive to the change of environmental temperature and possesses an excellent capability to suppress the temperature disturbance. Finally, a test scheme is established to verify the sensor performance of F-P probe. Test results indicate that the F-P cavity offers the sensitivity of 7.5V/um and the measuring accuracy of 9.4nm, and can well satisfies the practical requirement.

Keywords: Fabry-Perot cavity; low-finesse; fringe contrast; detection

1. INTRODUCTION

The fiber-optic Fabry-Perot(F-P) sensor, as a new type of sensor, is proved to has a bright application prospect in the areas of health monitoring of large-scale structure, aeronautics and astronautics and smart materials because of characteristics of high sensitivity, anti-electromagnetic interference, corrosion resistance, electrical insulation[1,2]. Compared with other types of fiber-optic sensors, the Fabry-Perot(F-P) sensor is provided with the simple structure and the small size, and is suitable for the mass production. So the fiber-optic F-P sensor has been applied in measuring various of physical parameters such as displacement, temperature, pressure and so on[3,4].
The extrinsic fiber-optic F-P cavity, as the sensing probe used for constituting the F-P sensor, is an important optical device. The F-P cavity is formed by a silicon capillary and two single-mode fiber-optic end-face. The incident fiber and the reflected fiber are inserted into a silicon capillary, which is used to keep the paralleling and coaxial alignment of two fiber-optic. Disturbed by the detecting parameters, the amplitude of output signal of F-P cavity alters with the change of cavity length based on multi-beam white light interference principle. As the change of output signal is relative with the measuring parameters, the change of detecting parameters can be demodulated by the signal conditioning and processing system.
In this article, the sensing mechanism and the operation properties of the fiber-optic F-P cavity are discussed, deeply and systematically. The research results lay a solid theoretical and experimental basis for promoting the practical application of the sensor as soon as possible.

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2. SENSING MECHANISM OF F-P CAVITY

2.1 Structure of the F-P sensor system

The structure of the F-P sensor system, consisting of the laser diode, single-mode fiber-optic coupler, F-P sensing probe, photodiode, is shown in the Fig.1. In the proposed fiber-optic F-P sensor system, the F-P sensor probe is illuminated by a laser diode through a 2×2 single-mode fiber-optic coupler. The reflected beam is detected from one of the input ports of the coupler. One of the output ports of coupler is connected to the F-P sensor probe, and the other output port of the coupler is dipped into the refractive index matching liquid to eliminate any reflected light beam from the unused port.

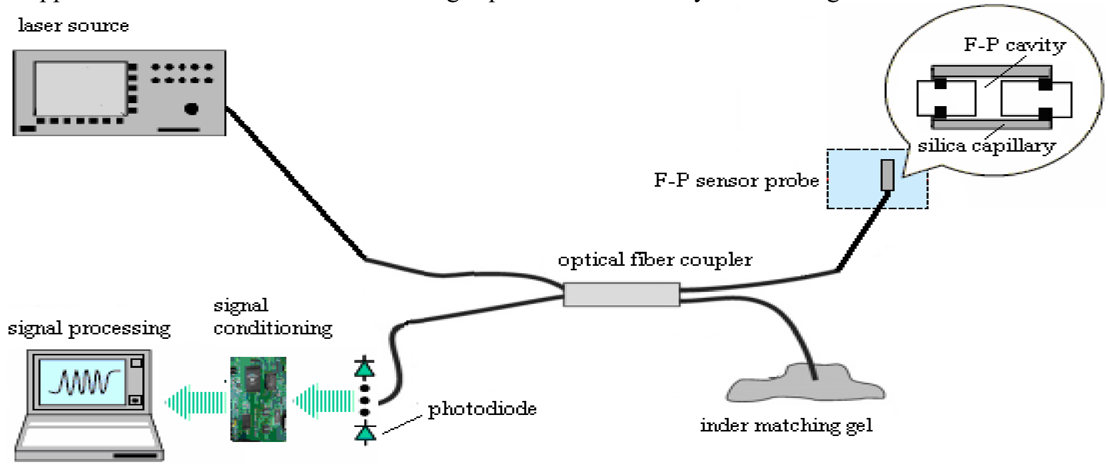

Figure 1 Structure of fiber-optic F-P sensor system

2.2 Interference characteristics of F-P probe

The interference properties of the fiber-optic F-P cavity dominate the performance of the F-P sensor. Considering the end-face reflectivity of the incident fiber and the reflected fiber constituting the F-P cavity is approximately equal in the F-P sensor system shown in the Fig.1, the interference intensity I_r of light beam reflected from the F-P cavity can be expressed as

$$\begin{aligned} I_r &= 2RI_0\left\{1+\exp[-(2L/L_C)^2]\cos\theta\right\} \\ &= A(1+V\cos\theta) \end{aligned} \tag{1}$$

