Research on wavelength demodulation algorithm in smart clothes based on FBG

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ABSTRACT

A wavelength demodulation algorithm in smart clothes for detecting human body temperature is proposed based on the fiber Bragg grating (FBG) sensor interrogation technology. The driven voltage corresponding to peak wavelength of reference spectrum can be calculated by the method of windowing to FBG reflected wave and weighted averaging to the data. The characteristic conic of F-P filter is attained by the least square fitting. Experimental result shows that the algorithm can solve the problem of low detecting precision due to the low resolution of scanning voltage. The correlative linearity of temperature and driven voltage of F-P is 0.998, and a resolution of 0.2 ^{o}C temperature can be obtained.

Keywords: wavelength demodulation, fiber Bragg grating, Fabry-Perot filter, smart clothes

1. INTRODUCTION

Smart clothes is a new field, which is a cross discipline of the micro-electronics technology, new sensor technology, modern communication technology, intelligent control technology, textile technology and other related new technologies. It can monitor the human body state changes of the external or internal environment with wearable and mobile convenience features, and it has become the focus of study abroad. At present, The United States, Britain, Belgium, Japan and other countries have made remarkable results in the study of smart clothes. In this paper, the smart clothes uesd for detecting the body temperature is studied. Various diseases caused by fever have gotten a very good prevention and controlled.

The body temperature signal is detected and demodulated based on the fiber Bragg grating (FBG) technology and F-P (Fabry-Perot) tunable filter. The typical wavelength scanning range of F-P tunable filter is tens of nanometer. Wavelength resolution can be picometer order. The measuring instrument is moderate cost. All the features can meet the requirements of the project. However, measured error is also produced due to the impact of the external environment, as well as the filter's non-linear characteristic. Most filters, especially those driven by piezoelectric ceramic have poor measurement repeatability owing to the hysteresis of piezoelectric ceramic. Therefore, it is necessary to calibrate the output wavelength of the filter each time when measuring.[1, 2] In the paper, the wavelength calibration method using standard reference grating spectra is presented. The system which can realize the distributed measurement using a number of gratings is established. The output wavelength of filter is calibrated real-timely by means of conic fitting. Reflected spectrum detected by the photodetector is a Gaussian spectrum which varies with the scanning wavelength. The peak wavelength is Bragg reflected wavelength. However, due to the resolution limitations of driven voltage of filter, the reflected spectrum collected by computer is discrete values. If the maximum of discrete values is simply regarded as a peak of reflected spectrum, it will lead to measured error. This article describes an algorithm of windowing to FBG reflected wave and weighted averaging to the data, which can improve the accuracy of the measurement.[3, 4]

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2. BODY TEMPERATURE SIGNAL DETECTION

The fiber Bragg gratings can be used as temperature sensors, which can be weaved into the different locations of clothes for temperature measurement, such as oxter, anterior chest, the back and other positions. A number of optical fiber Bragg gratings are carved into the fiber continuously, which the system can realize distributed measurement by multiplexing technology. The expectation of the temperature values acquired from different positions can be regarded as the final display output. The FBG sensing information is encoded by wavelength. At present, the common test device of wavelength encoding signal is spectrum analyser, which has higher accuracy and sensitivity, but is expensive, bulky, and whose application condition is harsh. So it is not suitable for engineering application. Therefore, studying in the practical multiplexing signal detection technology is the key to multiplexing sensor realization.

There are a lot of detection methods about FBG wave shifting. Among them, the non-equilibrium M-Z interferometer method has higher measurement sensitivity, but it is only suitable for dynamic testing, not for static testing; FBG matching tunable filter method has higher resolution, but the signal-to-noise ratio is lower; Tunable narrow-band light source detection method has higher signal-to-noise ratio and higher resolution, but the number of multiplexing FBG and measurement range is limited; Fabry-Perot tunable filter method has a more wide tuning range, which can greatly improve measurement scope and the number of multiplexing FBG sensor. The system structure is simple, but the modem speed is not high. The body temperature signal is a low-frequency signal, and compared with others, we prefer to use this wavelength demodulation method.[5]

3. THE PRINCIPLE OF DISTRIBUTED WAVELENGTH DEMODULATION

The schematic diagram of wavelength demodulation system based on F-P filter is shown in figure 1. The broadband light source and a tunable optical filter constitutes a tunable narrow-band light source. It scans sensing fiber Bragg grating and reference fiber Bragg grating. The transmitted light of standard reference grating and the reflected light of sensing grating is converted into voltage signal through photodetector and amplified. After A/D sampling, the signal can be processed by the microprocessor, such as digital filtering.

