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A FBG Demodulation System Based On Nonlinear Edge Filter and the Virtual Wavelength Method

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Abstract: **A fiber Bragg grating（FBG）demodulation method based on nonlinear edge filter is used. Its basic principle is to use the ratio of two light signals to compute physical quantities. But under the condition of the same physical quantities, as energy of light source is changed, the ratio of two light signals has a small difference. Therefore, the instability problem of the system can be found and the ratio value correction method is used to solve the problem. The instability problem should be widespread in all light intensities demodulation methods such as edge filter demodulation method and matched filter demodulation method. In order to simplify the relationship between physical quantities and the ratio, Omit the wavelength that is the middle physical quantity, we use the method of virtual wavelength. The relationship between the actual wavelength and virtual wavelength is established. Compared with demodulation method of linear edge filter, our method can not only solve the instability problem and can improve the wavelength accuracy, but also can simplify the process.**

Keywords: **fiber Bragg grating demodulation, virtual wavelength method**

I. INTRODUCTION

The fiber Bragg grating is widely used because of its huge advantages, its basic principle is based on the variation of wavelength to determine the physical quantities. At present there are many demodulation technology of fiber Bragg grating demodulation technology, such as tunable F - P filter method [1,2], the M - Z interferometer method [3], matched filtering method[4], linear edge filter method [5-8]etc, these methods have their characteristics the linear Edge filter demodulation method is also applied widely. In the method, the edge filter is a linear filter. The basic idea is that the physical quantities can be determined by the the ratio of the two light signals. The characteristic of the linear edge filter is that the relationship between the transmittance and wavelength is linear. But actually, it is difficult to obtain linear filter, only one part of the filter is approximate to linear processing. So we use the nonlinear filter demodulation method. Around this method, the related problem is studied In the process of dealing with the ratio of two light signals, we found that under the same external physical quantities, while the energy of the light source is changed, the ratio of the two signal has a small difference, so the problems of system instability is happened, therefore, we need to solve this problem. In fact, not only an edge filter demodulation method has the problem, but also matched filter demodulation method should have the same problem.

The actual wavelength is used to calculate the relevant parameters in the linear edge demodulation method， Therefore,

accurate wavelength need to be measured. But the wavelength is just an intermediate physical quantity, does not need the measurement and calculation. In the study of nonlinear filter demodulation method, virtual wavelength method is used by us. Not only Wavelength is virtual, but also the relevant parameters are virtual. The relationship between actual wavelength and virtual wavelength is established. Although the concept of virtual wavelength has been used by some author [9], but it has not been used in the FBG demodulation system, the principle of virtual wavelength method has not been deduced; the relationship between virtual wavelength method and actual wavelength method has not been established Finally, through the analysis of wavelength resolution of non-linear filter demodulation method, nonlinear filter demodulation method has more accurate. The relationship of wavelength resolution between the actual wavelength and the virtual wavelength is established.

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2. THE BASIC PRINCIPLE

Similar to the linear edge filter demodulation method. The demodulation system is shown in Figure 1, light is emitted from the light source, passes through the coupler 1, arrives in FBG, is reflected by FBG, passes through the coupler 1 again, reach coupler 2, Light is split into two light signals, one light signal is detected by P_1 Detector, the other light signal is detected by P_2 Detector after passes through the nonlinear filtering

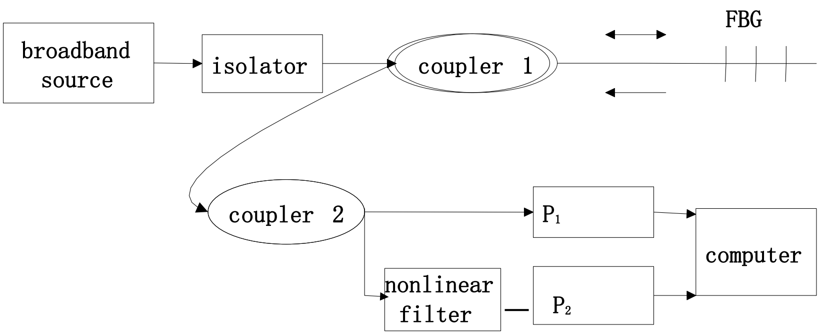

Fig.1 demodulation system of nonlinear filtering

Some devices can be used as the edge filter, such as F-P filter, CWDM （Coarse Wavelength Division Multiplexing. Where CWDM was adopted as the filter; the transmission curve is shown in fig.2

