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A sapphire fibre thermal probe based on fast Fourier transform and phase-lock loop*

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A sapphire fibre thermal probe with Cr^{3+} ion-doped end is developed by using the laser heated pedestal growth method. The fluorescence thermal probe offers advantages of compact structure, high performance and ability to withstand high temperature in a detection range from room temperature to 450°C. Based on the fast Fourier transform (FFT), the fluorescence lifetime is obtained from the tangent function of phase angle of the non-zeroth terms in the FFT result. This method has advantages such as quick calculation, high accuracy and immunity to the background noise. This FFT method is compared with other traditional fitting methods, indicating that the standard deviation of the FFT method is about half of that of the Prony method and about 1/6 of that of the log-fit method. And the FFT method is immune to the background noise involved in a signal. So, the FFT method is an excellent way of processing signals. In addition, a phase-lock amplifier can effectively suppress the noise.

Keywords: fluorescence thermometer, fast Fourier transform, phase-lock loop, sapphire optical fibre
PACC: 0760

1. Introduction

In recent years, the technique of the fibre-optic temperature measurement in fluorescence has aroused the interest of all.[1] It can be applied to the microwave heating in medical treatment or internal temperature-monitor in large transformers in which the conventional temperature sensors are hard to use. The fluorescence lifespan of metal-ion-doped ceramic reduces exponentially with the increase of the temperature, based on which a temperature-sensing device can be developed. Essentially, the relation between the fluorescence lifespan and the temperature is inherent and irrelevant to light intensity, so we can make a self-checked fibre-optic temperature device.[2−5]

2. Basic principle

The principle of the fluorescence temperature measurement is based on the basic physical phenomenon of the photoluminescence. The so-called photoluminescence essentially is the superthermal radiation luminescence when some materials are stimulated by ultraviolet, visible or a certain form of the infrared electromagnetic radiation. This kind of luminescence is a way that the incident photons release the energy that the materials have absorbed. It may be fluorescence or phosphorescence, or both. After the stimulating light disappears, the duration of fluorescence is determined by the excited state lifespan.[6] This kind of luminescence usually fades away exponentially. The time constant of the exponential decay can be used as a measure of the excited state lifespan and is called fluorescence lifespan or fluorescence decay time.[7]

The fluorescence lifespan of most materials used for fluorescence temperature measurement is long. The fluorescence corresponds to permissive transitions between electron energy levels in materials. Those transitions release the energy of electrons that are stimulated by incident light.[8,9] This is a way that electrons return from excited states to the ground state, which causes materials to luminescence. Any available competitive process can shorten the excited state lifespan. Because many competitive processes exist at the same time, some of them can generate

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light but some cannot luminesce. Therefore the fluorescence lifespan and fluorescence strength of all fluorescence materials will imply some temperature correlation within some homologous temperature. The temperature correlation is right the principle of fluorescence temperature measurement.[10]

3. Research method

Because of the separation of the fluorescence temperature response elements from the fibre optic bundles, the quartz fibre-optic fluorescence temperature sensor head must be optically gummed together, and more complex outer protection is required to reinforce the mechanical robustness and stability, which makes the sensor head thermal inertia enlarged and the dynamic response worsened.[11] At the same time, because components of quartz fibre-optic are subjected to the fluorescence work temperature, they must be coated with the precious metals, which, however, still cannot be applied in the case of higher temperatures. A sapphire optic-fibre is possessed of some good properties in physics and chemistry, such as melting point being as high as 2045°C, good optical entrance rate near infrared, and good resistance to high temperature. We use a laser to heat a small pedestal, so that a fluorescence-temperature-responding material like a small ruby crystal optic-fibre will grow on the top of the sapphire optic-fibre, which can be made into a sensor head that has compact structure, good resistance to high temperatures and stable operation. After both ends of the sapphire optic-fibre with Cr^{3+} are optically polished, one end of the Cr^{3+}:Al_2O_3 optic-fibre with Cr^{3+} is used as the temperature sensor head; the other is connected with a Y-type quartz optic-fibre.[12] A pulse-driven diode emits very bright green light, which is used as a stimulating light source with its luminescence centre wave length being 575 nm and spectrum bandwidth being 40 nm, and focused by a lens onto one end of a Y-type quartz optic-fibre to stimulate the crystal emitting fluorescence. The stimulated fluorescence is transmitted from the other end of the Y-type quartz optic-fibre to an interference filter. After filtering the stimulated light mixed, fluorescence signals arrive at the PIN Si photoelectric detector. After the photoelectric conversion and amplification the fluorescence signals are send to a signal processing circuit to measure the fluorescence lifespan.[13]

