A Fluorescence Optic-Fiber Temperature Sensor Using Phase-Locked Detection with Pulse Modulation Single Reference

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Abstract. A kind of fluorescence optic-fiber sensor is devised based on Modulated PLD with pulse modulation signals references (PLD-PMSR). The characteristic of fluorescence material absorption and emission is analyzed, and the optic-fiber temperature measurement probe based on LiSrAlF\(_6\):Cr\(^{3+}\) is designed. This system is good for the temperature measurement in the range of 20\(^\circ\)C to 50\(^\circ\)C. During the cause of experimentation, this temperature measurement method is proved to be effective and useful for its highly resolution and precision.

1. Introduction

The biomedical field is necessary of accurate measurement of temperature. The region around normal body temperature of 37\(^\circ\)C, and thus the 20–50\(^\circ\)C region is particularly important to the measure of high resolution and high accuracy, with interest for some laboratory applications over the 0 to 100\(^\circ\)C region being high and the error is greatly. A number of techniques may be applied to such measurement, often using optical means, and there are a number of special uses of an optical thermometer in potential monitoring and care. Fiber optic fluorescence techniques show real potential for use over the biomedical region [1,2]. Therefore, in this paper, a kind of fluorescence optic-fiber thermometer is devised based on crystal Cr: LiSAF. The characteristic of fluorescence material absorption and emission is analyzed, and the optic-fiber temperature measurement probe is developed. This system is particularly adapt to the temperature measurement in the field of Biomedical in the range of 20 to 50\(^\circ\)C. During the cause of experimentation, this temperature measurement method is proved to be effective and useful for its highly resolution and precision, 10\(^{-20}\)m\(^2\).

2. Absorption and emission spectra of Fluorescence Material

Figure 1 is the Absorption and emission spectra of LiSrAlF\(_6\):Cr\(^{3+}\). The fluorescence spans the wavelength region from 650nm to 1000nm with peak at 830nm, it lies within the most sensitive detection region of ordinary silicon PIN Photodiode. Such a broadband emission is the inverse of the transition which gives rise to the first absorption band. From the absorption spectra in Figure 1, the magnitude of the crystal field strength \(D_q/B\) in LiSrAlF\(_6\):Cr\(^{3+}\) is estimated to be 2.0. This indicates that LiSrAlF\(_6\):Cr\(^{3+}\) is of a low crystal field strength. This is verified by the sharp feature appearing at 650nm in the absorption spectrum arising from the \(^2E\) state.
3. The configuration of the PLD-PMSR system

The PLD-AMSR scheme can be directly adapted to a scheme using a pulse modulated excitation source, called PLD-PMSR, by replacing the sinusoidal output VCO with an ordinary VCO which generates a periodic rectangular pulse with a 50% duty cycle. There are at least two considerations which favor the use of rectangular pulse modulation in the PLD scheme. First, such a rectangular pulse can carry more excitation power from the light source than the sinusoidal one, therefore a higher signal-to-noise ratio can be achieved from the corresponding fluorescence response. Secondly, the rectangular pulse modulation of the excitation light source is simpler and much easier to be realized in practice.

An illustration of a PLD-PMSR scheme is depicted in figure 2, and the waveforms of some signals designated .As the excitation source is pulse modulated by a signal which is of the form of a rectangular wave, the dc-decoupled fluorescence response, \( v_f \), is given by:

\[
v_f = v_f(t) = \begin{cases} 
V_{d0} - \frac{2V_{d0}e^{-\alpha t}}{1 + e^{-\alpha t}}, & 0 \leq T < T/2 \\
-V_{d0} + \frac{2V_{d0}e^{-(T-T/2)/\tau}}{1 + e^{-\alpha t}}, & T/2 \leq T < T 
\end{cases}
\]

and

\[
v_f(t) = -v_f(t + T/2) \\
v_f(t) = v_f(t + nT), n = 1,2,3...
\]

\( v_r \), the reference signal, is obtained by delaying the modulation signal \( v_m \), by \( \alpha T \). Thus the output of the PSD may be expressed as:

\[
y = \frac{1}{T} \int v_{m1}(t)dt = \frac{1}{T} \left\{ \int_{0}^{T} v_f(t)dt + \int_{T/2}^{T} v_f(t)dt - \int_{T+T/2}^{T+T/2} v_f(t)dt \right\}
\]

\[
= \frac{2}{T} \int_{0}^{T} v_f(t)dt = k \cdot V_{d0} \left[ 1 - 4\alpha + \frac{4\alpha x}{1 + e^{-\alpha x}} \right]
\]

\[
= k \cdot V_{d0} \left[ 1 - 4\alpha + \frac{4\alpha}{x(1 + e^{-\alpha x})} \right]
\]

\[
= f(\alpha, x), (1 \leq \alpha \leq 1/2, x > 0)
\]

Figure 1. Absorption and emission spectra of LiSrAlF₆:Cr³⁺.
Where \( x \) is as defined in \( x = T/\tau \), \( y \) is plotted as a function of \( x \) with respect to different values, normalized to the product of \( k \) and \( V_{AO} \), \( x_0 \), the gain of the lifetime-to-period conversion of the system is given by:

\[
x_0 = x\big|_{f(x,\alpha)=0} = f_1(\alpha)
\]  
and is depicted as a function of \( \alpha \) as a solid line. This is rather close to that of the PLD-AMSR scheme, presented as a dashed line in the same figure, and \( y \) is determined only by the true fluorescence response.

