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Fiber Optic Temperature Sensor Design based on Fluorescent Lifetime

Pinwei Zhu*, Linkai Chen and Yinsheng Luo

Department of Electrical Engineering, Jiangsu University of Technology, Changzhou, Jiangsu, 213001, China

Abstract: The temperature is measured by the fluorescent lifetime of fluorescent material. In this work, the analog switch was controlled by single chip to trigger exciting light emission of LED. In order to measure the fluorescent lifetime, photoelectric detector, amplifier and active power filter were used. The modulation frequency of fluorescent signal was detected by phase locking detection method. Therefore, the temperature measurement in the range of 0°C ~ 450°C was realized. This sensor has advantages such as high accuracy, strong anti-electromagnetic interference and non-contact measurement.

Keywords: Fluorescent lifetime, phase locking detection, temperature sensor.

1. INTRODUCTION

Temperature is one of the most important parameters in measurement science and industrial process control. Traditional temperature sensors, including thermocouple, thermistor, semiconductor, *etc*., cannot be used for high temperature, high voltage, strong electromagnetic interference, *etc*. Fiber optic temperature sensor, however, has a very wide application prospect with its advantages, such as anti-electromagnetic interference, thermostability, corrosion resistant and miniaturization. There are many types of fiber optic temperature sensors, including fluorescent fiber optic temperature sensor, which is a product combining fluorescent analysis and fiber optic. This kind of sensor has not only optic transmission signal, which is free of ignition and detonation, but also good electrical insulating property like quartz, chemical resistance, and high voltage and strong electromagnetic field resistance. Therefore, it can be used for all the subjects in any special circumstance, which is difficult for other sensors, such as places with seal, high voltage, strong electromagnetic field, nuclear radiation, strict explosion-proof, water proof and corrosion prevention, extra small space or extra small work piece.

2. PRINCIPLES FOR TEMPERATURE MEASUREMENT WITH FLUORESCENT LIFETIME

Exposed in exciting light, the electronic absorption photon in florescent will transit from low energy level to unstable high energy level. Fluorescence will appear when the photon transit from high energy level to low energy level. However, when the exciting light stops, fluorescence will decay by index rule, rather than disappear immediately. The time constant of index decay can be used for measuring the lifetime of excited state, which is called fluorescent lifetime.

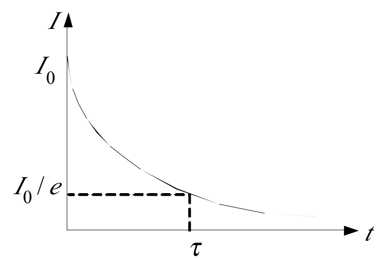

Fig. (1). Fluorescence decay curve.

The relationship between strength of fluorescent signal and time can be expressed as follows:

$$I(t) = I_0 e^{-t/\tau} + \varepsilon \tag{1}$$

where $I(t)$ is the strength of fluorescent signal; I_0 is the strength of excited fluorescent signal when $t = 0$; τ is fluorescent lifetime, which is the decaying time of fluorescent signal from I_0 to I_0 / e; ε is the identity noise generated by dark current for black-body radiation or circuit [1]. Fig. (**1**) shows the fluorescence decay curve.

As the inherent characteristic of fluorescent materials, fluorescent lifetime is a univalent function of temperature. In general, the higher the temperature is, the shorter the fluorescent lifetime will be. There is a one-to-one corresponding relation between temperature and fluorescent lifetime, so the temperature can be measured with the time constant. Because the fluorescent lifetime is related with temperature, instead of vibration, stress and other interference, the measurement accuracy is improved. Temperature measurement with fluorescent lifetime has good sensitivity and measurement accuracy in low and middle temperature range.