The fluorescence signals, which are stimulated from the optic-fibre temperature sensors that are based on the fluorescence effect, are generally very weak, and the electric signals, which are usually immersed in noise, are also very weak after the photoelectric conversion. In order to extract the signals from the noise, we must adopt a homologous weak signal measuring circuit.[14]

This is the key technique of the optic-fibre fluorescence temperature sensors. In the optic-fibre fluorescence temperature measuring system, in order to simplify the optical system design, we usually make some periodic marks to the light source, therefore a phase-lock amplifier is commonly adopted as the measurement device of the analogue signals from the photodetector, as shown in Fig.1. The phase-lock amplifier has the following characteristics: a very narrow bandwidth (B <1Hz), the great elimination of the system temperature-drifting factor and the effective suppression of the noise. It is a kind of amplifier with phase-sensitive detection to alternating signals. It makes use of the reference signals with the same frequency and phase as those of the signals to be measured, and only responds to the signals to be measured and those voice components that have the same frequency and phase as those of the reference signals. So it can obviously suppress useless noise, and improve the signal-to-noise ratio. In addition, the phase-lock amplifier has very high discernibility for weak signals, and is an effective tool to probe weak signals.[15] The basic unit of a phase-lock amplifier has three main parts: signal passage, reference passage and phase-sensitive detection.[16] The signal passage selects a frequency from the beginning signals with the noise and amplifies the selected signal, and preliminarily carries out the narrowband filtering of noise. The reference passage provides a reference voltage with the same frequency and phase as those of the signals to be measured through phase-lock and phase-shift.[17] The device of phase-sensitive detection constitutes the low-pass filter and mixing multiplicator.

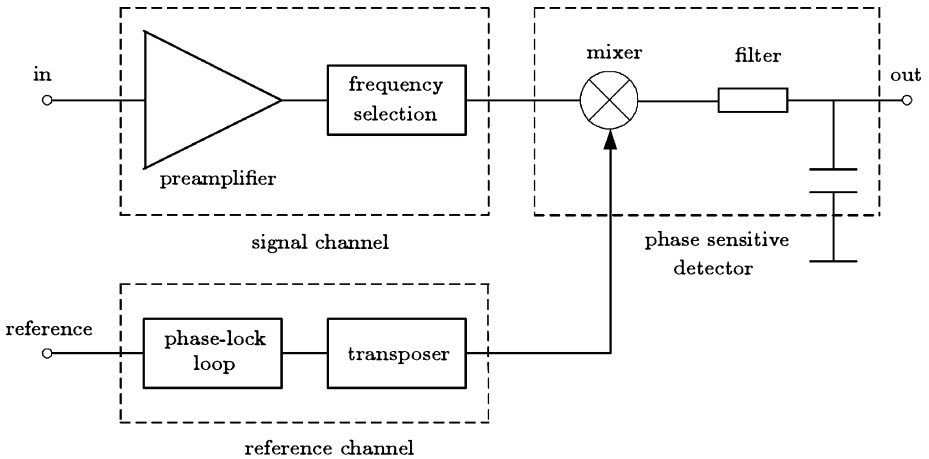


Fig.1. Phase-lock amplifier.