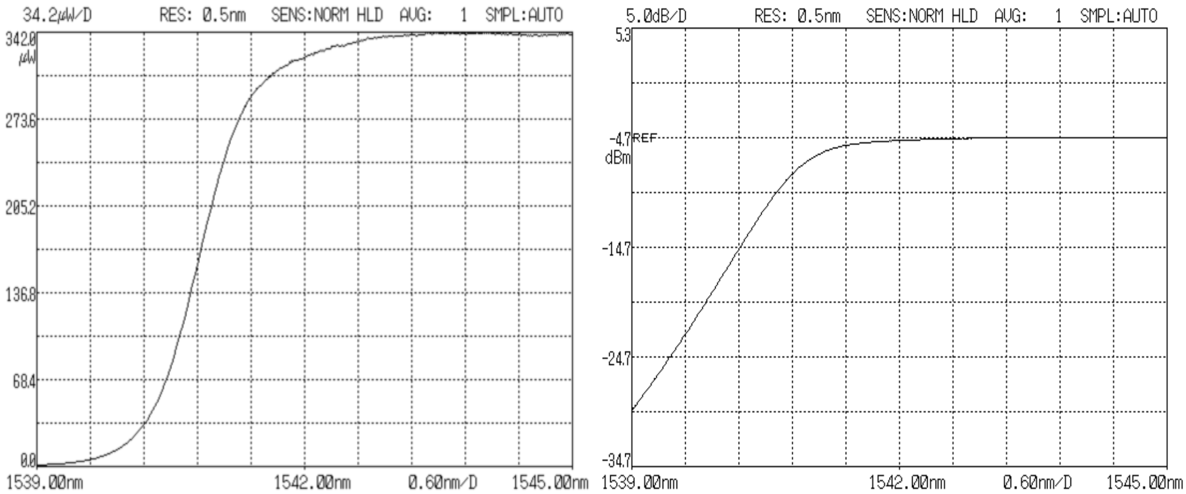

Fig.2 a. Curve of wavelength and light power Fig.2 b. Curve of wavelength and the logarithmic of light power

According to figure 1, if the signal of P_1 detector is I_1, the signal of P_2 detector is I_2, the ratio between I_2 and I_1 is m, the formula (1) can be derived,

$$m = \frac{I_2}{I_1} = kD(\lambda) \qquad (1)$$

Where, λ is wavelength, m is ratio between I_1 and I_2, $D(\lambda)$ is the transmittance curve of the filter, formula (1) shows that ratio is affected by the transmittance of the filter, if there is a linear relationship between $D(\lambda)$ and wavelength, a linear relationship between the ratio and the wavelength is established, that is the linear edge filter demodulation method. If transmittance of filters is approximate linear relationship with wavelength, the linear edge filter method will produce the error. According to the formula (1), the nonlinear edge filter demodulation method is adopted here. That is formula (2)

$$\lambda = k_0' + k_1'm + k_2'm^2 + k_3'm^3 + k_4'm^4 + k_5'm^5 + \qquad (2)$$

Where $k_0', k_1', k_2', k_3', k_4', k_5'$ is Polynomial coefficient. We assume that n=1/m, Formula (3) can be expressed in polynomial curve

$$\lambda = k_0 + k_1 n + k_2 n^2 + k_3 n^3 + k_4 n^4 + k_5 n^5 + \qquad (3)$$

Where k_0, k_1, k_2, k_3, k_4, and K_5 are polynomial coefficient. Therefore, basic principle of nonlinear filter demodulation method is obtained. When the curve of the filter is fitted by polynomial, not only a single polynomial can be used, but also piecewise polynomial can be used

3. THE INSTABILITY PROBLEM

While the physical quantity such as temperature and pressure conditions is constant, the wavelength of FBG is constant, according to the formula (2) and (3), the ratio should be constant, but we found that if light energy is changed, the ratio has the small variation, the instability is showed in Table 1.