Where R is the reflectivity of F-P cavity, I_0 the light intensity entering into the F-P cavity, A a constant, A=2RI_0, L the length of F-P cavity, θ the interference phase of F-P cavity, V the functions of the fringe visibility, V=exp(-(2L/L_C)^2), L_C=[4ln(2c^2)/($\pi^2\Delta f^2$)]$^{1/2}$, c and Δf are the light velocity and FWHM of beam entering into the F-P cavity, respectively.

It can be concluded from Eq.(1) that the intensity distribution of light beam reflected from the F-P cavity is approximate to a cosine function within a Gaussian envelope, and the fringe visibility follows a Gaussian distribution too. The simulation results for the intensity distribution of reflected light beam and the fringe visibility of the F-P cavity are shown in Fig.2 and Fig,3, respectively.

In order to obtain the maximum sensitivity, the differentiation of Eq.(1) can be express as

$$k_s = \left|\frac{dI_{\text{gzr}}}{dL}\right| = 8RI_{z0}\exp\left(-\left(\frac{2L}{L_C}\right)^2\right)\left(\frac{2L}{L_C^2}\cos\theta + \frac{\pi f}{c}\sin\theta\right) \tag{2}$$

According to Eq.(2), the expression 2L/(L_C)2<<1 can be obtained and interference visibility V is about 1 when the length of the F-P cavity is far less than L_C, we have