3. PHASE LOCK DETECTION (PLD) OF FLUORESCENT LIFETIME

The way to detect fluorescent lifetime includes Marquardt method, Prony method, integral method, numerical

*Address correspondence to this author at the Department of Electrical Engineering, Jiangsu University of Technology, Changzhou, Jiangsu, 213001, China; Tel: +8613861038275; E-mail: incipin@163.com

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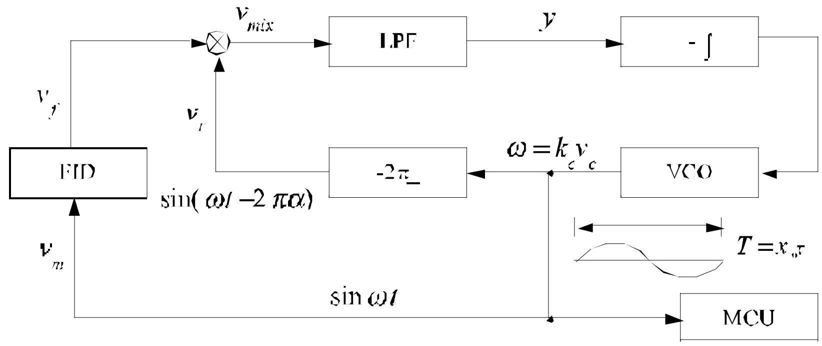

Fig. (2). Phase-locked detection of fluorescence lifetime.

curve-fitting method, phase lock detection method, *etc*. [2]. This design adopts the phase lock detection method to realize the measurement of fluorescent lifetime without exciting light interference. This method has characteristics of simple circuit and low cost. Fig. (**2**) is shows the phase-locked loop detection system.

FID-the fluorescence inducing and detecting devices

LPF-low pass filter

VCO-voltage controller oscillator

Fluorescent signal will be sent into phase-locked loop circuit and mixed with a reference signal differing a fixed delay ratio α from exciting modulating signal in phase position. After the mixed signal v_{mix} gets across the low-pass filter and makes a further integral, it will feed the output frequency controlling voltage-controlled oscillator back. With this negative feedback process, the output of voltage-controlled oscillator will tend to stabilize and stabilize at a certain frequency value at last [3]. In the fluorescent simulation and detection module, the exciting light signal v_m is the sinusoidal signal with frequency ω. Driven by exciting light, the fluorescent sensor will change its response signal v_f by corresponding sin rule. However, this response signal will lag behind drive signal with phase position signal φ. Therefore, the response signal of fluorescent probe v_f can be expressed as follows:

$$v_f = V_A \sin(\omega t - \varphi) \tag{2}$$

In Formula (2), the lagging phase φ is the function between modulation frequency of exciting light ω and fluorescent lifetime τ. The relation between them is

$$\varphi = \omega\tau \tag{3}$$

The fluorescent lagging phase φ should be kept constant in measurement, so the corresponding fluorescent lifetime τ will be obtained by measuring the period of modulation signal T or the frequency ω. This system is called phase-locked detection of fluorescence lifetime (PLD) for the measurement with fixed phase difference. The detailed analysis process is as follows [4].

The amplitude V_A of fluorescent signal, which is dependent on φ, is the function between modulation frequency ω and fluorescent lifetime τ.

$$V_A = \frac{V_{AO}}{\sqrt{1+\tan^2\varphi}} = \frac{V_{AO}}{\sqrt{1+(\omega\tau)^2}} \tag{4}$$

In above formula, V_{AO} is a constant, which is independent on φ.

The input signal phase of low-pass filter lags behind the modulation signal phase of exciting light $2\pi\alpha$. Therefore, the output of low-pass filter can be expressed as follows:

$$y = \frac{2}{\pi} kV_A \cos(2\pi\alpha - \varphi) = \frac{2kV_{AO}}{\pi\sqrt{1+\tan^2\varphi}} \cos(2\pi\alpha - \varphi)$$
$$= \frac{2kV_{AO}}{\pi\sqrt{1+(2\pi/x)}} \cos[2\pi\alpha - \arctan(2\pi/x)] = f(x,\alpha) \tag{5}$$