Table 1 The relationship of the signal of the two detectors and the ratio n (Unit: V)

I_1	6.873	5.887	5.093	4.211	3.143	2.268	1.432
I_2	0.794	0.675	0.584	0.482	0.359	0.254	0.157
N	8.656	8.722	8.721	8.737	8.755	8.929	9.121

In order to solve the problem of instability, we use the following method

$$n = \frac{1}{m} = \frac{I_1}{I_2 - C_2} \qquad (4)$$

Where, I_1 is the signal which is detected by P_1 detector, I_2 is the signal which is detected by P_2 detector, C_2 is a fixed constant, although its value is very small, but it plays a very important role, because it influence the stability of the ratio.

In order to show the correctness of the modified method, In figure 3, we draw several different temperature curves of relationship between the I_1 and ratio n , from the Fig 3 it is shows that the modified ratio has the more stability at

19.96 ℃, 35.5 ℃, 40.62 ℃,50.31 ℃, As a result, FBG system stability has been greatly improved, demodulation accuracy also got corresponding improvement.

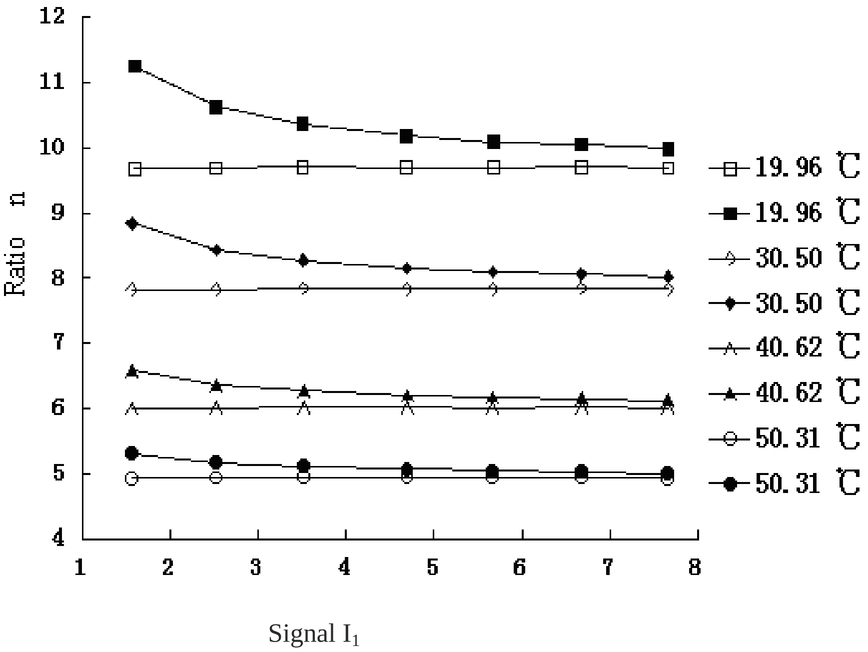

Fig.3 curves of relationship between the I_1 and ratio n, Each pair of figure, the curve of the above is not modified, straight line has been modified

In fact, not only edge filter demodulation methods have the problem, but also the matched filter demodulation method should have the same problem. So, the modified method can be used as reference for related research, our modified method also plays an important role in these researches.

4. VIRTUAL WAVELENGTH METHOD

4.1 The basic principle of virtual wavelength method

The basic principle of fiber Bragg grating is that wavelength has linear relationship with temperature, so that is formula (5)

$$\lambda = a_0 + a_1 T \qquad (5)$$

While a lot of different temperature T and the ratio are measured, formula (5）is used to compute the coefficient of formula (3), formula (5) can be used to determine the Polynomial coefficient of formula (3).If another fiber Bragg grating is used. Formula (5) is used to measure temperature that is the actual wavelength method. So a lot of data of temperature, wavelength and the ratio are used to determine the coefficient of formula (3). In fact, the wavelength is just an intermediate physical quantity, The wavelength need not be measured and calculated; in order to reduce the unnecessary trouble, we adopt virtual wavelength method.

Our goal is to detect physical quantities. So in the formula (3) and (5), if the temperature and the ratio are the actual quantities, other coefficient and wavelength is the virtual coefficient, we call it the virtual wavelength method. Here we describe the basic principle.