$$k_s = 8RI_{z0}\frac{\pi f}{c}\sin\theta \tag{3}$$

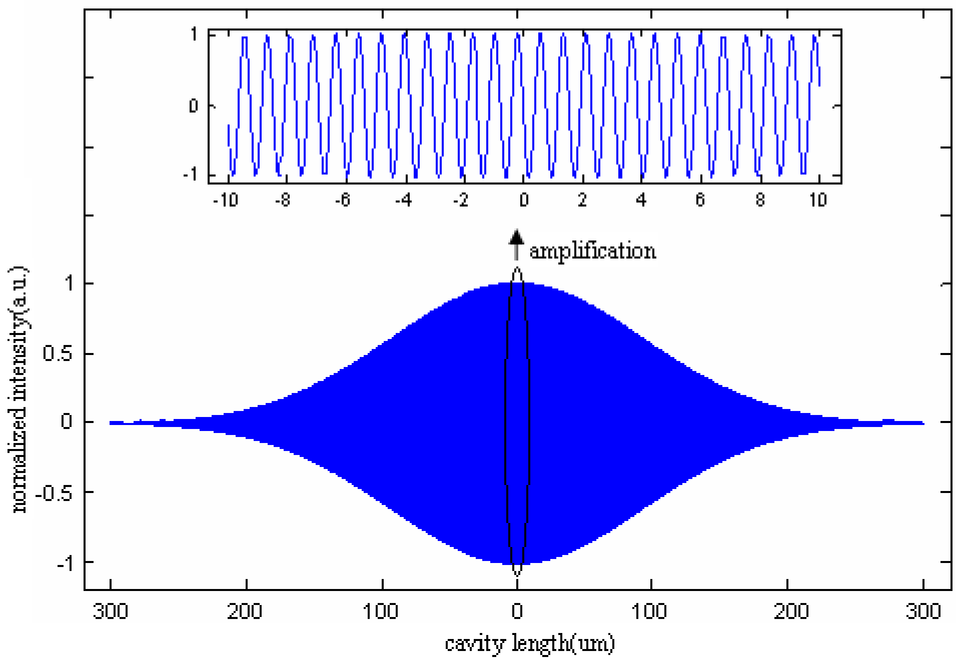

Figure 2 Interference-intensity distribution of F-P cavity

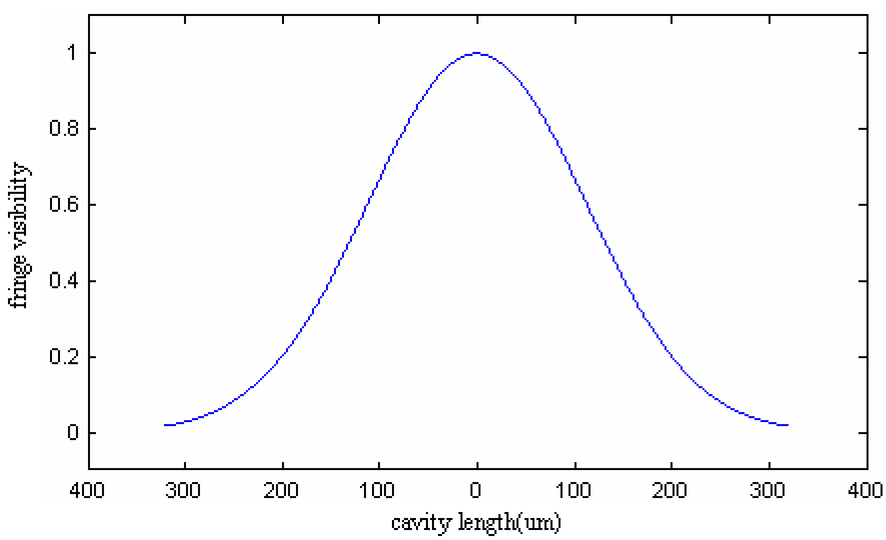

Figure 3 Fringe visibility via cavity length

Considering the expression $2RI$ is equal to 1 and the range of cavity length changes from 17um to 19um, the simulation results for the relationship between the interference intensity and the sensitivity can be obtained, which is shown in Fig.4. It can be concluded from simulation results that the maximum sensitivity of the F-P cavity is achieved when the length of the F-P cavity is located at the midpoint of the linear region of the interference intensity. Therefore, the length of F-P cavity must be reasonably designed to ensure the maximum sensitivity of the F-P sensors.

3. OPERATION PROPERTIES AND TEST RESULTS OF F-P PROBE

The change of cavity length ΔL induced by the ambient temperature can be depicted as

$$\Delta L = \left(a_g L_g - a_i L_i - a_f L_f\right)\Delta T \tag{4}$$

where ΔT is the variation of the temperature, α_g, α_i and α_f are the coefficient of thermal expansion of the silicon capillary, the incident fiber and the reflected fiber, respectively.
Under the cavity length is far less than the welding distance of the F-P cavity, Eq.(4) is simplified as

$$\Delta L = \left(a_g - a_i\right) L_g \Delta T \tag{5}$$

In accordance with the Eq.(5), the disturb of the ambient temperature can be well eliminated under the coefficient of thermal expansion of the silicon capillary is approximately equal to the one of the single-mode fiber-optic.

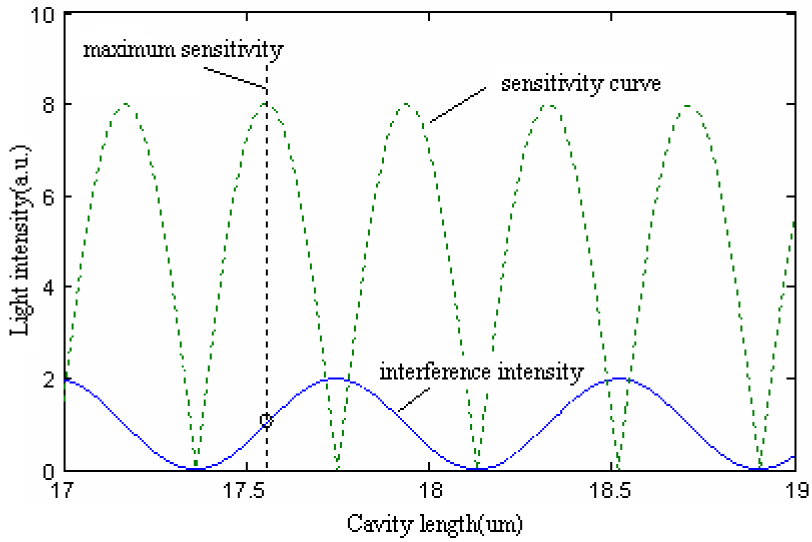

Figure 4 Interferenc intensity and sensitivity curve of F-P cavity

In fiber-optic F-P sensing probe, the coupling efficiency between the incident fiber and the reflected fiber directly determines the interference contrast of the F-P cavity, which dominates the signal to noise ratio of the F-P sensor. Considering the coupling loss caused by the divergence of the transmitting beam in the space and the aperture effects of fiber optic, the optical field distribution of fundamental mode of light beam propagating in the free space can be described by Huygens-Fresnel diffraction integral[5]