There are three main methods of measuring fluorescence lifespan; they are the data fitting method, analogue phase-lock method, and digital phase-lock method. Among them the data fitting method can be used not only to measure the fluorescence lifespan, but also to analyse signals. The data fitting method of measuring fluorescence lifespan primarily covers the method of Marquardt, the method of Prony, logarithms fitting (log-fit) method etc.[18] In order to improve the signal-to-noise ratio, we need a kind of more effective fitting method. Since fluorescence signals are of single-valued exponential decay, we can apply the FFT to this kind of signal, and then calculate the fluorescence lifespan from the non-zero terms in the FFT transform result. The deviation of the fluorescence lifespan in using the method is far smaller than that in using the Prony method or logarithms fitting method, but close to the result from the method of Marquardt.[19] It is not subjected to the influence of the background noise, but at the same time the fitting time is greatly shorten by using the FFT. After the stimulating light stops, the fluorescence cannot disappear at once, but fades away exponentially. The time in which fluorescence fades away calls the fluorescence lifespan. The fluorescence lifespan is a function of temperature, and is independent of light intensity. The fluorescence-attenuating signal can be expressed as

$$f(t) = A\exp(-t/\tau) + B, \tag{1}$$

where A denotes the start light intensity, B represents the background noise originating from the black radiation or dark current of the circuit carrying the electric current, which is the direct current component. When digitally sampling by using digital sampling cards or other means, we obtain the following expression:

$$\begin{aligned} &f_k(t) = A\exp(-k\Delta t/\tau) + B, \\ &k = 0, 1, \cdots, N-1, \end{aligned} \tag{2}$$

where Δt is the interval of sampling time. We can perform the fitting to the signal to work out the fluorescence lifespan τ.

The nth term of FFT in formula (2) is

$$\begin{aligned} F_n &= \sum_{k=0}^{N-1} f_k \exp\left(-\mathrm{j}\frac{2\pi n}{N}k\right) \\ &= \sum_{k=0}^{N-1} A\exp\left[-\left(\frac{\Delta t}{\tau} + \mathrm{j}\frac{2\pi n}{N}\right)k\right] \\ &\quad + B\sum_{k=0}^{N-1}\exp\left(-\mathrm{j}\frac{2\pi n}{N}k\right) \\ &\quad n = 0, 1, \ldots, N-1. \end{aligned} \tag{3}$$

The zeroth term is

$$F_0 = A\frac{1-\exp(-N\Delta t/\tau)}{1-\exp(-\Delta t/\tau)} + NB, \tag{4}$$

which is dependent on the background noise. While the other items ($n \neq 0$) can be simplified as

$$\begin{aligned} F_n =& A\frac{1-\exp(-N\Delta t/\tau)}{1-\exp(-\Delta t/\tau)\exp(-\mathrm{j}2n\pi/N)}, \\ &n = 0, 1, \ldots, N-1. \end{aligned} \tag{5}$$

Except the zeroth term, the other terms are independent of the background noise. We use the first non-zero term to calculate the fluorescence lifespan. Applying the FFT to the formula (5) with $n = 1$, the formula (5) can be changed into

$$\begin{aligned} F_1 =& A\left[1-\exp(-N\Delta t/\tau)\right] / \{[1-\exp(-\Delta t/\tau)] \\ &\times \cos(2\pi/N) + \mathrm{j}\exp(-\Delta t/\tau)\sin(2\pi/N)\}. \end{aligned} \tag{6}$$

This term is complex, and its tangent function of the phase angle is expressed as follows:

$$Q_1 = \mathrm{tg}\,\varphi_1 = \frac{\mathrm{Im}F_1}{\mathrm{Re}F_1} = \frac{-\exp(-\Delta t/\tau)\sin(2\pi/N)}{1-\exp(-\Delta t/\tau)\cos(2\pi/N)}. \tag{7}$$

