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Correlation Demodulation of Output Spectrum of Fabry-Perot Cavity

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Abstract: Based on the correlation theory, a demodulation method of fiber Fabry-Perot cavity length is proposed. The method applies a special correlation factor to form a signal which is similar with the output signals of Fabry-Perot cavity, and then the maximum correlation coefficient which is corresponding to a single peak at the cavity length is calculated. The output signal characters are analyzed theoretically and calculated numerically by correlation demodulation method. A system using the Gauss broad-band light source and high precision spectrometer is set up to confirm the demodulation method experimentally. Results show that the output spectrum can be demodulated well in this system.

Keywords:nonlinear signal; correlation demodulation; Fabry-Perot cavity

1 Introduction

During recent years, Fabry-Perot cavities have been applied to a variety of areas, such as fiber communication, fiber sensor and fiber laser. Especially in monitoring system, Fabry-Perot cavities are suitable for online and high-precise measurement. Firstly, the material of the fiber Fabry-Perot cavity is silicon dioxide, so it can withstand high temperatures and it is much less sensitive to the change of temperature than other common sensors. Secondly, it is easy to transmit signals with fiber. In addition, its response is high-speed and its sensitivity to high-level signals is adequate [1-4]. Generally speaking, the length of Fabry-Perot cavity reflects the variation of external parameters such as the pressure. Thus the length demodulation of Fabry-Perot cavity is the key factor of measurement system. However, the cavity length is difficult to be demodulated because of the nonlinearity and weakness of spectral signal.

At present, many demodulation methods have been provided in the reference and were classified as intensity modulation method and phase modulation method [5-14]. The intensity modulation method has high sensitivity and high response speed, but the system achieves lower accuracy under the conditions of external interference, so it is less paid attention to. The phase modulation method has the high noise immunity because of applying the spectrometer in the measurement system, so it is widely used in the practical engineering. Therefore many phase modulation methods have been the research hotspots, for example Fast Fourier Transform demodulation method, Discrete Gap Transform demodulation method, tunable cavity demodulation method and optical wedge demodulation method etc.

According to the characteristic of Gauss distributed optical source, fast Fourier transform demodulation method can demodulate directly the cavity length. In this method, the data samples are one-to-one correspondence with the equal optical wavelength interval and the peak frequency is related to cavity length in the frequency domain [5-8]. It has some disadvantages, for example, the demodulation speed is very slow and it is only suitable to some special cases. Discrete Gap Transform demodulation method was proposed for the series and parallel mixed multiplexing system [9, 10]. A system set up on DSP platform was designed to demodulate the variation of cavity [11]. It is simple and reliable, but the cost is high. In addition, the

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IJNS.2008.08.15/162

tunable cavity demodulation method was set up for a system based on the tunable Fabry-Perot filter [12]. When the length between Fabry-Perot cavity and the tunable Fabry-Perot filter are equal, the output arrives peak value. The optic wedge demodulation method is similar with the tunable cavity demodulation method [13, 14]. When the thickness of the optic wedge equates to the measurement cavity length, the output optic intensity is peak value [15]. The theoretical foundation of these two methods above is the correlation theory. And they have advantages of low cost, high speed and high sensitivity.

In this paper, the correlation demodulation method is considered. Based on the correlation theory, our method applies a special correlation factor to form a signal which is similar with the output signals of Fabry-Perot cavity, and then calculates the maximum correlation coefficient which is corresponding to a single peak at the cavity length.

2 Theory Analysis

The principle of Fabry-Perot cavity is similar to that of the parallel platewhich is based on the multi-beam interference principle as shown in figure 1[15, 16]. If there is a phase difference between the transmission light and reflection light, the multi-beam interference will be happened.

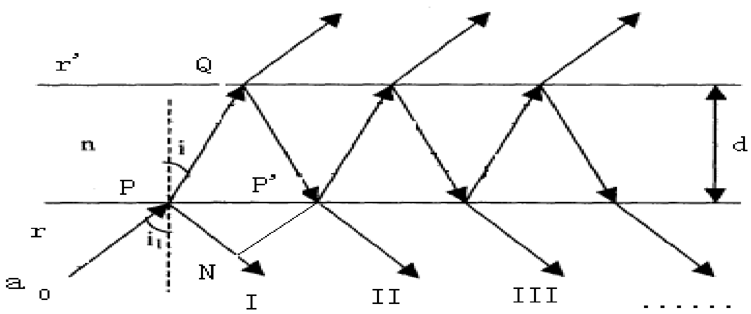


Figure 1: Structure of parallel plate

As shown in Figure 1, the adjacent light path difference L is,

$$L = n\overline{PQP'} - n_0\overline{PN} = n\frac{\overline{PP'}}{\sin i} - n_0\overline{PP'}\sin i \tag{1}$$