$$E(r_g, L) = E_0 \frac{\omega_0}{\omega(L)} \exp\left(-\frac{r_g^2}{\omega^2(L)}\right)$$

$$\omega_0 = a_r (0.65 + \frac{1.619}{F_0^{\ 1.5}} + \frac{2.879}{F_0^{\ 6}})$$

$$\omega(L) = \omega_0 \sqrt{\omega_0 + \left(\frac{L}{L_R}\right)^2} \tag{6}$$

where r_g is the radial component of cylindrical coordinates, E_0 the normalized amplitude of optical field distribution of fundamental mode, ω_0 the mode field radius of the light field propagating in the step-type single-mode fiber, a_r the core diameter of the single-mode fiber-optic, F_0 the normalized frequency of single-mode fiber-optic, $F_0=(2\pi a_r/\lambda)NA$, NA the numerical aperture of single-mode fiber, $\omega(L)$ the mode diameter of optical field propagating in the air, L_R the rayleigh distance, $L_R=(\pi\omega_0^2)/\lambda$.
Based on the Eq.(6), an overlap integral between the optical field of the returning Gaussian beam with the mode field radius $\omega(L)$ and the optical field of the Gaussian beam propagating in the optical fiber with the mode field radius ω_0 can be calculated. Thus the coupling coefficient C_s between two optical fields is as follow

$$C_S(L) = \frac{2\omega_0 \omega(L)}{\omega_0^2 + \omega^2(L)} \tag{7}$$

According to the definition of the interference fringe and combining with the Eq.(7), we have

$$V(L)=\frac{I_{gr_{\max}}-I_{gr_{\min}}}{I_{gr_{\max}}+I_{gr_{\min}}}=\frac{2(1-R)C_S(2L)}{1+(1-R)^2C_S^2(2L)} \quad (8)$$

Considering the diameter of single mode fiber $2a_r$ and the numerical aperture of single mode fiber are equal to 8.3um and 0.14, respectively, the curve about the interference intensity of the F-P cavity changing with the cavity length is shown in Fig.5, and the relationship between the contrast of the interference intensity and the cavity length is shown in Fig.6.

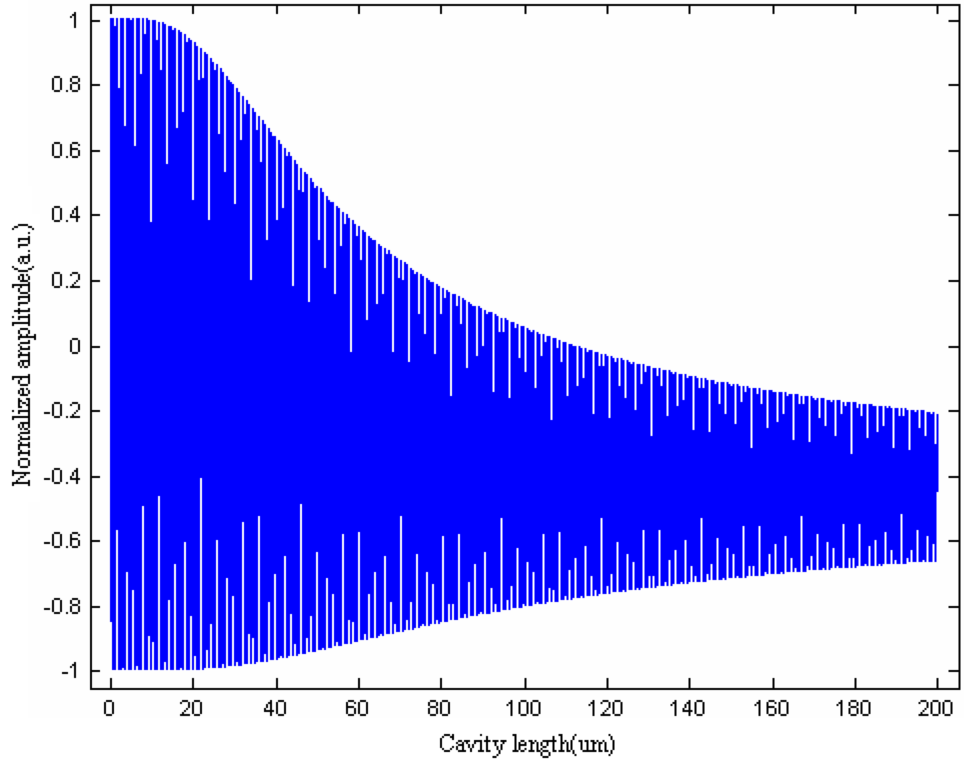

Figure 5 Interference fringe via cavity length (L=0~200um)