4. The working principle of the system

4.1. Signal system

The whole structure of the detection system is illustrated in Figure 3. It is composed of an optical system used to excite and transmit fluorescence and the electronic system used to probe and process the fluorescence signals. The absorption spectrum of LiSrAlF\(_6\):Cr\(^{3+}\) spans the wavelength region from the ultraviolet to near 750 nm with a peak falling between 600 nm and 700 nm. As shown in Figure 1, the isolation of the excitation light at the fluorescence detection stage was provided by a simple doped glass filter. This glass filter has a long-pass band starting at 720 nm, and this matches well the LiSrAlF\(_6\):Cr\(^{3+}\) emission spectrum shown in figure 1. Thus, the separation between the excitation light and fluorescence emission in wavelength terms, little compromise has been required between efficient transmission of fluorescence and good isolation of excitation light at the detector stage. This is a near perfect optical arrangement and a much higher signal to noise ratio is obtained.

Although no significant excitation light leakage was observed in the received fluorescence signal, the pulse profile of the laser diode output is not ideally rectangular as in the case of the other scheme. Thus the single-sided PLD-PMSR technique was employed to form the PLD module in this thermometer system, so that the lifetime measurement is produced only using the decay part of the fluorescence signal, and much better measurement repeatability could be achieved from the use of the single-sided PLD-PMSR technique. Through the long-pass filter, then enter PLD-PMSR to carry on
the signal processing through the light electricity locator, get the fluorescence life span, end through single slice the machine system get the temperature value measure.

4.2. Probe system
The construction of the temperature probe is also depicted schematically in Figure 4. The volume of the LiSrAlF₆:Cr³⁺ sample used was about 0.3×0.2×0.3mm³, although this specific size is not critical. It is housed, using optical adhesive, on the sensor port of a 1×2 bi-directional fiber coupler made from 200µm hard-clad silica fiber. With the outer plastic coating, the total diameter of the fiber used is about 0.6mm.

![Figure 4. The probe of fiber temperature.](image)

The configuration of the clinical RF applicator in which the thermometer was employed[8]. The RF antenna is placed in a pure silicone catheter which is to be planted at the location of the prostate. The retention balloon near the end of the catheter is used to help secure the position of the RF antenna. Its inflation or deflation is controlled through an air tunnel in the wall of the catheter, of which the entrance is indicated. To monitor the temperature of the tissue under RF treatment, the temperature probe is placed in the catheter along with the RF treatment, the temperature probe is placed in the catheter along with the RF transmission cable and with the position of the sensor tip at the point with maximum RF power output.

5. The working principle of the system
The data for the fluorescence lifetime are plotted against temperatures in figure 5. This shows that the LiSrAlF₆:Cr³⁺ fluorescence lifetime decreases monotonically with temperature increase, although it is rather insensitive to temperature variance around 0°C or below. From about 5°C, the fluorescence lifetime drops more and more sharply with temperature increase. This is seen explicitly from the rapid increase in its temperature sensitivity with temperature increase. The fluorescence intensity recorded also decreases with temperature increase, and this is as would be expected according to the configurational coordinate model for the Cr³⁺ fluorescence in low strength fields.

![Figure 5. The curve of fluorescence to temperature.](image)
measurement repeatability of the system is observed to be better than 0.1°C at 20°C, a precision of such an order could be achieved over the region from 25 to 120°C by using this thermometer system.

6. Conclusion
The configuration coordinate model for Cr³⁺ fluorescence in low strength fields has been applied to fit the LiSrAlF₆:Cr³⁺ fluorescence lifetime over the 25-70°C, and in the range of 20°C to 50°C is precision. The deviation of the fitting errors achieved is 0.12%. And such a close agreement indicates that a precision of 0.2°C can be provided by the use of this model in the calibration of the corresponding thermometers. A precision like this is more than adequate for the application discussed here, where the need for temperature resolution is limited to ±0.5°C.

Table 1. The experiment data in the system.

| Normal Temperature(°C) | Experiment result(°C) | Lifetime(τ,ns) | Accuracy(°C) |
|------------------------|-----------------------|----------------|--------------|
| 20                     | 20.22                 | 62.81          | 0.050        |
| 30                     | 30.31                 | 60.13          | 0.020        |
| 40                     | 39.81                 | 57.66          | 0.015        |
| 50                     | 50.22                 | 53.57          | 0.010        |
| 60                     | 59.76                 | 49.14          | 0.007        |
| 70                     | 70.21                 | 47.87          | 0.003        |
| 80                     | 79.65                 | 42.21          | 0.001        |

References
[1] Wicksheim K.A 1986 A new fiberoptic thermometry system for use in medical hyperthermia SPIE Proceedings 713, 150–157
[2] Zhang Z.Y, Grattan K.T.V. and Palmer A.W. 1992 Fiber optic high temperature sensor based on the fluorescence lifetime of alexandrite Review of scientific Instruments 63 3869–73
[3] Zhang Z.Y, Grattan K.T.V. and Palmer A.W. 1992 Sensitive fiber optic thermometer using Cr: LiSAF fluorescence for bio-medical sensing applications Proceedings of 8th Optical Fiber Sensors Conference (Monterey, California, January) 93-96
[4] Wu J.L and Wang Y.T 2005 Ruby(Al₂O₃:Cr³⁺)Fluorescence Thermometer Using PLD-PMSR Technique Semiconductor Photonics and Technology 11 259–262
[5] Grattan K.T.V. and Sun T 2000 Fiber optic sensor technology: an overview Sensors and Actuators 40–61
[6] Zhang Z.Y, Grattan K.T.V. and A.W. Pamler, 1993,Phase-locked detection of fluorescence lifetime Rev. Sci. Instrum. 64 2531–33
[7] Sun T, Grattan K.T.V. and Sun W M 2001 Fluorescence based optical fiber fire alarm system 15th Optical Fiber Sensors Conference 471–474
[8] E.Maurice, G.Monnon, B.Dussardier et al 1995 Erbium-doped silica fibers for intrinsic fiber-optic temperature sensors Applied Optics 8019–25