In above formula, x is the ratio between modulation period T and fluorescent lifetime τ, $x = T/\tau$, and k is the gain of low-pass filter. In Fig. (**2**), the output y of low-pass filter is sent to integrator and the output signal V_c of integral output $-y$ is fed back to control the output frequency ω of voltage-controlled oscillator (VCO). If ω is different from ω_0, ω will increase with increasing integral of $-y$ when $\omega < \omega_0, y < 0$, and will decrease with increasing integral of $-y$ when $\omega > \omega_0, y > 0$. Moreover, ω always changes towards the direction of ω_0, which is

$$\omega_0 = \frac{\tan(2\pi\alpha - \pi/2)}{\tau} \tag{6}$$

Above formula is an expression when $y = 0$. At this time, the phase-locked detector is in lock state, under which the fluorescent response signal lags behind the drive signal phase.

$$\varphi = 2\pi\alpha - \pi/2 \tag{7}$$

Meanwhile, the ratio between modulation period T and fluorescent lifetime τ is expressed as follows:

$$x_0 = x|_{f(x,\alpha)=0} = \frac{2\pi}{\tan(2\pi\alpha - \pi/2)} \quad (8)$$

when α is certain, therefore, fluorescence lagging phase φ keeps constant according to Formula (7) and the value x_0 is also constant according to Formula (8). The system will reach lock state with $y = 0$ after a while no matter it is in which internal state. When the change of fluorescent lifetime τ to be measured causes the change of ω_0 (because $\varphi = \omega_0\tau$ is a constant), modulation frequency ω will change toward ω_0 to keep stability. According to

$$x_0\tau = 2\pi / \omega_0 = T \quad (9)$$

where the fluorescent lifetime τ can be obtained with modulation frequency ω_0 under lock sate of measurement system. In general, $\alpha = 0$ in order to make measuring error minimum and system design convenient. This system adopts micro-power consumption phase-locked loop integrated circuit CD4046B, internal integration phase comparator, phase amplifier, voltage-controlled oscillator, *etc*. Therefore, the required phase-locked detection can be realized by connecting simple external circuits. The measurement of fluorescent lifetime in phase-locked loop principle has relatively wide fluorescence measurement range and high accuracy.

4. FLUORESCENT LIGHT SOURCE AND THE DESIGN OF ITS DRIVE CIRCUIT

4.1. Selection of Light Source

At present, the emitters of fluorescence are mainly impure single crystals. The fluorescent emitter for temperature-sensing element in this fiber temperature detection system is $Cr^{3+}:Al_2O_3$. The center wavelength of absorption peak is $550\,nm$, and the bandwidth is $100\,nm$. In order to match with the wavelength of absorption peak, the exciting light resource is the green super-bright LED with low temperature sensibility and simple drive. The spectral half width is about $40\,nm$ and the central wavelength is about $575\,nm$, which moves toward long wavelength slightly with the increasing working current. In addition, the rated continuous working current is $40\,mA$ and the maximum pulse working current is about $300\,mA$ (the duty ratio of pulse current is 1:10). Fig. (**3**) is the luminescence spectrum of exciting light source LED. Fig. (**4**) shows that fluorescent emitter emits strong narrow-band fluorescence around $694\,nm$, and the exciting light absorbed by fluorescence sensing head in middle and short wavelength area is relatively large. For the unabsorbed exciting light, the center of which shifts to $610\,nm$, edge filter will be added in fluorescence detection system of fiber temperature detection to eliminate the influence of exciting light. Edge filter for long wavelength or narrow-band interference filter will be used generally [5, 6].

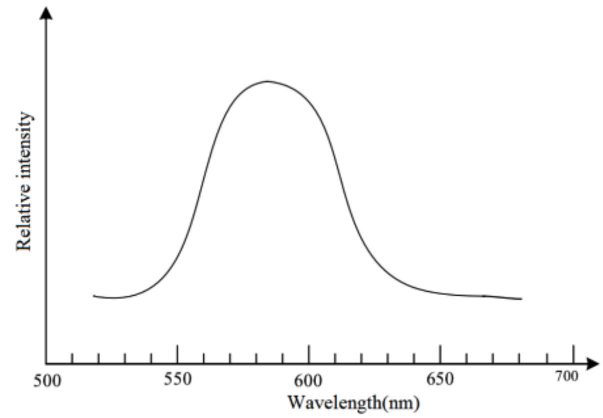

Fig. (3). The luminescence spectrum of LED.