where n is the refractive index of plate and i is the incident angle. Assumed the thickness of plate that is, the cavity length is d, then

$$\overline{PP'} = 2d\tan i \tag{2}$$

Then the phase difference is defined as

$$\delta = 2\pi\frac{L}{\lambda} = \frac{2\pi}{\lambda}2nd\cos i \tag{3}$$

If absorption of reflecting surface is neglected, the reflectance R is ratio of the reflected-beam intensity to the incident-beam intensity and the input intensity is I_0, the output intensity can be represented as Eq. (4).

$$I(d,\lambda) = \frac{4R\sin^2(\frac{2\pi d}{\lambda})}{(1-R)^2 + 4R\sin^2(\frac{2\pi d}{\lambda})} \cdot I_0 \tag{4}$$

where d and λ are the length of the cavity and the incident wavelength, respectively.

In practice engineering application, monochromatic light source is expensive and it is difficult to be controlled. The polychromatic light source of Gaussian distribution is used to replace the monochromatic light source. Suppose the intensity of polychromatic light source is [3]

$$I_0(\lambda) = I_0 \cdot e^{-(\frac{\lambda-\lambda_P}{B_\lambda})^2} \tag{5}$$

where λ_P is the peak wavelength of the source spectrum and B_λ is the half-width of Gaussian function. The output intensity is

$$I(d) = \int_{\lambda_{\min}}^{\lambda_{\max}} I(d,\lambda)\mathrm{d}\lambda = \int_{\lambda_{\min}}^{\lambda_{\max}} \frac{4R_1\sin^2(\frac{2\pi d}{\lambda})}{(1-R_1)^2+4R_1\sin^2(\frac{2\pi d}{\lambda})} \cdot I_0^2 \cdot e^{-(\frac{\lambda-\lambda_P}{B_\lambda})^2}\mathrm{d}\lambda \tag{6}$$

Thus the correlation demodulation can be represented by correlation coefficient [17]. If there are two signals $x(t)$and$y(t)$, the correlation coefficient is defined as

$$\rho_{xy} = \frac{\int_{-\infty}^{\infty} x(t)y(t)dt}{\left[\int_{-\infty}^{\infty} x^2(t)dt \cdot \int_{-\infty}^{\infty} y^2(t)dt\right]^{1/2}} \tag{7}$$

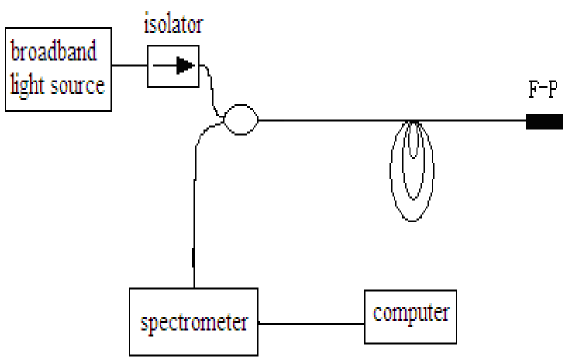
When $x(t)$and$y(t)$ are completely dissimilar, that is, they are mutually independent and uncorrelated, the value of correlation coefficient is 0. When $x(t)$and$y(t)$ are fully similar, the value is 1. Thus we can calculate the value of correlation coefficient to judge the similarity degree of two signals.

If the spectrum of the broadband light source and the reflectance R are known, the function which has a variable parameter$l$, can be constructed and presented by means of software and hardware. The value of parameter$l$ covers all possible values of cavity length, that is,$l = d + \Delta l$, where $\Delta l$is the difference between the measured length and the constructed value. Thus the output signal after correlation is expressed as

