Optic-fiber Sensor Based on Fluorescence Spectrum Analysis

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Keywords: Fluorescence optic-fiber thermometer; ruby material; Fluorescence Spectrum Analysis.

Abstract: A kind of fluorescence optic-fiber thermometer is devised based on the solid-state ruby fluorescence material. The characteristic of fluorescence material absorption and emission is analysised, and the optic-fiber temperature measurement probe based on ruby is developed. This system is particularly adapt to the temperature measurement in the rang of 20℃ to 600℃. During the cause of experimentation, this temperature measurement method is proved to be effective and useful for its highly resolution and precision.

1 INTRODUCTION

Apart from being a desirable precious gem stone, ruby is well-known as the laser crystal used in the world's first successful operation of a laser. It is also among the earliest of materials for which the fluorescence lifetime properties were proposed for thermometric applications [1]. The actual use of ruby as the sensor element in a fiber optic fluorescence lifetime thermometer was perhaps first reported by Grattan [2] [3]. In this thermometer system, an LED was used as the excitation light source and a silicon PIN diode was employed for the detection of the fluorescence signal. Using that system, temperature measurement was achieved over the region from room temperature to 1700C.This thermometer system described below is devised in an effort to extend the measurement range of this compact and low-cost system and further improve and conveniently extend its performance.

2 DESCRIPTION OF THE DEVICE

This ruby fluorescence thermometer is schematically depicted in Figure 1.A green LED was used as the excitation source, which can pump into the strong absorption band centered at 550nm[4], as show in the absorption spectrum of ruby in figure 2.As the radiation of the green LED contains a weak emission band in the red portion of visible spectrum, which overlaps part of the fluorescence emission spectrum, a short pass optical filter, F1 shown in Figure1, with a cut-off wavelength at 630nm is used to eliminate this red 'tail' of the LED emission. The fluorescence emission spectrum is obviously at longer wavelengths, as shown in Figure3, with the strongest emission on the R-lines (around694nm). Thus, a readily available long-pass doped glass filter could then be used as the filter, F2 in figure1, to isolate the excitation light from the fluorescence emission at the detector stage. However in order to achieve better isolation, an 'off-the-shelf' band-pass interference filter with the pass-band centered at 694.3nm and a bandwidth of 12nm, designed for laser uses, was employed as the F2 instead in Figure1.

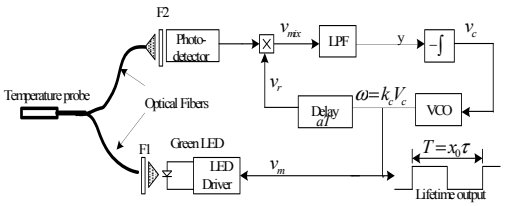

Figure1. The ruby fluorescence lifetime based fiber optic thermometer system.

F1: short-pass optical filter; F2: R-line band-pass optical filter.

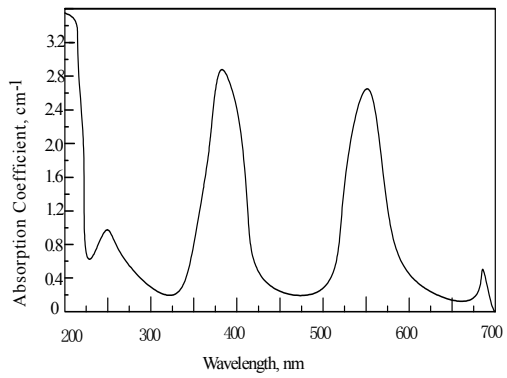

Figure 2.The absorption spectrum of ruby.

In this system, gold-coated silica fibers were first used to fabricate the probe for temperature measurement up to 6000C.The core diameter of the fiber used was 400μm. The probe was configured in the reflection-type configuration, it is shown in figure 4.

Due to the relatively low emission intensity of the LED light source then available, the intensity of the induced fluorescence respond which could be detection of several nanowatts. Thus a comparatively poor signal-to-noise ratio of the detected fluorescence response was observed, An even less favorable signal-to-noise ratio would be expected at higher temperatures due to decrease in the fluorescence intensity with the increasing temperature.

