Optical fiber temperature sensor based on wavelength-dependent detection

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Semiconductor fiber temperature sensors have been used widely in many fields, but most of them pick up temperature by measuring the optical intensity of certain fixed narrow-band in absorption spectrum. Furthermore, they are sensitive to the loss of optical intensity and the fluctuation of light source power. The novel temperature measurement system proposed in this paper is based on the semiconductor absorption theory and the spectral analysis of method. To measure temperature, the sensor model detects not the certain narrow-band spectrum but the most spectra of the optical absorption edge. Therefore the measurement accuracy and the stability can be improved greatly. Experimental results are in agreement with theoretical analysis results perfectly.

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Fiber temperature sensors have been applied widely. It is reported that semiconductor fiber-optic sensor has been used for temperature measurement based on the optical absorption. But most of them are sensitive to the loss of optical intensity and the fluctuation of light source power. Therefore measurement accuracy and stability are not high enough for many applications[1−4].

This paper describes a novel fiber sensor for temperature measurement. The measurement system exploits the displacement of the optical absorption edge in semiconductors under changes of temperature, and the temperature value is obtained by analyzing spectrum[5].

Based on Lambert's absorption law, for intrinsic semiconductor GaAs, absorption characteristics can be described as

$$I(\theta,x) = I_0(1-R)\exp\left[-\alpha(\theta)x\right], \tag{1}$$

where I_0 is the incident intensity, x is the thickness of semiconductor absorption material, R is the reflection factor of the semiconductor material at the incident plane, θ is the temperature, and $\alpha(\theta)$ is the absorption coefficient at the temperature θ. The absorption coefficient of GaAs crystal is given by

$$\alpha(\theta) = A\left[h\nu - E_g(\theta)\right]^{1/2}, \tag{2}$$

where A is material constant, $E_g(\theta)$ is the band gap related to θ, h is the Plank constant, and ν is frequency of light wave. According to Panish's research, within the temperature range of 20 − 937 K, the band gap can be given by

$$E_g(\theta) = E_g(0) - \frac{a\theta^2}{b+\theta}, \tag{3}$$

where $E_g(0)$ is the band gap at zero Kelvin temperature, a and b are empirical constants. For GaAs semiconductor material, $b = 300$ K, $a = 5.8 \times 10^{-4}$ eV/K, $E_g(0) = 1.522$ eV. Thus the intrinsic absorption wavelength is

$$\lambda_g(\theta) = \frac{hc}{E_g(\theta)}, \tag{4}$$

where c is the velocity of light. According to previous studies, within the temperature range of 200 − 600 K, the band gap can also be rewritten by

$$E_g(\theta) = E_g(0) - k\theta, \tag{5}$$

where k is constant related with GaAs and equals to 4.7×10^{-4} eV/K. Band gap has linear dependent relationship with temperature within this range.

Transmission curve of GaAs crystal is shown in Fig. 1. The absorption band edge generates the motion of translation with temperature variation, but temperature changes do not impact the shape of absorption band edge. The quick-change fraction in the absorption band edge is approximately an aligning. Point a is the crossing point of aligning and horizontal coordinates. The wavelength of crossing point a is λ_T. Thus, the coordinate value of a point is (λ_T, 0). There is difference between λ_T and λ_g. Intrinsic absorption wavelength λ_g is the least wavelength, which can generate intrinsic absorption; λ_T is the initiative wavelength which leads to the quickest absorption coefficient changes. If the coordinate value of point b is ($\lambda_T + \Delta$, T_b), the absorption band edge is approximately given by

$$T = \frac{T_b}{\Delta}(\lambda - \lambda_T), \quad \lambda_T < \lambda < \lambda_T + \Delta, \tag{6}$$

where T is the relative transmittance, T_b is the relative

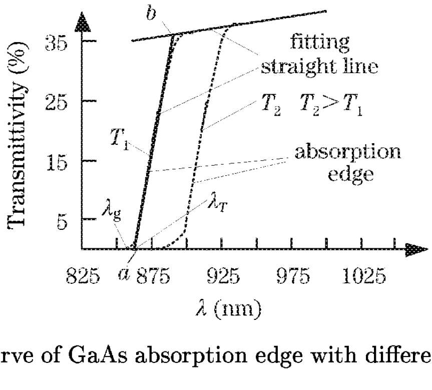

Fig. 1. Curve of GaAs absorption edge with different temperature.