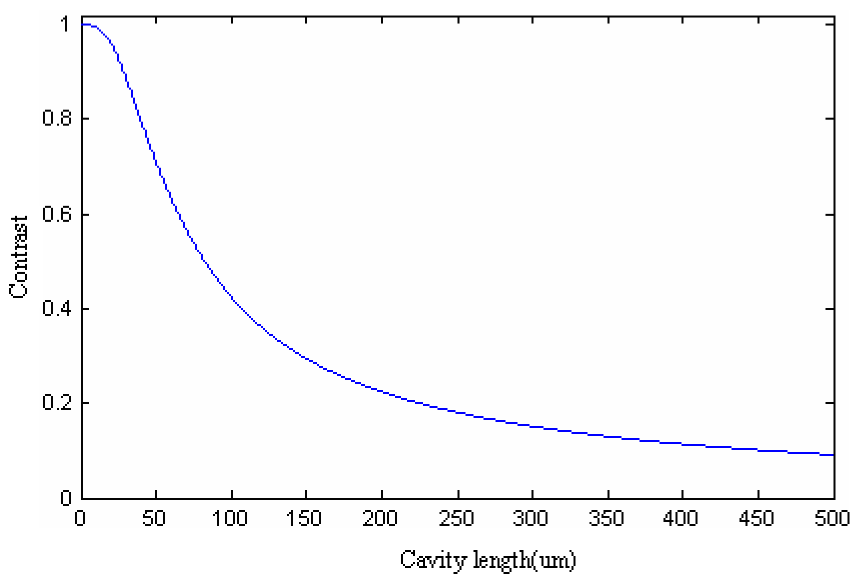

Figure 6 Interference fringe contrast via cavity length

According to Fig.1, the test scheme is established to test the performance of the F-P cavity. As the initial length of the F-P cavity is equal to 17.76um and the cavity length of the F-P cavity changes from 17.66um to 17.85um, the output signals of sensor system is shown in Fig.7. It can be concluded that the sensitivity of 7.5V/um can be obtained with the measuring accuracy of 9.4nm, and the linearity of the F-P sensor system is about 2.2%.

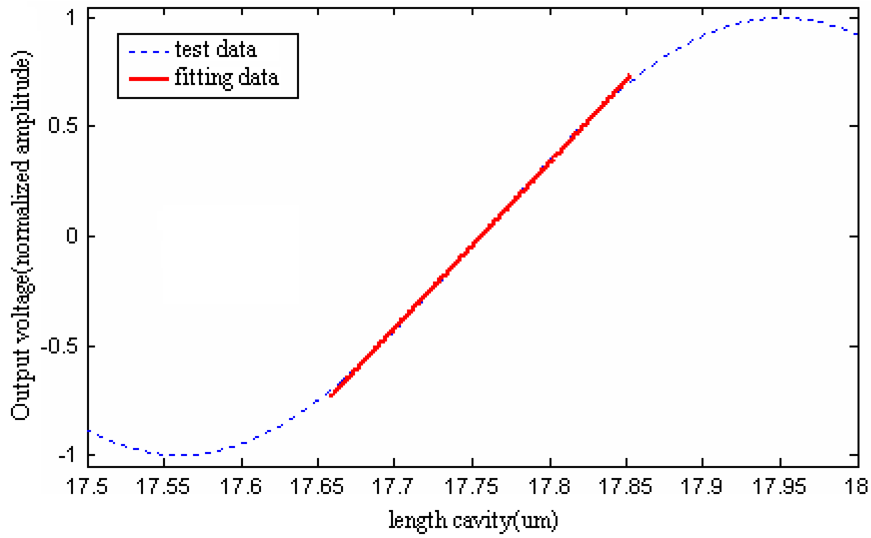

Figure 7 Test results

4. CONCLUSIONS

The fiber-optic F-P sensors is an important member of optical fiber sensors and the low-finesse F-P cavity is a important optical devices used as the sensing probe. In order to illuminate the sensing mechanism, light-intensity distribution, characteristics of interference fringes and sensitivity of low finesse F-P cavity is elaborated. Test results indicate that the F-P sensor system can successfully detect the change of cavity length induced by some parameters such as the strain, temperature and so on. The linearity of sensor system is 2.2% with the measuring precision of 9.4 nm and the sensitivity of 7.5V/um. Thus the low-finesse F-P probe has an excellent performance for constituting the sensor system which can be used to detect various parameters.

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