We assume that the equation of the fiber Bragg grating is described by (6)

$$\lambda_s = a_0' + a_1' T \qquad (6)$$

Where, we assume that $a_0' \ and \ a_1'$ are the virtual constant, λ_s can be obtained by formula (6),so the λ_s is the virtual wavelength. At the same temperature, according to the formula (5) and (6), the formula (7) is obtained.

$$\lambda = \frac{\lambda_s - a_0'}{a_1'} a_1 + a_0 \qquad (7)$$

According to the formula (3) and (7), the formula (8) is obtained.

$$\lambda_S = a_0' + \frac{(k_0 - a_0)}{a_1} a_1' + \frac{a_1'}{a_1} k_1 n + \frac{a_1'}{a_1} k_2 n^2 + \frac{a_1'}{a_1} k_3 n^3 + \frac{a_1'}{a_1} k_4 n^4 + \frac{a_1'}{a_1} k_5 n^5 + \qquad (8)$$

Let

$$K_0 = a_0' + \frac{(k_0 - a_0)}{a_1} a_1' \; ; \quad K_1 = \frac{a_1'}{a_1} k_1 \ \ldots \quad K_5 = \frac{a_1'}{a_1} k_5 \qquad (9)$$

Formula (9) is obtained.

$$\lambda_s = K_0 + K_1 n + K_2 n^2 + K_3 n^3 + K_4 n^4 + K_5 n^5 + \qquad (10)$$

Formula (8) and (10) are the relationship between virtual wavelength and ratio n; it can be seen from the formula (9) that there is a linear relation between the actual polynomial coefficient and the virtual polynomial coefficient, the virtual coefficient can be obtained by the actual coefficient completely; formula (10) and formula (3) show coefficient formula are identical.

If we use the formula (6) to calculate the coefficients of formula (10), or use the formula (10) to calculate the variation of physical quantity, besides ratio and physical quantity, wavelength is the virtual wavelength; all the coefficients are virtual coefficient. So the method is called virtual wavelength method

Therefore, in the formula (6), Coefficient was arbitrarily set, wavelength measurement is omitted, Processing is simplified.

On the other hand, in the range of filter, if a new FBG is replaced, the polynomial coefficients do not need to be changed, Virtual coefficient a_0', a_1' of the formula (6) need to be calculated. If the two ratio of the new FBG are n_1 and n_2, the corresponding temperatures are T_1 and T_2, according to the formula (10), the new virtual wavelength λ_{s1}, λ_{s2} can be obtained, according to the formula (6), Formula (11) can be obtained.

$$a_0' = \lambda_{s1} - \frac{\lambda_{s1}-\lambda_{s2}}{T_1 - T_2} T_1, \quad a_1' = \frac{\lambda_{s1}-\lambda_{s2}}{T_1 - T_2} \tag{11}$$

Thus the new Virtual coefficient a_0', a_1' can be obtained. We use the different FBG to calculate Virtual coefficients a_0', a_1', then we use these virtual coefficients to calculate physical quantities, we get the same results with actual wavelength.

4.2 Data analysis of virtual wavelength method:

In the experiments, the relationship between virtual wavelength λs and the ratio n is shown in figure 4. At the same time, the curve between actual wavelength λ and ratio n is also showed in the figure 4.