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transmittance at point b, and Δ is the side-play amount of wavelength from point b to point a. After introducing an energy factor ΔE, E_T is defined as modified band gap and given by

$$E_T = E_g - \Delta E. \tag{7}$$

Then we can get

$$\lambda_T = hc/E_T. \tag{8}$$

The difference between λ_T and λ_g is so small that ΔE is small enough to be ignored compared with $E_g(0)$. According to the above equations, the mathematic model of temperature measurement system can be expressed as

$$\theta = \frac{\lambda_T \cdot E_T(0) - hc}{\lambda_T \cdot k}. \tag{9}$$

Temperature is measured through the relation of temperature θ and wavelength λ_T.

GaAs crystal is used as probe. It is made into isosceles right angle triangular prism and its thickness is 250 μm. In order to meet the requests of measurement, light needs to generate total reflection in GaAs probe. According to total reflection law, the critical angle which generates the total reflection in GaAs crystal is about 18°, so the prism is designed in this configuration[6]. Light transmission path in probe is about equal to the diameter of prism. Figure 2 shows the configuration of temperature probe.

Based on the above theoretical analysis, the light emitted by light source is coupled into incident fiber by focusing lens and reflected by probe. Then light emits from the exit end of the receiving fiber tip and is turned into parallel beams by collimating lens. Beams inject into flat diffraction grating which has light-splitting function, then focus on the surface of the charge coupled device (CCD). The spatial distribution of different wavelengths according to different diffraction angles is changed into discrete voltage signals which truly mirror the relation of light intensity and wavelengths. They are used to fit mirror-curve of absorption edge by the method of least squares and determine λ_T. Figure 3 shows a total schematic configuration of the temperature measurement system.

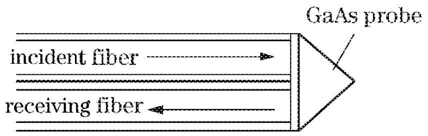

Fig. 2. Configuration of the temperature probe.

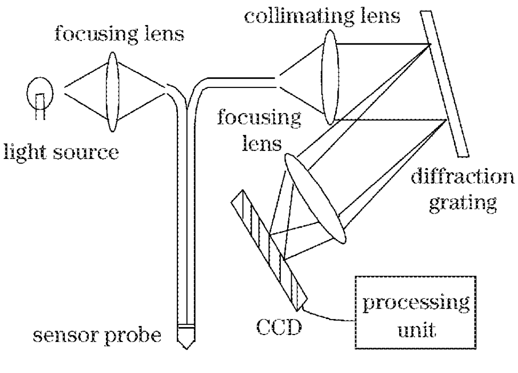

Fig. 3. Schematic of temperature measurement system.

Regression analysis is used in signal processing. Regression equation can be got from experimental results and expressed by

$$\lambda = p + qU, \tag{10}$$

where p and q are regression coefficients, U is the output voltage signal from CCD and λ is wavelength. So, there is one-to-one correspondence between voltage signal and wavelength and when output voltage signal is zero, Eq. (10) is expressed by

$$\lambda_T = p, \tag{11}$$

and temperature can be determined easily by Eq. (9) after regression coefficient p is determined.