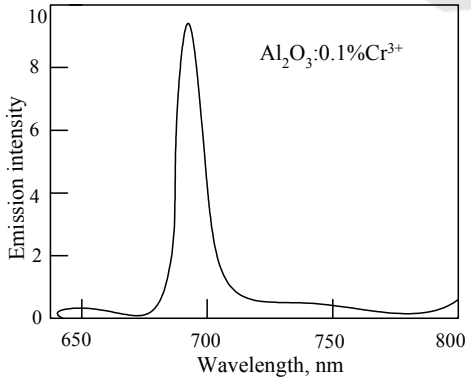

Figure3.The emission spectrum of ruby.

To tackle the poor signal-to-noise ratio problem the 'phase and modulation method' [3] to measure the fluorescence life time, with the employment a fixed frequency, high Q-value bandpass electronic filter to the wideband noise in the fluorescence signal. Though the effectiveness of this scheme adequately demonstrated, its measurement range is limited by the fixed single modulation frequency, and a slight drift in the parameters of the high Q-value bandpass filter could introduce error in the phase measurement.

To solve this problems, the PLD-PMSR[5] technique was applied to the ruby based thermometer system, as shown in Figure1.Here,the phase shift ratio, α ,is chosen to be 3/8,an optimum value according to the discussion given earlier, and tugging of he lifetime to period conversion.

3 THE DESIGN OF HIGH-TEMPERATURE FIBER PROBE

The novel feature of the temperature probe used is the use of gold-coated fibers, which h are well suited to the specific application allow high temperatures to be reached, as they have more favorable characteristics for such high temperature regions than the plastic-clad silica (PCS) fibers used in earlier work[3]. Which is soldered using gold-working techniques developed specifically to secure it to the end of the optical fibers. This enabled a strong and secure joint to be made and produced a probe, which could be totally immersed in the hot region, where the measurement is to be made. As the fiber was small, the gold and crystal were of small mass, and so the thermal response of the device could be relatively rapid and the cost of expensive material kept low. The aim was to measure continuously over the range from room temperature to 6000C.

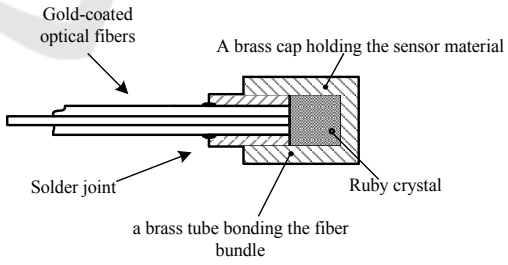

Figure 4.Schematic of the fiber-optic probe used with the ruby fluorescence lifetime based thermometer described in this system.

The feasibility of developing such a high-temperature fiber optic probe was based on the availability of fibers with a high-temperature cality. Normal plastic-clad silica (PSC) fiber is limited to a maximum operating temperature of 1500C but in order to exploit the much higher temperature

capability of sapphire-based sensor materials such as ruby, another type of fiber is needed, such as that available in gold coated form, fabricated, and of the types available the highest temperature capability has an upper limit of 7500C.This considerable improvement over PCS fibers is achieved through the use of a thin gold coating on the silica material. The probe was constructed[6] with four 400-μm fibers using two of them to carry the excitation light and two to receive the fluorescence a compromise of flexibility and sufficient fiber end-face arear. The fibers were of fused silica core and doped silica cladding. The numerical aperture was 0.22 and the clad-to-core ratio of diameter used was 1:1.1[7].A particular advantage of such fiber was that the metal coating offered the additional possibility of a direct metal to metal seal between this fiber coating and the metal capsule containing the ruby material. The thinness of the fiber coating,however, meant that considerable research was needed to develop optimum techniques for achieving this joint, avoiding stripping the coating from the fibers and overheating the joint[7].

A number of probe-fabrication techniques were tried before a successful and reproducible technique was established, such as using gold solders and fluxes , and a low temperature flux was finally chosen as the most suitable. It proved impossible, as expected, to use a conventional soldering iron and a soldering iron burner combination for jointing as this crude approach merely resulted in the stripping of the gold from the fiber. The probe was fabricated using a modified vacuum-deposition plant. The method was described in detail in reference and a schematic of device is shown in figure4.