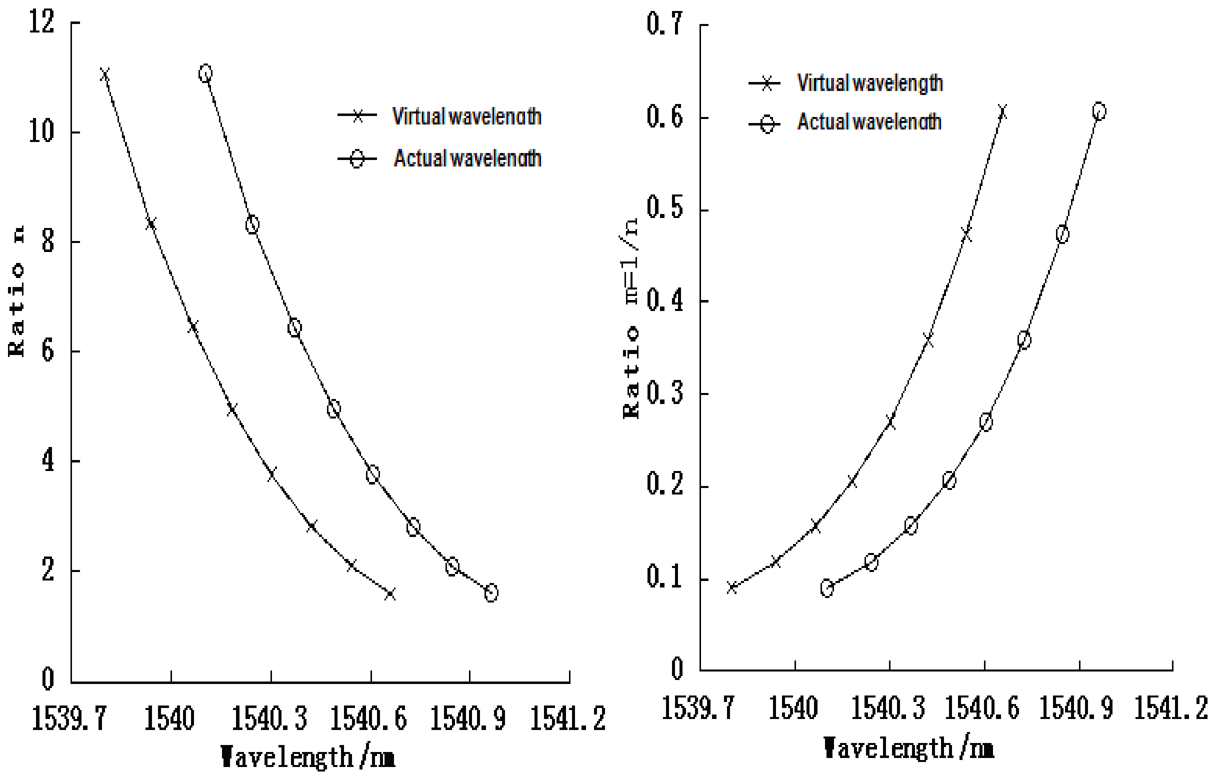

Fig.4 a. the curve of λs,λ and the ratio n **Fig.4 b. the curve of λs,λ and the ratio m**

From the figure 4 it can be seen that (1).virtual wavelength, the actual wavelength and the ratio is nonlinear relationship, this is the reason why polynomial fitting is used. (2) in the linear edge filter method, the ratio of logarithm has linear relationship with wavelength ,but the method depends on linear filter, In general, linear filter are approximate. The nonlinear edge filter method is more reasonable. (3) virtual wavelength method is suitable for the traditional linear filter method.

In the experiment, the relationship between the temperature and virtual wavelength is shown in figure 5.

In the relationship between wavelength and temperature, the figure 5 shows that virtual wavelength method and actual wavelength method is a parallel relationship, Figure 5 is further evidence that the virtual wavelength method is feasible.