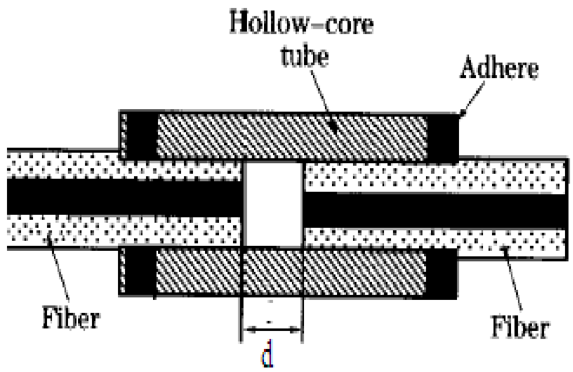
$$I(d,l) = \int_{\lambda_{\min}}^{\lambda_{\max}} I(d,l,\lambda)\mathrm{d}\lambda = \int_{\lambda_{\min}}^{\lambda_{\max}} I(d,\lambda)\cdot I(l,\lambda)\mathrm{d}\lambda = \int_{\lambda_{\min}}^{\lambda_{\max}} I(d,\lambda)\cdot I(d+\Delta l,\lambda)\mathrm{d}\lambda \tag{8}$$

We calculate the correlation coefficient value of $I(d)$ and$I(d+\Delta l)$. When$\Delta l = 0$,$d = l$ that is$I(d) = I(l)$, the correlation coefficient is the peak value. As long as the cavity length corresponding to the peak value is got, the demodulation has been accomplished.

From above analysis, the most important procedure is to generate the correlation function with our programs. The output signals containing cavity length information are received by fiber optic spectrometer. The correlation demodulation system is shown in figure 2.



(a) System composition



(b) Fabry-Petot cavity composition

Figure 2: Demodulation system

The measuring system consists of a broadband light source and an isolator. The Fabry-Perot cavity is illuminated by Gauss distributed incident light. The variations of spectrum of reflect light responses the variations of cavity length. The spectrometer receives the spectrum signal of reflect light. The computer generates the correlation function and the result.

To be worth, for reducing the effects of the output signal fluctuation, the normalization processing is important to calculate the correlation coefficient. Therefore, the normalized reflect light$I'(d)$ is

$$I'(d) = \frac{I(d) - I_{\min}}{I_{\max} - I_{\min}} \tag{9}$$

3 Experiments

In our experiment system the white light source is used and its spectral range is ranged from 500nm to 700nm. Figure 3 shows the normalization spectrum curve. The length of Fabry-Perot cavity is 40μm and its reflection coefficient is 0.04. The output spectrum is shown in Figure 4.

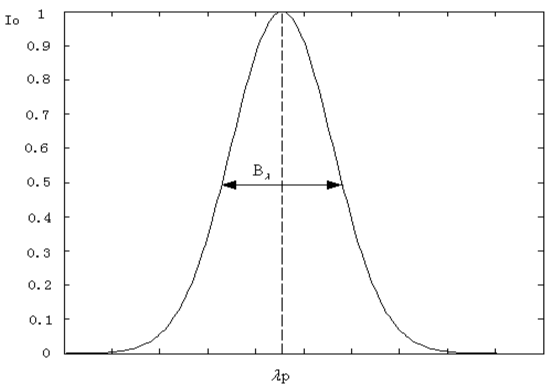


Figure 3: The normalization spectrum of Gaussian source

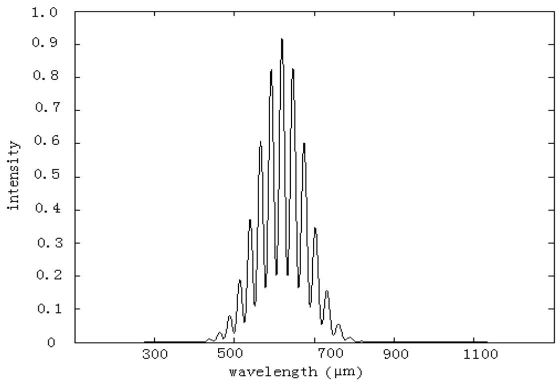


Figure 4: The normalization output spectrum of cavity

The parameter$l$ takes a range from 0 to 100μm, that is, the change ofΔl. According to the theory analysis in section 2, when $\Delta l = 0$, $d = l$ and the correlation coefficient is at peak value. In particular, the low frequency range(010μm) has a maximum value, which should be eliminated. The correlation coefficient curve is shown in Figure 5. And it is easy to see $d = l = 40$. So this correlation demodulation method can accurately calculate the given cavity length.