4. THE EXPERIMENTATION OF THE THERMOMETER SYSTEM

The fluorescence lifetime output was monitored via the period of the modulation frequency as indicated in Figure1, and a characteristic calibration curve is shown in figure5 on a logarithmicscale, over a range from 30^0C to 50^0C.In the region between 150^0C and 450^0C, maximum sensitivity is seen. Beyond 500^0C,the calibration curve tends to 'flatten out' quite dramatically, and the sensitivity of measurement achievable in this region is limited, as shown by the dashed line in Figure5, which represents the relative temperature sensitivity of the observed fluorescence lifetime, $S_{\Delta\tau/\tau}$, defined as:

$$S_{\Delta\tau/\tau} = \left| \frac{(\Delta\tau/\tau)}{\Delta T} \right| \quad (1)$$

Where τ is the observed lifetime; $\Delta\tau$ and ΔT are the increments of the lifetime and temperature.

The intensity of the fluorescence emission with temperature change[10], detected at the photodetector stage, is shown in Figure6.It falls off rapidly with temperature increase over the whole temperature region. This result doesn't contract the earlier experimental evidence of Burns and Nathan[11] who showed that the fluorescence quantum efficiency of the ruby fluorescence, integranted over the entire band from 620nm to 770 nm, is independent of temperature in the region from –1960C to 2400C,for the emission detected here is only the R-line part of the total fluorescence emission. The reduction in R-line emission intensity with temperature increase, from room temperature to 2400C,was mainly due to the increasing thermal elevation of the excited Cr^{3+}ions from the 2Estate to the ^{4}T2state.This is supported by the research on the temperature dependence of ruby fluorescence which shows an increase in broadband emission with temperature increase over the above region.

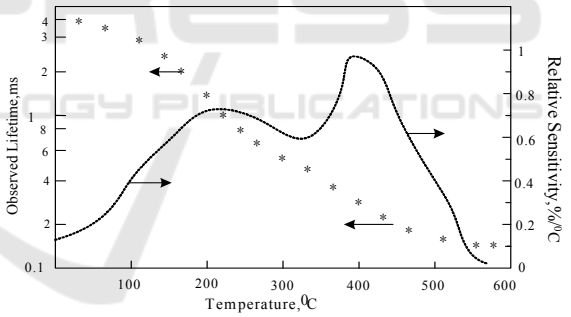

Figure 5. Chracteristic calibration curve for the ruby fluorescence based thermometer in the region from roo temperature to –5500C.

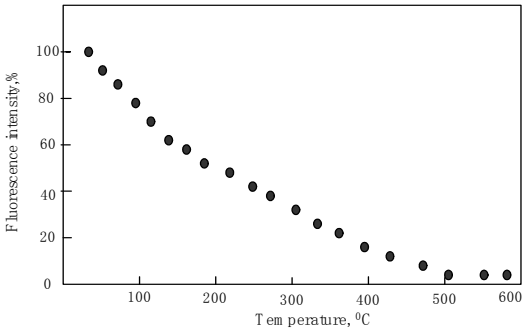

Figure 6. The ruby intensity recorded in the experiment.

Intrinsically, the ruby fluorescence lifetime is not suitable for the sensing of temperature below a temperature approximately defined by the water freezing point(0^0C),as its temperature sensitivity is quite low over that region. Low sensitivity has also limited the performance of the ruby based thermometer system up to 50^0C,and thus poor measurement reproducibility was found at 40^0C for the system shown in Figure1,where the long-term drift in the time-constant of the entire electronic system, especially that of the high-gain photodetector, could be much higher than the resolvable change in the fluorescence lifetime.

5 CONCLUSIONS

As with all other thermometer systems based on the fluorescence of refractory materials, the highest temperature which could be measured is generally limited by the difficulty in the detection of the extremely short lifetime under increasingly poor signal-to-noise conditions, caused by low fluorescence efficiency and shortening lifetime at high temperature. From the data in the experimentation at 6000C the fluorescence intensity is reduced to 0.7% of its maximum value, occurring at 3400C,and the fluorescence lifetime is 1 μ s. A cost-effective solution to further extending the high temperaturr measurement limit of a fluorescence based thermometer can be found through the use of other fluorescent materials, such as using alexandrite as the sensing material.

ACKNOWLEDGEMENTS

This project is supported by the Key project of Hebei Provincial Department of Education (No.ZD2016040) ; This project is supported by Hebei science and technology research item(No.12201708D); The project is supported by Hebei Normal Universty application fund (No.L2015k09).

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