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A microfiber temperature sensor based on fluorescence lifetime

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ABSTRACT

We demonstrate micro/nanofiber temperature sensors based on micro/nano particles fluorescence lifetime. Dependence of the fluorescence intensity, branching ratio and lifetime on temperature are investigated from 30°to 210°. Compared with the intensity-based micro sensors, the lifetime-based micro sensors perform better in terms of accuracy, stability, and response speed. Precision of the proposed temperature sensor is obtained as high as 2°in the temperature range of 30°to 210°. This lifetime-based sensing technology won‘t be affected by external deformation of the sensors, proving it is a temperature selective sensor enabling eliminating interference of surrounding environment and background noise. Experiments and simulations show that response time of the micro sensor can be 50–100 times faster than that of conventional sensors.

1. Introduction:

Temperature sensing is widely used in various fields, including biology, mechanics, architecture and materials etc [1]. Compared with other types of temperature sensors, fiber-optic sensors have unique advantages, including good electrical insulation, immunity to electromagnetic interference and high flexibility etc [2–6]. For example, a new sensing method using C-type micro-structured fiber proposed by Yong Zhao et al. has realized double parameter measurement with a precision of 7.609 nm/°C [7]. Recently, with the rapid developing of micro/nanotechnology, miniaturization has become the trend of optical fiber sensors. Optical sensors based on micro/nanofibers have attracted increasing research interests due to the small footprint, high sensitivity, fast response, high flexibility and low optical power consumption [8–10]. However, the reported micro/nanofiber sensors based on long period gratings [11], peaks of resonant wavelength measurement [12,13] and optical interference [14] are easily affected by external environmental factors like drifts of the excitation light, deformation, humidity etc [15]. High stability and high selection detection of micro/nanofiber sensors is still a big challenge until now.

In this paper, a micro/nanofiber temperature sensor based on micro/nano particles fluorescence lifetime has been proposed. It combines the advantages of micro/nanofiber sensors and conventional fluorescence lifetime-based sensors [16–22] with high stability, high accuracy and fast response. The total diameter of the probe is about 2 μm. In experiments, the stability of the lifetime-based sensing has been proved to be better than that of the intensity-based sensing, and the measurement accuracy with 2 °C has been achieved. Experimental and simulation results show the response speed of micro sensor has increased by 50 to 100 times compared to the conventional sensor. The lifetime-based micro sensor with small footprint, high stability and fast response has great potential for application in many fields like biology, micro electronic device and so on.

2. Experiments and results

The configuration of our fiber sensors is shown in Fig. 1(a). Fluorescent particles coated on the input microfiber are excited by a 405 nm laser. The excited fluorescence of the particles is coupled into output

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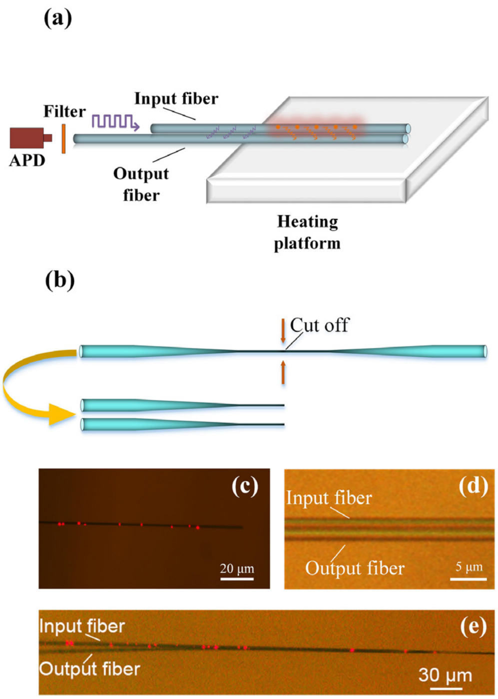

Fig. 1. (a) Schematic illustration of the fiber sensor for temperature measurements. (b) Schematic of the fabrication process of tapered optical fibers (c) CCD image of the input taper coated with fluorescent particles. (d) Details of the two combined tapers (e) CCD image of the entire fiber sensor under a 405 nm laser excitation.

microfiber. A long pass filter is inserted between the output fiber and the avalanche photodiode detector (APD), so that only signal light can be detected. Surrounding temperatures of fluorescent particles can be controlled by tuning the heating platform. The micro/nanofiber tapers with a diameter about 1 μm are fabricated with a flame-heated fiber-tapering system with a tapering speed of 0.2 mm/s and an optimized hydrogen flow [23,24]. Then, two micro tapers are obtained by cutting off the fabricated fiber in the middle of the waist (Fig. 1(b)). Fluorescent particles ($Mg_6As_2O_{11}$:Mn^{4+}) used in following experiments are uniformly dissolved in alcohol solution and coated on the surface of microfiber with a pipette. The characterization of fluorescent particles is given in Supplementary Material (Fig. S1 and table S1). We have compared about 5 kinds of fluorescent materials, and $Mg_6As_2O_{11}$:Mn^{4+} is found to be the best suitable for lifetime based temperature sensor due to its high photoluminescence quantum efficiency, long decay time (which makes the data acquisition and analysis easy). As shown in Fig. 1(c), when laser (405 nm) is input into the microfiber, particles coated on the microfiber will be excited. In experiments, when two micro tapers get closed after careful manipulation, they will be tightly attached to each other (Fig. 1(d)). Fig. 1(e) shows the CCD image of the entire probe under the working condition. The fluorescence of the particles will be scattered and coupled into the output fiber for detection.