The tangent function Q_1 of the phase angle of the first non-zero FFT term is a single-valued function of fluorescence lifespan. It is independent of the start light and background noise. We can calculate the fluorescence lifespan τ from Eq.(7)

$$\tau = \Delta t \ln\left\{\left[Q_1\cos(2\pi/N) - \sin(2\pi/N)\right]/Q_1\right\}. \tag{8}$$

4. Experimental results and analyses

To compare the FFT method with other fitting methods, we adopt computer simulation and the model to be used is as follows:

$$f_k = \exp(-k\Delta t/\tau) + C_{\mathrm{rn}} + B, \quad k = 0, 1, \ldots, N-1, \tag{9}$$

where C_{rn} is the random noise. First, we compare the deviations in using the three different methods: log-fit method, FFT method, and Marquardt method under the random noise. The experimental results are shown in Fig.2.

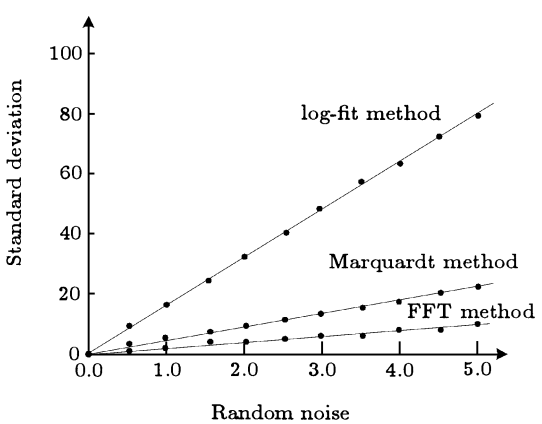


Fig.2. The standard deviations caused by different methods under the random noise.

It can be seen from Fig.2 that, of the three deviations, the deviation caused by the FFT method is the smallest, which is close to the result of the Marquardt method, and the deviation given by the log-fit method is the largest.

Second, in a real system, the fluorescence signals are always intermixed together with the background noise. The influence of the background noise on the systemic deviation in different methods is indicated in Fig.3.

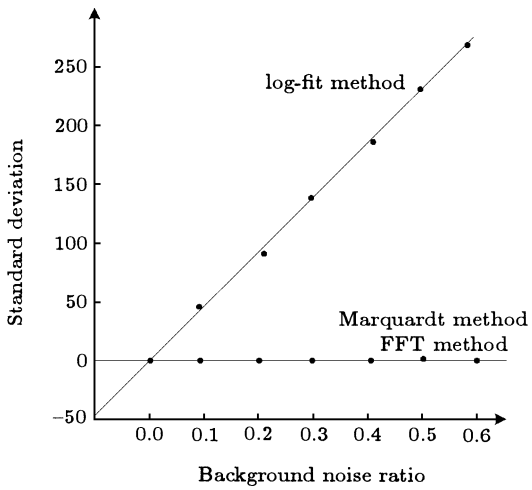


Fig.3. The influence of the background noise on the systemic deviation in different methods.

We can see from Fig.3 that the Marquardt method and the FFT method are immune from the background noise of the signal. The log-fit method is obviously influenced by the noise. Because the Marquardt method needs a recursive program that costs a lot of computing time, it cannot be adopted in systems in spite of its high accuracy.

5. Conclusions

A sapphire optic-fibre thermal probe with Cr^{3+} ion-doped end is developed by using the laser heated pedestal growth method. The fluorescence thermal probe offers advantages of compact structure, high performance and ability to withstand high temperature. In a detection range from room temperature to 450°C, using FFT, the fluorescence lifetime is obtained as a tangent function of the phase angle of the non-zero terms in the FFT result. This method has advantages such as quick calculation, high accuracy and immunity to the background noise. This FFT method is compared with other traditional fitting methods, indicating that the standard deviation of the FFT method is about half of that of the Prony method and about 1/6 of that of the log-fit method. In addition, the FFT method is immune from the background noise involved in a signal, so the FFT method is an excellent way of processing signals.

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