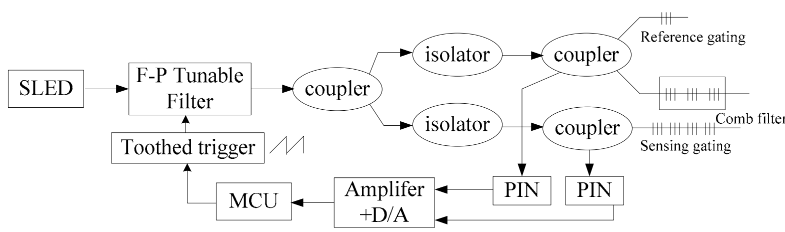

Fig. 1. Wavelength demodulation system based on F-P filter

The characteristic of driven part in Fabry-Perot tunable filter is non-linear. At the same time, it varies with time and temperature. Therefore, the data from the system will be unreliable. It is necessary to use precision fixed reference gratings for calibration in each scanning cycle in order to complete the reflected wave of FBG demodulation accurately. Etalon and a reference grating are added in the wavelength demodulation system. In a scanning cycle, etalon reflect the interval peaks. Computer will collect the signal of peak voltage when the wavelength of filter output is equal to the peak of transmitted spectrum of etalon. Each wavelength corresponding to the peak is fixed, so we can calibrate the wavelength of filter output. The relationship between driven voltage and wavelength of filter output is established by detecting the driven voltage corresponding to the peak.[6, 7, 8, 9] Reference grating reflect a standard peak signal to determine the location of etalon peak. In the sensing channel, there will be a peak output when the narrow-band wavelength from the filter is equal to the Bragg wavelength of sensing grating. The driven voltage corresponding to the peak of fiber Bragg grating is determined by the peak detection method.[10, 11, 12] By substitution of the driven voltage into the relationship equation between driven voltage and wavelength of filter output, the wavelength of sensing gratings can be demodulated.

4. WAVELENGTH DEMODULATION ALGORITHM OF BODY TEMPERATURE SIGNAL

Scanning voltage is applied to the F-P tunable filter, and various reflected wavelengthes can be decoded by the F-P cavity. The optical signal is changed into pulse signal through the photodetector and other circuit. The signal processing unit sampled the entire scanning cycle, simultaneously counting methods used to detect each pulse signal of reference grating and the corresponding scanning voltage location of the rising edge and falling edge. Suppose $a_1, a_2 \ldots a_N$ is the sampling voltage sequence, and N is the number of sampling points in a scanning cycle. According to the FBG demodulation principle, how to determine the position of FBG reflected peak wavelength is the key to wavelength demodulation. The solution to the problem is finding the sampling point number of each peak corresponding to the sampling voltage $a_1, a_2 \ldots a_N$. Then the F-P filter characteristic curve is fitted by the least square. By substitution of the sampling point numbers of peak wavelength into the F-P filter characteristic curve, the sensing FBG reflected wavelength is demodulated in the measured temperature. It is denoted by λ_{Bi}. By substitution of λ_{Bi} into formula (1), human body temperature T can be calculated as follows:

$$T = \frac{\lambda_{Bi} - \lambda_i}{p} + T_0 \tag{1}$$

In which λ_{Bi} is the demodulated sensing FBG reflected wavelength, T_0 is the constant temperature, λ_i is the FBG central wavelength when the temperature is T_0, p is the sensitivity coefficient of sensing grating. The schematic of human body temperature detection is shown in Figure 2.

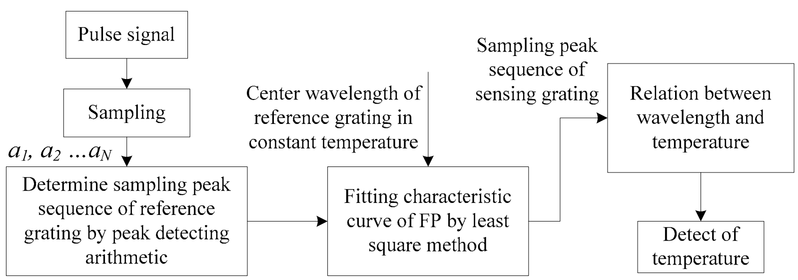

Fig. 2. The schematic of human body temperature detection.

4.1 Peak detection algorithm

The wavelength demodulation system used in smart clothes is an embedded system, which exists a lot of restrictions in the data storage. In order to guarantee real-time data processing, the number of sampling points N is less as much as possible. If N is small, the wave displacement resolution becomes larger.[13, 14] Sensing resolution can be improved by increasing the fiber laser scanning step number or reducing the scanning step. However, the addressing time will be longer if the scanning step is too long, i.e. the demodulation speed will be slower.