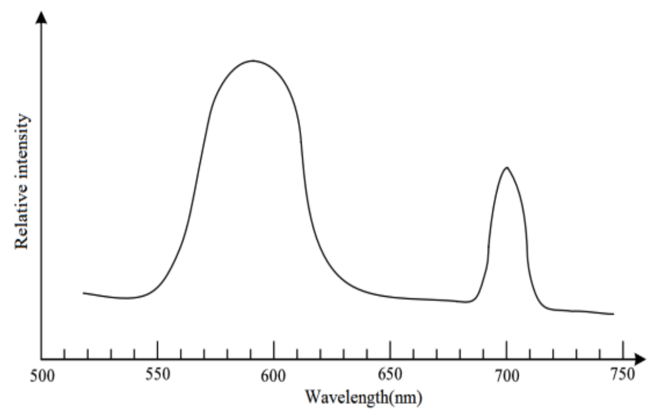

Fig. (4). The spectrum of exciting light of LED *via* sensor probe ($Cr^{3+}:Al_2O_3$).

4.2. Design of Light Source Drive Circuit

In order to repeat the detection of fluorescent fall time, periodic fluorescent fading signal should be emitted by fiber-optics probe. Therefore, LED light source driven by periodic pulse circuit will generate pulse light wave. Fig. (**5**) shows the drive circuit used in this system.

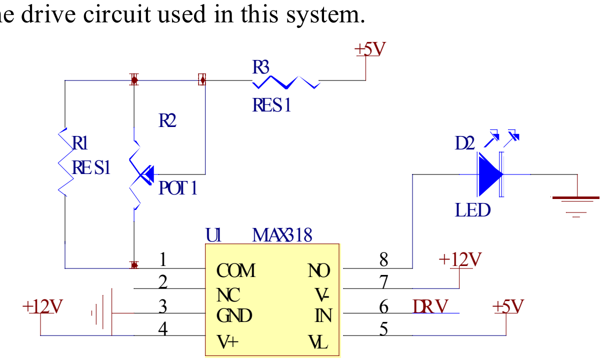

Fig. (5). Schematic of the LED drive circuit.

Precise CMOS single analog switch chip MAX318 is used to drive LED in circuit [7]. MAX318 is single-pole single-throw normally open (SPST-NO) switch, which is controlled by high-low level output by single chip. The maximum output current is 100mA and its six feet are connected with single chip. With the duty ratio of LED pulse current, the single chip may control LED on for 1ms and off for 9ms.

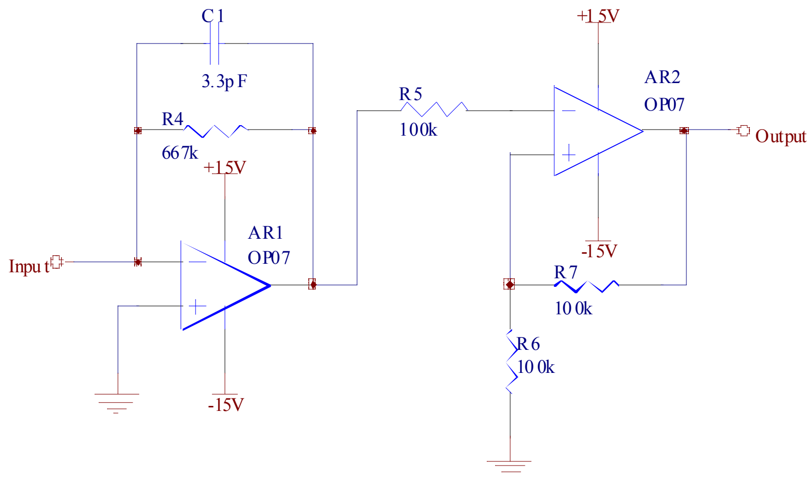

Fig. (6). Fluorescence signal amplification circuit.