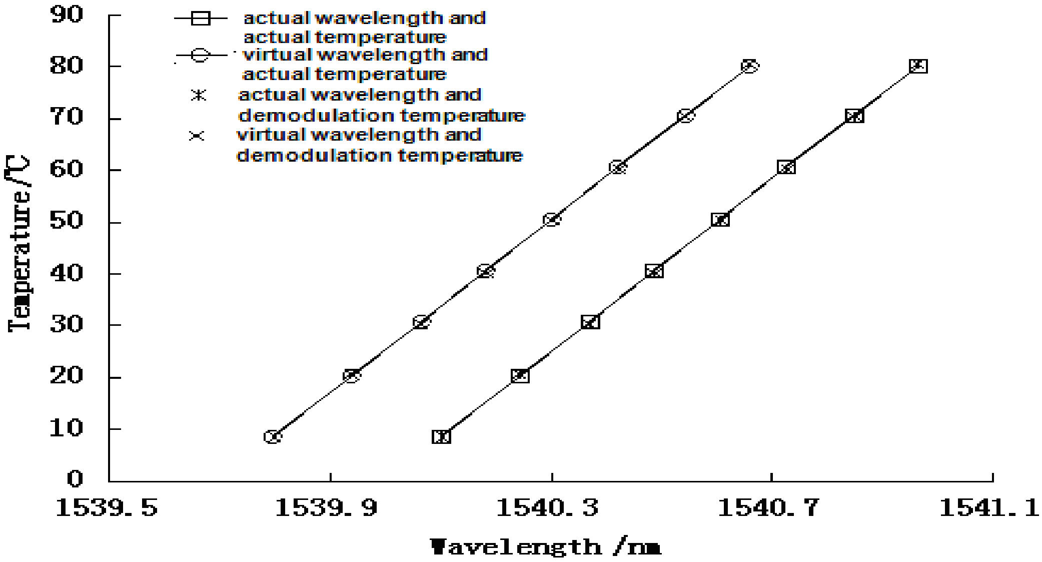

Fig.5. Curve of wavelength and temperature

5. WAVELENGTH RESOLUTION

The nonlinear optical filter demodulation method is used, the relationship between wavelength and ratio is formula (3) and (10), and the derivative of the two formulas are the formula (12) and (13)

$$\Delta\lambda = (k_1 + 2k_2 n + 3k_3 n^2 + 3k_4 n^3 + 5k_5 n^4)\Delta n \quad (12)$$

$$\Delta\lambda_s = \frac{a_1'}{a_1}(k_1 + 2k_2 n + 3k_3 n^2 + 3k_4 n^3 + 5k_5 n^4)\Delta n \quad (13)$$

Formula (12) is the resolution of actual wavelength. Formula (13) is the relationship between actual wavelength and virtual wavelength, if $a_1' = a_1$, we obtain $\Delta\lambda = \Delta\lambda_s$.

According to the formula (5) and (6), the formula (14) could be obtained, that is

$$\Delta T = \frac{\Delta\lambda_s}{a_1'} = \frac{\Delta\lambda}{a_1} \quad (14)$$

So the virtual wavelength method can not change the precision。But Polynomial accuracy is higher than the linear accuracy, so the the nonlinear edge filter demodulation method has more accuracy, so the nonlinear edge filter demodulation method has more accuracy.

therefore, we used the formula (12) to calculate the wavelength resolution.

The wavelength resolution depends on the coefficient, ratio and the variation of the ratio. The polynomial coefficient k0, k1, k2, k3, k4, k5 o f one filter are 1539.6479,0.09502, -0.0077596,0.0004098, -1.1568×10^{-5},1.325×10^{-7}, we assume that the ratio n is changed in the range of 3-10. The variation of the ratio Δn consists of two parts.

The first part Δn is the maximum error caused at constant light source energy; this error is very small, Δn changes within 0.005. After calculation, the wavelength resolution of the first part is less than 1pm.

The second part Δn is the biggest error caused by the change of light source energy, before instability has not been modified, the maximum error is very large, from figure 3 we can see that; after instability has been modified, the maximum error is 0.015, after calculation, the wavelength resolution of the second part is less than 3pm. At present, we did not find the related paper to discuss this part.

6. CONCLUSION

The paper developed a demodulation system of FBG based on nonlinear filters, and around this method, the related research has been studied.

On the basis of the linear filter demodulation system, the nonlinear demodulation system is established. This method is an improvement of linear filter demodulation system.

System instability is resolved. If the physical quantity is a fixed constant, experiment found that the ratio has variation while the light source power is changed. The system instability will directly led to a decline in demodulation accuracy, in order to improve the stability of the demodulation system, the experiments adopt ratio value correction method. The experimental results show that the system has a good stability.

The virtual wavelength method is used. Physical quantity such as temperature is directly determined by the ratio. In order to correspond with the actual situation, so the virtual wavelength method is used. When virtual wavelength method was used to measure temperature, the variation of physical quantity is directly calculated. The corresponding virtual wavelength theory is established, the experiment data show that the virtual wavelength method is correct, virtual wavelength method can effectively applied in the related research.

Virtual coefficient of FBG is modified, if a new FBG sensor is replaced, the polynomial coefficient of filter doesn't need to be revised, only the virtual coefficient of FBG is modified, this is the formula (11), and the correction method is very simple.

Finally, the wavelength resolution of the formula of the virtual wavelength method and actual wavelength method are established, and their wavelength resolution were calculated and tested. Nonlinear filter demodulation method has the advantages of high stability and more accuracy,

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