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Demodulation of micro fiber-optic Fabry–Perot interferometer using subcarrier and dual-wavelength method

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ABSTRACT

Subcarrier technology and dual-wavelength demodulation method are combined for tracking the cavity length variation of a micro fiber-optic Fabry–Perot (F–P). Compared with conventional dual-wavelength demodulation method, two operation wavelengths for demodulation are modulated with two different carrier frequencies, respectively, and then injected into optical link connected with the F–P cavity. Light power reflected for the two wavelengths is obtained by interrogating the powers of Fast Fourier Transform (FFT) spectrum at their carrier frequencies. Because the light at the two wavelengths experiences the same optical and electrical routes, measurement deviation resulting from the drift of optical and electrical links can be entirely eliminated.
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1. Introduction

The fiber-optic F–P sensor has been widely used in measurement of temperature [1–3], strain [4–7], vibration [8], acceleration [9], refractive index [10–12], pressure [13–15], et al., due to its advantages of simple structure, small size, light weight, temperature insensitivity and precision. Intensity and white-light interferometric demodulation methods are most commonly used to obtain cavity length variation induced by the measurand. White-light interferometry can be used to obtain the absolute cavity length, while it is relatively complex in that it always involves some movable elements or some expensive spectrum receivers [16–17]. Intensity demodulation is quite simple, but this method is susceptible to fluctuation of the light intensity, vibration of the optical path, variation of the fiber transmission attenuation and parameter drift of electrical circuits [18–21].

In this paper, a novel demodulation method based on subcarrier technology for micro F–P cavity is presented and demonstrated. The two light beams with different wavelengths modulated at different frequencies propagate the same optical path and electric circuits. Compared with the intensity demodulation method [18–21], the influences from light source, optical path and detector etc. can be completely eliminated. Compared with the white-light interferometric demodulation method [16–17], the cost of demodulation method we demonstrated is quite low and simple, and has higher measurement speed.

2. Sensing system structure and principle

The demodulation system is shown in Fig. 1. An in-fiber air cavity used as a strain sensor is machined by a 157 nm laser system with micrometer scale cavity length [4,12,21–23]. Due to the cavity length variation of such a micro F–P cavity is always less than λ/4, intensity demodulation is suitable.

Assume the intensity of each modulated light that with different wavelengths are

$$I_1 = A_1 + B_1 \cos(2\pi f_1 t) \quad (1)$$

$$I_2 = A_2 + B_2 \cos(2\pi f_2 t) \quad (2)$$

where A_1 and A_2 are DC components of light intensity, B_1 and B_2 are AC components of light intensity, f_1 and f_2 are modulated frequency, t is the time. The light is split into two beams as 1:99. 1% of the light is sent into the reference channel while 99% of the light into the signal channel.

Assume the total loss α for reference channel and β for signal channel. The reflectivity of two different wavelengths in the F–P cavity are $R(\lambda_1)$ and $R(\lambda_2)$

$$R(\lambda_1) = 2R[1 - \cos(4\pi l/\lambda_1)] \quad (3)$$

$$R(\lambda_2) = 2R[1 - \cos(4\pi l/\lambda_2)] \quad (4)$$

where l is length of the F–P cavity and the surface reflectivity R in F–P cavity is approximately 4%.

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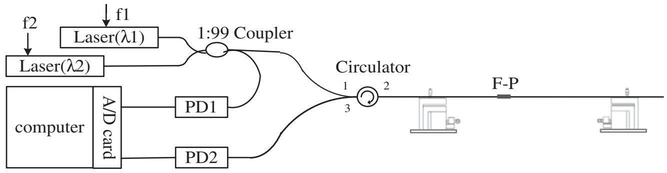

Fig. 1. Demodulation system.

After sampling with an A/D card, the voltage signals converted from reference channel and signal channel are given by the expressions:

$$V_1 = [A_1 + B_1 \cos(2\pi f_1 t) + A_2 + B_2 \cos(2\pi f_2 t)]\alpha \quad (5)$$

$$V_2 = [A_1 + B_1 \cos(2\pi f_1 t)\beta R(\lambda_1) + [A_2 + B_2 \cos(2\pi f_2 t)]\beta R(\lambda_2). \quad (6)$$

V_1 and V_2 are detected and then fast-fourier-transformed. M_1 and M_2 are amplitudes of corresponding peaks at f_1 and f_2 in FFT spectrum from V_1 and can be expressed as:

$$M_1 = \frac{1}{2}B_1\alpha \quad (7)$$

$$M_2 = \frac{1}{2}B_2\alpha. \quad (8)$$

Also, we get the peak amplitudes N_1 and N_2 from FFT spectrum of V_2 as follows:

$$N_1 = \frac{1}{2}B_1\beta R(\lambda_1) \quad (9)$$

$$N_2 = \frac{1}{2}B_2\beta R(\lambda_2). \quad (10)$$

For eliminating the influences the drift induced by optical and electrical link. The following calculation is performed:

$$\frac{N_1}{M_1} = \frac{\beta}{\alpha}R(\lambda_1) \quad (11)$$

$$\frac{N_2}{M_2} = \frac{\beta}{\alpha}R(\lambda_2). \quad (12)$$

So, the influence by optical source has been eliminated. For obtaining the cavity length, by using Eqs. (11) and (12), we get

$$K = \frac{\frac{N_1}{M_1}}{\frac{N_1}{M_1} + \frac{N_2}{M_2}} = \frac{R(\lambda_1)}{R(\lambda_1) + R(\lambda_2)} = \frac{1 - \cos\left(\frac{4\pi l}{\lambda_1}\right)}{1 - \cos\left(\frac{4\pi l}{\lambda_1}\right) + 1 - \cos\left(\frac{4\pi l}{\lambda_2}\right)} \quad (13)$$

$$K' = \frac{\frac{N_1}{M_1}}{\frac{N_2}{M_2}} = \frac{R(\lambda_1)}{R(\lambda_2)} = \frac{1 - \cos\left(\frac{4\pi l}{\lambda_1}\right)}{1 - \cos\left(\frac{4\pi l}{\lambda_2}\right)} \quad (14)$$

K and K' are only relative to l, and unrelated to light intensity and electrical parameters. It is also found that K has a better linearity than K' to l, so Eq. (13) is used to calculate.

3. Static strain test

In the experiment, two semiconductor lasers with wavelengths of $\lambda_1 = 1535$ nm and $\lambda_2 = 1554$ nm are used. Line widths are both 0.2 nm. The two light sources are modulated by two sine-wave electrical signals with 200 kHz and 500 kHz, respectively. Peak to peak voltage of the signals is 1 V. Then the light is mixed together. 1% of the light is sent into the reference channel and 99% of the light into the signal channel.

The light of the signal channel firstly passes through a circulator, and then is sent into F–P cavity. The reference signal and sensing signal are detected by the two detectors (New focus 1153) and collected through an A/D acquisition card (PCI4712AS2), and finally sent to the computer for calculation. K is calculated using the principle given above. The F–P cavity used here, with a cavity length of 29.70 μm and a contrast of 23 dB, is fabricated by the 157 nm laser, as shown in Fig. 2. The sensor is fixed on two translation stages. The distance between two fixed points is 380 mm, and the displacement accuracy of the translation stages is ~1 μm.

For a certain F–P cavity, the ratio K is unique. Therefore, the ratio K and the cavity length l could be obtained by using an optical spectrometer (Si720, MOI, USA). With the translation stages, the relationship between the ratio K and displacement are confirmed. When the translation stage changed, the cavity length is obtained by using an optical spectrometer (Si720, MOI, USA), then the relationship between the cavity length and the ratio K are obtained.

For verifying the method whether it could remove intensity variation of optical link or electrical route. Parameters of lasers and detectors, state of the optical link are randomly changed. It is observed that K keeps an unchanged relationship with the applied stain, as given by Fig. 3(a). The experimental and simulated results are also compared, as shown in Fig. 3(b). It is found that the experimental results agree with the simulated result.

Then, in order to confirm the relationship between the ratio K and F–P cavity length, a static strain test is carried out again using an optical spectrometer (Si720, MOI, USA) to observe relationship between the cavity length and displacement, as shown in Fig. 4. Here, the cavity length l is calculated by using white-light interferometry.

Furthermore, the relationship between K and cavity length is also achieved from Figs. 3 and 4, as shown in Fig. 5. There is a very good linear relationship between ratio K and the cavity length, as shown in Fig. 5.

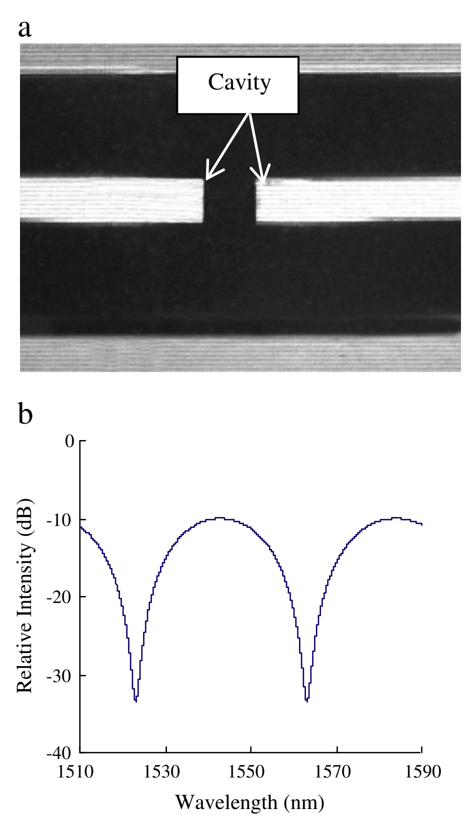

Fig. 2. (a) Photograph of the F–P cavity acquired by an optical microscope in a transmission mode (b) reflective optical spectrum of the F–P cavity.

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