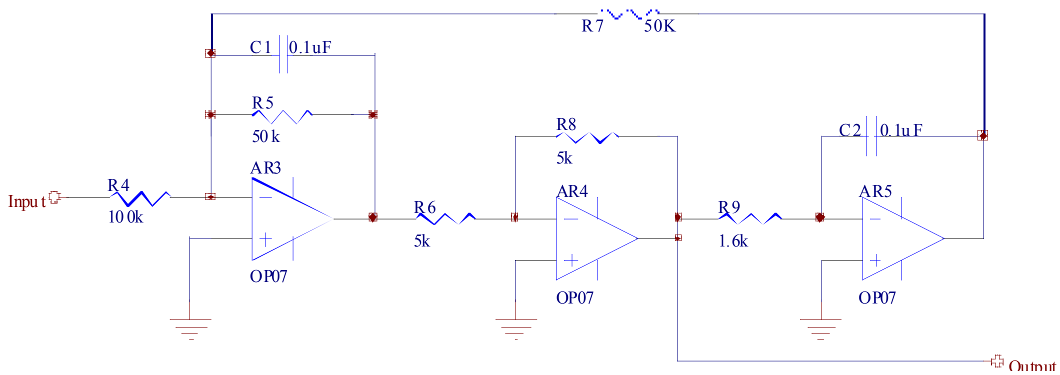

Fig. (7). Filter circuit.

5. FLUORESCENT SIGNAL PROCESSING SYSTEM

This system will conduct the further processing through amplification circuit and filter circuit after transforming fluorescence into electrical signal by photoelectric detector.

5.1. Fluorescent Signal Amplification Circuit

Because of the weak fluorescent signal, the electric signal output by photoelectric detector with noise signal is small. Therefore, the electric signal should be amplified with amplification circuit. Fig. (**6**) shows the amplification circuit used in this system. The whole amplification circuit is composed of two levels. The first level is current/voltage converter and the second is voltage amplifier. The output voltage of current/voltage converter is $V_o = I_{in} \cdot R_1$, which shows that the bigger the R_1 is, the larger the output signal will be. However, the value of R_1 is limited by circuit process and circuit noise amplification factor, so it should not be too large. $R_1 = 667\,k\Omega$ in this circuit. The second level of amplification circuit is voltage amplifier, which will amplify the electrical signal based on the amplification by the first level. The fine operational amplifier 0P07 has low bias and low offset current [8].

5.2. Filter Circuit

Fluorescent voltage signal with noises will be obtained after being amplified by amplification circuit. In order to restrain the noise interference, this system adopts second-order low-pass active power filter, which is shown in Fig. (**7**), because of the low fluorescent signal frequency. This filter has relatively high signal to noise ratio for its capability of highlighting the signal in useful frequency band and reducing signals in other frequency band and interfering noise. Reactive element used in this filter is always capacitor, rather than the inductor for its large volume, heavy weight and expensive price.

Exciting light stimulates florescent probe emitting fluorescence. The signal will enter fluorescence lifetime phase-locked detection circuit after majority of noise has been filtered when getting through the photoelectric detector, amplification circuit and filter circuit. At the same time, frequency output by phase-locked loop will be entered into single chip system for handling to obtain the measured temperature.

6. EXPERIMENT RESULTS AND ANALYSIS

This experiment system is mainly composed of exciting light source, fluorescent fiber probe, photoelectric detection and signal processing circuit, phase-locked fluorescence lifetime detection circuit, *etc*. As previously mentioned, the measurement of fluorescence lifetime τ in phase-locked detection method is realized by measuring modulation frequency. However, the relationship between fluorescence lifetime and modulation frequency is nonlinear. In order to improve the measuring accuracy, temperature will be

Table 1. Fluorescence lifetime at different temperatures.