The coupled mode theory describes the reflected properties of fiber gratings. The fiber grating reflected spectrum is a complex function of λ given by the coupled-mode equations.[15, 16] The spectrum form of Gaussian has a better approximation with fiber Bragg grating spectral type. In order to be easy for math processing, the reflected spectrum can be regarded as the Gaussian approximatively when the fiber grating reflectivity is not particularly high. The expectation of Gaussian function is the position of central wavelength of FBG reflected wave. The wavelength of Gaussian function is central symmetry. So we can determine the position of FBG peaks by weighted averaging to the data of FBG reflected wave. This method effectively resolves the problem of little sampling points leading to the decline the accuracy of the wavelength demodulation. Compared with the traditional wavelength demodulation method, the new method ensures the accuracy of wavelength demodulation, reduces the quantity of data sampling and is applicable to embedded system. Meanwhile, it cut the cost of the experiment. The demodulated algorithm of FBG is shown in figure 3.

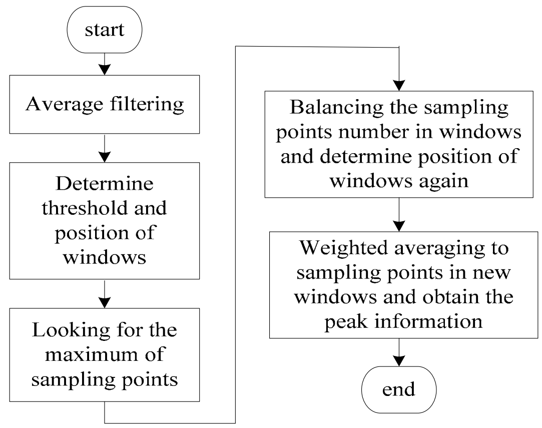

Fig. 3. The demodulated algorithm of FBG

The FBG reflected wave is mixed with noise in the sampling process. First, in order to reduce noise interference, the glitch noise can be removed by mean filter. Second, an appropriate threshold is set in order to filter out most noise and the information of which is less than the minimum peak value. The points whose threshold comes across with the FBG reflected wave are regarded as left endpoint and right endpoint of the window. Each window has a FBG reflected peak after the treatment. The corresponding position of maximum value in each window is found by comparison method, and the position is regarded as the center, then the points are selected symmetrically in order that the data in the window is greater than or equal to the threshold. Finally, do the weighted averaging to the data in the windows by formula (2) and get corresponding number of peak sampling point more accurately.

$$\eta = \frac{\sum v_i \times i}{\sum v_i}, i = 1, 2, \cdots, N \tag{2}$$

In which η is the corresponding number of peak sampling point of reference grating, v_i is the scanning voltage when the number of the sampling point is i. Because sampling point numbers and scanning voltage added in the piezoelectric ceramic is a linear relationship, the sampling points number is the quantitative value of scanning voltage.

4.2 The fitting algorithm of F-P filter characteristic curve

The central FBG wavelength is calibrated to realize the accurate demodulation for FBG reflected wavelength, using curve fitting algorithm by reference point. In this paper, a real-time curve fitting algorithm is proposed, which realizes the dynamic curve fitting, and ensures high-precision measurements. The dynamic curve can remove random error due to intensity jitter. At the same time, it can remove error to a certain extent caused by accident or the inherent characteristics of F-P.

The characteristic conic of F-P filter is fitted by the least square method. The formula is

$$\begin{cases} m \times a_0 + a_1 \times \sum_{i=1}^{m} n_i + a_2 \times \sum_{i=1}^{m} n_i^{\,2} = \sum_{i=1}^{m} \lambda_i \\ a_0 \times \sum_{i=1}^{m} n_i + a_1 \times \sum_{i=1}^{m} n_i^{\,2} + a_2 \times \sum_{i=1}^{m} n_i^{\,3} = \sum_{i=1}^{m} \lambda_i \times n_i \\ a_0 \times \sum_{i=1}^{m} n_i^{\,2} + a_1 \times \sum_{i=1}^{m} n_i^{\,3} + a_2 \times \sum_{i=1}^{m} n_i^{\,4} = \sum_{i=1}^{m} \lambda_i \times n_i^{\,2} \end{cases} \tag{3}$$

In which m is the number of windows. n_i is the quantitative value of scanning voltage corresponding to the peak of FBG reflected wave in each windows. λ_i is the central wavelength of reference Bragg grating under the constant environment. Coefficients a_0, a_1 and a_2 are uniquely determined by formula (3). Finally, the sampling point numbers of peak wavelength is applied to the quadratic curve equation. The sensing FBG reflected wavelength is demodulated into the measured temperature. The polynomial fitted by the least square method is that

$$\lambda = a_0 + a_1 \times n + a_2 \times n^2 \tag{4}$$

In which λ is the central wavelength of sensing grating under testing environment. n is quantitative value of scanning voltage corresponding to the peak of FBG reflected wave.