In order to analyze the absorption edge of GaAs, the relation of wavelengths and light-sensitive units of CCD detector needs to be determined by the spectrum calibration experiment of CCD. Linear interpolation method is used in calibration. The wavelength change rate is expressed as

$$K_i = (\lambda_m - \lambda_n)/(C_m - C_n), \tag{12}$$

where K_i is wavelength change rate, λ_m and λ_n are adjacent standard spectral lines, C_m and C_n are light-sensitive unit ordinal numbers of CCD, which correspond to wavelength λ_m and λ_n. The calibration equation of all spectral lines between λ_m and λ_n is given by

$$\lambda_x = \lambda_1 + K(C_x - C_1), \tag{13}$$

where λ_x is random wavelength, C_x is light-sensitive ordinal number that corresponds to wavelength λ_x. Six standard spectral lines 435.833, 576.96, 730.966, 809.312, 871.666 and 1092.146 nm of Hg source are selected to calibrate wavelengths within the range from 400 to 1100 nm. The fractional experiment results are shown in Table 1.

After the calibration of CCD, temperature measurement test was conducted. A quartz-tungsten halide lamp is selected as the light source and the light emitting from the source is coupled into incident optical fiber by focusing lens and transmitted to GaAs crystal probe. The GaAs semiconductor temperature probe was placed into the furnace where temperature can be adjusted from 20 to 160°C and the reference temperature is applied by the copper-constantan thermocouple. Measurement results are output every 5°C.

Table 1. Fractional Data Recorder of Calibration Experiment of CCD (Unit: nm)

Standard Wavelength	Calibration Results
546.073	546.165
579.016	579.044
853.592	853.286
928.637	928.976

Table 2. Experiment Results of Temperature Measurement (Unit: °C)

Standard Temperature	20.00	25.00	30.00	35.00	40.00	45.00	50.00
Results of Test	20.23	25.21	29.81	35.27	40.36	44.79	49.52
Standard Temperature	55.00	60.00	65.00	70.00	75.00	80.00	85.00
Results of Test	55.51	60.42	64.67	70.54	75.42	79.51	85.41
Standard Temperature	90.00	95.00	100.00	105.00	110.00	115.00	120.00
Results of Test	89.62	94.61	99.56	105.42	109.58	115.43	120.49
Standard Temperature	125.00	130.00	135.00	140.00	145.00	150.00	155.00
Results of Test	124.58	129.46	135.47	140.42	144.62	150.45	154.51

Measurement accuracy of the system is mainly affected by the stability of light source and the resolution of grating. So by enhancing the stability of light source by constant-current source and using high-resolution grating, high accuracy can be reached. The resolution of system reaches 0.01 °C by using 16 bits analog-digital converter and high resolution grating.

This method measures temperature according to wider spectrum range than traditional way which measures temperature by the given wavelength. Therefore the whole measurement system has higher accuracy and is not sensitive to local perturbation. In this measurement system, the temperature measurement range is from 20 to 175 °C, measurement accuracy is ±0.5 °C and higher than temperature measurement methods by optical intensity modulation at given wavelength whose accuracy is about ±1 °C. System long-term stability reaches to ±1 °C. As can be seen in Table 2, this measurement system meets the needs of most fields, especially for electric power system.

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References

1. K. Kyuma, S. Tai, T. Sawada, and M. Nunoshita, IEEE J. Quantum Electron. **18,** 676 (1982).
2. C. Chang, Z. Li, and Y. Q. Zhou, Chin. J. Lasers B **10,** 29 (2001).
3. X. Y. Dong, B. O. Guan, Y. Zhang, G. Y. Kai, Q. D. Zhao, X. Y. Dong, and C. D. Yao, Chin. J. Lasers (in Chinese) **28,** 587 (2001).
4. W. J. Bock, M. Beaulieu, and A. W. Domanski, IEEE Trans. Instrumentation and Measurement **41,** 68 (1992).
5. J. P. Meng, J. G. Yang, H. Tan, and S. L. Hu, Spectroscopy and Spectral Analysis (in Chinese) **22,** 721 (2002).
6. Y. Zhao and Y. B. Liao, Sensors and Acuators B **86,** 63 (2002).