Temperature/(K)	lifetime/(ms)	Temperature/(K)	lifetime/(ms)
273.0	3.723	353.0	2.704
283.0	3.648	363.0	2.592
293.0	3.529	373.0	2.537
303.0	3.427	383.0	2.465
313.0	3.335	393.0	2.408
323.0	3.219	403.0	2.328
333.0	2.964	413.0	2.239
343.0	2.813	423.0	2.176

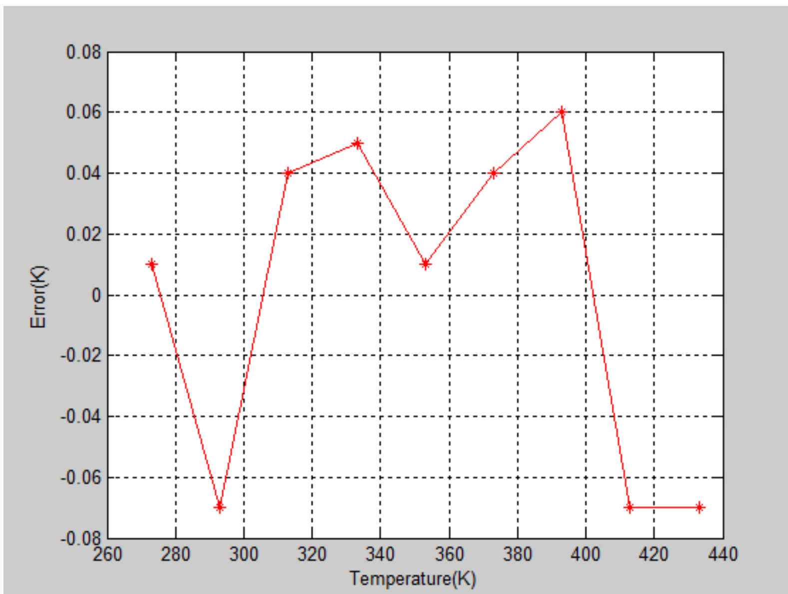

Fig. (8). Measurement results comparison.

measuring by table look-up [9, 10]. At first, the fluorescence lifetime of fluorescent emitter under different temperatures will be measured with FL920 transient fluorescence spectrophotometer of English EI Company. Therefore, a fluorescence lifetime-temperature table can be established with the obtained fluorescence lifetime corresponding to each working temperature. The data table for fitting ratio and temperature should be established in software and stored in internal storage. In actual measurement, the fitting ratio will be obtained by a series of calculation with actual measured values, and the corresponding temperature will be got by looking up the table. Table **1** shows the fluorescence lifetime at different temperatures.

Fig. (**8**) shows the comparison between measuring results of standard instrument and in method of this work. The horizontal axis refers to the temperature at sampling site, and the vertical axis is the difference between temperatures measured with standard instrument and this sensor. This figure shows that the measuring accuracy of system is up to $\pm 0.1K$.

In actual measurement, the stability and repeatability of system are better at $473K$ than at $673K$. This is because the strength of fluorescent signal will reduce with the increasing temperature, while the thermal radiation signal on background will increase rapidly. Therefore, the signal to noise ratio of system tends to worsen with the increasing temperature. In addition, the response time of system significantly increases and the response speed slows down, and the frequency even shakes with the rising frequency and reduced fluorescent signal. The experiment shows that temperature measurement accuracy is relatively high in the range of $273K \sim 723K$, while the error of repeatability will gradually increase out of the range.

CONCLUSION

Temperature measurement with fluorescence temperature characteristics of fluorescence materials and optic-fiber sensing technology is a feasible and effective method. Fluorescence lifetime can be correctly measured in phase-locked detection methods with the fluorescent signal after amplification and filtering. Fluorescence optic-fiber temperature sensor has advantages, including medium insulation, anti-electromagnetic interference, high measuring accuracy, *etc*. Moreover, long-distance remote measuring can be realized by transmission between exciting light source and fluorescence with optic fiber. Therefore, it can be applied in temperature measurement of transformer coil, wire end and automatic welder.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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