A device for fluorescence temperature measurement based on fast fourier transform*

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(Received 16 June 2007)

A sapphire fiber thermal probe with Cr^{3+} ion-doped end was grown using the laser heated pedestal method. The fluorescence thermal probe offers advantages of compact structure, high performance and the ability to sustain high temperature from the room temperature to 450 °C. Based on the fast fourier transform (FFT), the fluorescence lifetime is obtained from the tangent function of the phase angle of the first non-zeroth item of FFT result. Compared with other traditional fitting methods, our method has advantages such as fast speed, high accuracy and being free from the influence of the base signal. The standard deviation of FFT method is about half of that of the Prony method and close to the one of the Marquardt method. In addition, since the FFT method is immunity to the background noise of the signal, the background noise analysis can be skipped.

CLC numbers: TN247 **Document code:** A **Article ID:** 1673-1905(2008)02-0147-3

DOI 10.1007/s11801-008-7074-y

Temperature is one of the most important parameters in measurement science and industrial process control. The importance of temperature measurement is around our scientific researches and daily lives. For example, almost all chemical reactions are temperature related. Very often, in chemical plants the temperature is the only guidance in the production line. Current existing instruments have offered wide choices for industrial production, laboratory or special industrial applications. However, because of the continuously expanding application fields of the temperature measurement, the innovation, research and development for temperature measurement and control techniques is constantly going on. Some newly emergent applications require accurate temperature measurement for targets having difficulty to be accessed, such as deleterious or sportive objects. During recent years, the technique of the fiber-optic temperature measurement in fluorescence has aroused the considerable research interest. It can be applied to the microwave heating in medical treatment or internal temperature-monitor for large transformers where the conventional temperature sensors are hard to use. Note that the fluorescence lifetime of some 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 lifetime and the temperature is inherent and independent to light intensity, so we can make a self-calibrated fiber-optic temperature device.[1]

The mechanism of the fluorescence temperature measurement is based on the photoluminescence, which is essentially 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 channel through which the incident photons release their energy absorbed by the materials. It can be fluorescence or phosphorescence, or both. After the pump light disappears, the duration of fluorescence is determined by the lifetime of the excited state. This kind of luminescence usually decays exponentially. The time scale of this exponential reduction can be used as a measure of the excited state's lifetime and is called fluorescence lifetime or fluorescence decay time.

The setup of the fluorescence thermal measurement is shown in Fig.1.

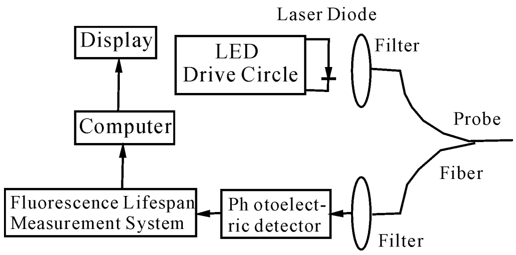

Fig.1 The system of fluorescence thermal measurement

* This project has been supported dy the Natural Science Research Foundation of Education Bureau of Hebei Province, China (Grant No.2001265)

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Because of the separation of the fluorescence temperature response elements form the fiber optic bundles, the quartz fiber-optic fluorescence temperature sensor head must be optically gummed together, and more complex outer protection is required to reinforce the mechanical robustness and the stability making the sensor head thermal inertia enlarged and the dynamic response worsened. At the same time, because the components of quartz fiber-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 temperature. A sapphire optic-fiber has the good physical and chemical performances including high melting point of 2045 ℃, good optical entrance rate near infrared, and good high-temperature optic-fiber material[2]. We use a laser to heat a small pedestal, so that fluorescence-temperature responding materials like a small ruby crystal optic-fiber will grow on the top of the sapphire optic-fiber, which can be made into a compact-structure, high-temperature and stable-function sensor head. After both ends of the sapphire optic-fiber with Cr^{3+} are optically polished, one end of the Cr^{3+} : Al_2O_3 optic-fiber with Cr^{3+} is used as the temperature sensor head; the other is connected with a Y-type quartz optic-fiber. A pulse-driven diode emits very bright green light, which is used as a stimulating light source with its luminescence wave-length centered at 575 nm. The spectrum bandwidth is 40 nm. The green light is focused by a lens onto one end of a Y-type quartz optic-fiber to excite the fluorescence. The stimulated fluorescence is transmitted from the other end of the Y-type quartz optic-fiber to an interference filter. After filtering the mixed stimulated light, fluorescence signals are detected by the PIN Si photoelectric detector. After the photoelectric conversion and the amplification fluorescence signals are sent to a signal processing circuit to measure the fluorescence lifetime.

There are three main methods of measuring fluorescence lifetime, being the data fitting method, analogue phase-lock method and digital phase-lock method[3]. Among them the data fitting method can not only measure the fluorescence lifetime, but also make analyses of the signals. The data fitting method of measuring fluorescence lifetime primarily covers the method of Marquardt, the method of Prony, logarithms fitting (log-fit) method and etc. In order to improve the signal-to-noise ratio, we need a more effective fitting method. Since fluorescence signals undergo exponential decay, we can apply FFT to the signals in order to calculate the fluorescence lifetime from the non-zero terms in the FFT result. The deviation of the fluorescence lifetime using this method is far smaller than that using the Prony method or logarithms fitting method, but near to the result from the method of Marquardt. It is not subjected to the influence of the background noise, but at the same time the fitting time is greatly shortened by using the FFT. When the stimulating light has gone, the fluorescence would not disappear immediately, but fades away exponentially. The time that fluorescence fades away is called the fluorescence lifetime. The fluorescence lifetime 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 initial 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

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

Where Δt is the interval of sampling time. We can perform the fitting to the signal to find the fluorescence lifetime τ[4-7].