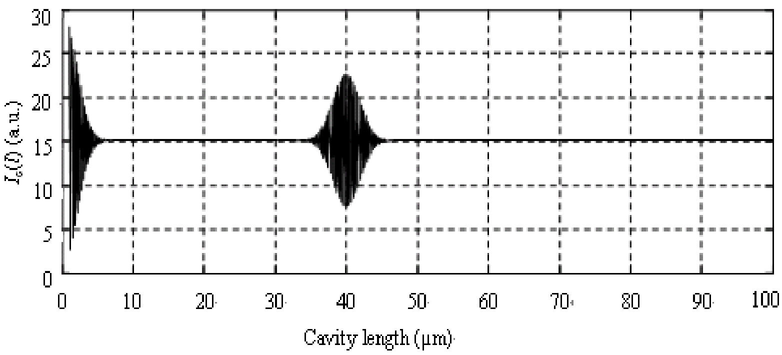


Figure 5: Simulated curve of correlation coefficient

The correlation demodulation experiment system is illustrated in figure 6. The motor drives uniformly the composite materials equi-strength beam stretch, then the measuring instrument receives the spectrum and demodulates the cavity length. And the result is shown in figure7. The pertinence coefficients is more than 0.999, and the standard deviation is about 0.49μm

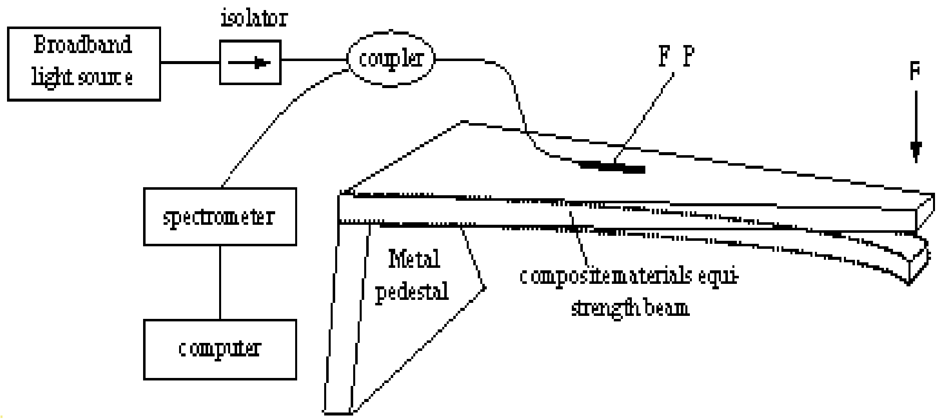


Figure 6: Correlation demodulation experiment system

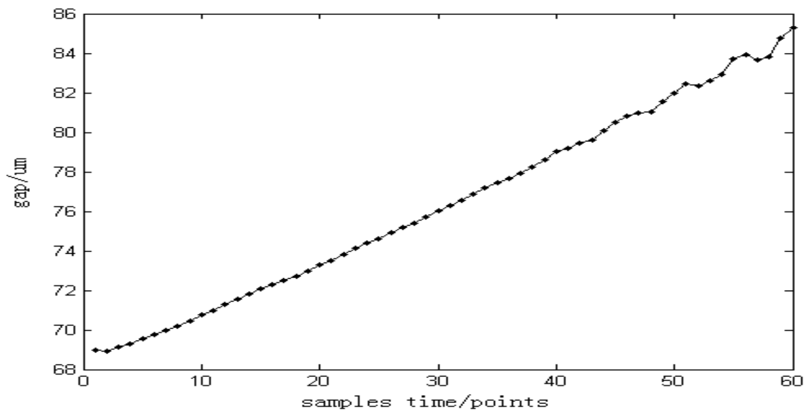


Figure 7: Experiment result

As indicated in figure 7, the measurement data has good linearity and small fluctuation. Thus this demodulation system can demodulate the cavity length and be applied in the practical engineering applications.

4 Conclusions

A correlation demodulation method of output spectrum of fiber Fabry-Perot cavity is reported. A special correlation factor similar with the output spectrum signals of Fabry-Perot cavity is generated to calculate the correlation coefficient. There is a maximum value corresponding to a single peak at the cavity length. Based on the correlation theory, the output signal characters are analyzed theoretically and calculated numerically. And a correlation demodulation system consisting of broad-band light source and spectrometer is designed. Then the pertinence coefficient 0.995 and the standard deviation 0.49μm are obtained experimentally by this system. Thus this demodulation method is valid and practical.

Acknowledgments

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