In our experiments, different kinds of fluorescent particles have been tested. Results show $Mg_6As_2O_{11}$:Mn^{4+} fluorescent particles are the most suitable for their high fluorescence efficiency, long lifetime span, high-temperature sensitivity and wide response range. To study the temperature dependent optical parameters of $Mg_6As_2O_{11}$:Mn^{4+} particles, CW laser and 20 Hz square-wave modulated laser are used to excite the particles.

The fluorescence lifetime of our particles is obtained by analyzing the slope of the fluorescence intensity when the excitation light is periodically applied. In a cycle, when the pump light is off, the fluorescence intensity decays exponentially [25,26] and lifetime τ can be estimated as

$$I(t) = I_0 \exp(-t/\tau) + I_d \tag{1}$$

where $I(t)$ is the time-dependent fluorescence intensity, I_0 is the initial fluorescence intensity, t means time and τ is the fluorescence lifetime, I_d represents the background noise. When we use the digital acquisition card to collect the signal, we get the following form

$$I(t) = I_0 \exp(-k\nabla t/\tau) + I_d \tag{2}$$

where ∇t is the sampling interval and N is the sampling length and $k = 0, 1, \ldots, N-1$.

For the conventional sensing system, the background noise I_d is very small and can be neglected. However, for microfiber sensors, the signal light is weak, novel methods should be taken to eliminate the effects of the background noise. Here, a method based on fast Fourier transform (FFT) has been proposed to fit the fluorescence lifetime. The fluorescence lifetime of the particles is obtained from the tangent function of the phase angle of the non-zeroth items of the FFT result [27]. The non-zeroth items of Fourier transform

$$F_n = \sum_{k=0}^{N-1} I_k \exp(-j\frac{2\pi n}{N}k) \tag{3}$$

can be written as

$$F_n = I_0 \frac{1-\exp(-N\nabla t/\tau)}{1-\exp(-\nabla t/\tau)\exp(-j2n\pi/N)}. \tag{4}$$

Obviously, except for the 0th item, all the other items are independent of background signal I_d. In our work, the first nonzero item is used to calculate the fluorescence lifetime. The tangent value of this item Q_1 is a univalent function of the lifetime τ.

$$Q_1 = \tan\varphi_1 = \frac{\mathrm{ImF_1}}{\mathrm{ReF_1}} = \frac{-\exp(-\nabla t/\tau)\sin(2\pi/N)}{1-\exp(-\nabla t/\tau)\cos(2\pi/N)}. \tag{5}$$

From the tangent value Q_1 of the item, we can calculate the fluorescence lifetime τ, which is independent of the initial intensity I_0 and the background noise I_d.

$$\tau = \frac{\nabla t}{\mathrm{In}\{[Q_1\cos(2\pi/N)-\sin(2\pi/N)]/Q_1\}}. \tag{6}$$

In experiments, the fluorescence spectrum and intensity under the CW 405 laser excitation are recorded from 30 °C to 210 °C. As depicted in Fig. 2(a), with the increase of temperature, the intensity of the emission peak around 660 nm decreases gradually while intensities of other spectral lines are nearly unvaried. Accordingly, using a 650 nm long-pass filter in front of the APD, the emission peak around 660 nm can be selected to detect temperatures. Fig. 2(b) shows the dependence of the normalized average fluorescence intensities around 660 nm on temperatures with a step of 10 °C. We can find the normalized fluorescence intensity decreases monotonically from 30 °C to 210 °C. When input light is 20 Hz square-wave modulated 405 nm laser, the fluorescence decay lines of the particles under different temperatures are shown in Fig. 2(c). With the increase of the temperature, the curves turn to be steeper, meaning a shorter lifetime τ. To analyze the dependence of the fluorescence lifetime on temperature, sampling length is set as $N = 18750$ and sampling interval is 0.8 μm. The calculated results show the fluorescence lifetime varies monotonically with temperature. With the increase of temperature from 30 °C to 210 °C, the fluorescence lifetime decreased significantly from 3.99 ms to 2.70 ms (Fig. 2(d)). It should be pointed out that, in our experiments, it is proved that the excitation intensity has no effect on the fluorescence lifetime (Fig. S2). The lifetime change under different temperature is caused by the photoluminescence quantum efficiency change. As shown in Fig. 2(a), under a fixed excitation intensity, with the increase of temperature, the intensity of the emission peak around 660 nm decreases gradually, indicating the decrease of quantum efficiency with the increase of temperature.