The n th term of FFT in formula (2) is

$$F_n = \sum_{k=0}^{N-1} f_k \exp\left(-j\frac{2\pi n}{N}k\right) = \sum_{k=0}^{N-1} A\exp\left[-\left(\frac{\Delta t}{\tau} + j\frac{2\pi n}{N}\right)k\right] + B\sum\exp\left(-j\frac{2\pi n}{N}k\right) \tag{3}$$

$$n=0,1,\cdots,N-1$$

$$F_1=A[1-\exp(-N\Delta t/\tau)]/\{[1-\exp(-\Delta t/\tau)]\cos(2\pi/N)+j\exp(-\Delta t/\tau)\sin(2\pi/N)\} \tag{4}$$

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

$$Q_1 = tg\varphi_1 = \frac{\mathrm{Im}F_1}{\mathrm{Re}F_1} = \frac{-\exp(-\Delta t/\tau)\sin(2\pi/N)}{1-\exp(-\Delta t/\tau)\cos(2\pi/N)} \tag{5}$$

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

$$\tau = \Delta t\ln\{[Q_1\cos(2\pi/N) - \sin(2\pi/N)]/Q_1\} \tag{6}$$

To compare with other fitting methods, we carry out computer simulation and the model is as follows[8-9]

$$f_k = \exp(-k\cdot\Delta t/\tau) + C_{rn} + B \qquad k=0,1,\cdots,N-1 \tag{7}$$

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

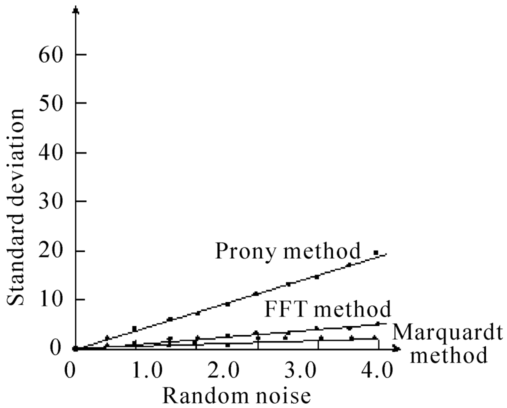

Fig.2 The deviations by using different methods under the random noise

It can be seen from Fig.2 that, of the three deviations, the deviation of FFT method is the smallest, which is close to the result of the Marquardt method, and the deviation of 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 in different methods is indicated in Fig.3.

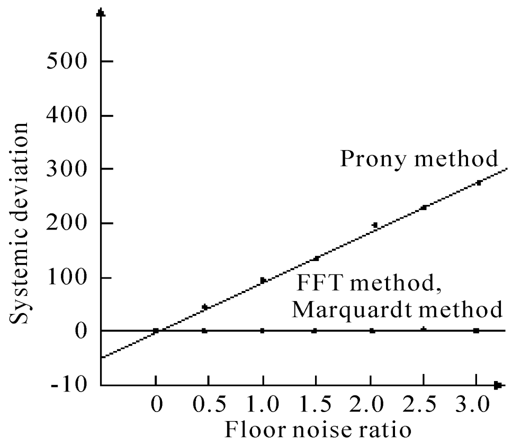

Fig.3 The influence of the background noise under different methods

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 time, it cannot be adopted in practical systems in spite of its high accuracy.

A sapphire optic-fiber thermal probe with Cr^{3+} ion-doped end is developed by using the laser heated pedestal growth method in a detection range from room temperature to 450 °C. This method has advantages such as quick calculation, high accuracy and immunity to the background noise. We can adopt the laser diode for higher intension and coupling efficiency so that the resolving power can be advanced.

References

[1] YE Lin-hua., Infrared&Millimeter Wave, **16** (1997):437(in Chinese).

[2] KTV Grattan, A W Palmer, and Z Zhang. Rev.Sci.Instrum.,**62** (1991), 1210.

[3] R R Sholes, and J G Small, Rev.Sci.Instrum., **51** (1980), 882.

[4] ZHANG Zhi-yi, TV Grattan, and AW Palmer. Phys.Rev.B, **48** (1993), 7772.

[5] S.A.Wade, J.C.Muscat, and S.F.Collins, Review of Scientific Instruments, **70** (1999), 4279.

[6] YE Lin-hua, SHEN Zhong-ping, and ZHAO Wei-zhong Photoelectron&Laser, **13** (2002), 773. (in Chinese)

[7] Z.Y.Zhang, K.T.V.Grattan, and A.W.Andrew SPIE, **2388** (1995), 190.

[8] T.Sun, Z.Y.Zhang, K.T.V.Grattan, Review of Scientific Instruments, **68** (1997), 3447.

[9] Z.Y.Zhang, K.T.V.Grattan, and A.W. Palmer, Review of Scientific Instruments, **69** (1998), 139.