5. EXPERIMENTAL RESULTS AND ANALYSIS

In this paper, we use the sensor system to conduct a detailed temperature sensing experiments to prove the validity of the human body temperature detection. Broadband light source is a light-emitting diode, and the central wavelength is 1545.0nm in the experiment. The spectral width of F-P filter is 108nm. Bandwidth is 0.162nm. Tunable range is 1520nm-1570nm. The central wavelengths of the five reference FBG are respectively 1529.960nm, 1533.232nm, 1535.640nm, 1539.384nm,1544.590nm when the temperature is 30.6 ^{o}C. The central wavelengths of sensing FBG are 1530.287nm, 1535.892nm, 1546.361nm. In the experiment, scanning voltage is divided into 2000 points. There are 2000 voltage points. Every point represents a voltage position. The voltage position corresponding to the peak wavelength of reference gratings and sensing gratings are shown in table 1.

Table. 1. Data of Bragg gating sensor array

Class number	Reference 1	Reference 2	Reference 3	Reference 4	Reference 5	Sensor 1	Sensor 2	Sensor 3
1	1524.245	1396.736	1287.468	1113.356	822.356	1473.258	1250.452	920.352
2	1524.336	1397.775	1286.239	1113.303	823.402	1473.393	1250.373	920.445
3	1523.293	1396.639	1287.9346	1112.430	821.316	1473.255	1250.352	920.347

The characteristic conic of F-P filter is fitted with the data of reference gratings and sensing gratings from table 1 by the least square method. The result of fitting is shown in figure 4. The fitting equation is that

$$y = -1 \times 10^{-5} x^2 + 0.0021x + 1548.9 \tag{5}$$

In which y is the central wavelength of FBG reflected wave. x is the quantitative value of scanning voltage corresponding to the peak of FBG reflected wave. The correlative linearity of the curve is 0.998. The result shows that the characteristic curve of F-P filter has a good linear relationship. The peak information can be detected accurately with less sampling points by the peak detection algorithm proposed in the paper. It solves the problem of data storage and data-processing speed in embedded system.

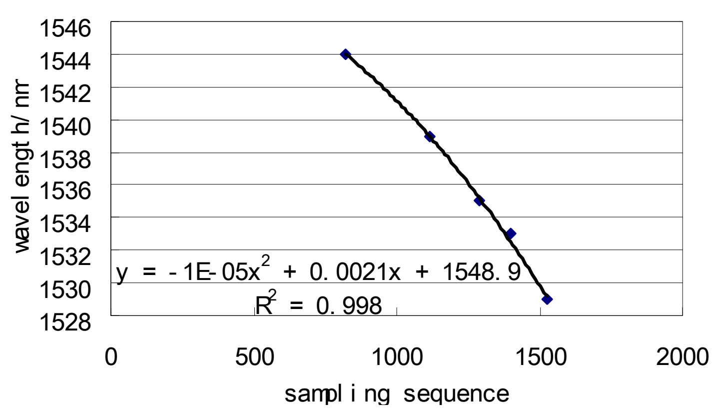

Fig. 4. The characteristic curve of F-P filter

By substitution of the sensing gratings data into the fitting equation, the central wavelength λ_i (i=1, 2, 3) of sensing gratings are detected. The result and error analysis are shown in table 2. Wavelength detection error can be less than 2pm by the least square fitting. The detection precision of body temperature can reach 0.2 ^{o}C when sensitivity coefficient of sensing gratings is higher than 10pm/ ^{o}C. It can meet the engineering requirements.

Table. 2. Error analysis of conic by the least square fitting

Central wavelength	The first group/nm	The second group/nm	The third group/nm	Exact value/nm	Mean square error of the first group/pm	Mean square error of the second group/pm	Mean square error of the third group/pm
λ_1	1530.2889	1530.2861	1530.2898	1530.287	1.4	1.4	1.2
λ_2	1535.8896	1535.8918	1535.8917	1535.892			
λ_3	1542.3623	1542.3609	1542.3627	1542.361			

6. CONCLUSION

Wavelength demodulation algorithm based on FBG in smart clothes was studied in the paper. The output wavelength of filter was calibrated in C-band using standard reference system. Multiple gratings distributed measurement was achieved, and a higher accuracy is obtained. Measured error brought from the low resolution of scanning voltage was reduced by the peak detection algorithm proposed in the paper. The algorithm is applied to embedded system. The characteristic curve of F-P filter is fitted real-timely by the conic fitting, which can reduce greatly the measured error caused by the drift of F-P filter's cavity length and the nonlinearity of piezoelectric ceramic. The effectiveness of the algorithm has been verified in the smart clothes experiment.

7. ACKNOWLEDGMENTS

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