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Novel digital iteration algorithm for fluorescence lifetime measurement of multi-probe fiber thermometer

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ABSTRACT

We report a novel digital iteration algorithm for fluorescence lifetime (FL) measurement, which is proved suitable for the fluorescence lifetime-based multi-probe fiber thermometer application. The algorithm utilizes only one set of fluorescence decay sampling data to decide the FL by using the basic addition and subtraction computation. Iteration number of about 10–12 times is sufficient to reach the final stable value. As a result, the algorithm features robust, high efficiency, strong anti-noise and immune to background level. The algorithm has been successfully used in a sapphire fiber-based multi-probe thermometer covering the temperature range from room temperature to 1000 °C and confirmed suitable for practical application.

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1. Introduction

Fiber-optic thermometers are important in widespread applications as they feature the characteristics of intrinsic immunity to electromagnetic interference, wide dynamic range, high sensitivity and multiplexing capability. The related techniques have been rapidly developed in the past decades. Several types of fiber-optic thermometers have been commercialized, which include the fiber Fabry-Perot (FP) [1,2], Fiber Bragg grating (FBG) [3], thermo-radiation [4], Raman scattering effect [5] and the fluorescence lifetime (FL)-based sensor systems [6,7]. Among these, the fiber thermometers based on the temperature dependence of the FL of some specific sensing materials, such as ruby crystals or rare-earth ion doped glasses, are especially valuable as they are normally simple in both principle and structure, stable over long operation period and can cover wide temperature range. FL-based sapphire fiber thermometer can even work over the range from room temperature to as high as 1800 °C if the schemes of FL and thermo-radiation detection are combined together [8].

Clearly, the performance of the FL-based fiber thermometer is mainly determined by the physical characteristics of the sensing probes and the accuracy of the FL measurement. Sensing materials with supreme fluorescence temperature dependence as well as excellent physical and chemical properties are especially important for the performance of the FL-based fiber thermometers. Many kinds of sensing probes have been investigated, these including ruby, Cr^{3+}: YAG [9], Cr^{3+}: $GdAlO_3$ [10] and Tm^{3+}:YAG [11], etc. The techniques to determine the FL have also been extensively investigated in the 1980 and 1990s' of last century and many methods have been proposed. Among these, the phase locked detection (PLD) method [7] proposed by Zhang et al. has advantages of high accuracy and strong anti-noise. This technique applied an electronic circuit to determine the FL accurately by periodically modulating the fluorescence exciting light source. The circuit would adjust the modulation period of the light source automatically according to the output error signal from the electronic hardware until the period was locked to a value proportion to the FL, at which the error signal was close to zero. As a result, the FL can be determined by just measuring the modulation period and this eased the signal processing requirement. When multi-probes are used in a thermometer system, however, the same numbers of exciting light sources would be required because they need to be modulated separately to follow the FL change of each probe. The requirement of many independent exciting light sources and the related driving circuits generally makes the system complicated.

With the fast development of electronic devices, the on-chip computation capability of a Field–Programmable Gate Array (FPGA) chip has enabled the FL determination through digital approach. With this development, FL determination can even be applied in bio-photonic to enhance the image resolution recently [12]. By sampling a set of fluorescence decay curve, it would be possible to determine the FL by directly fitting the decay curve. Many fitting methods have been proposed, which include Prony's method [13], Fourier transform of a transient signal [14] and Log-fit algorithm [14].

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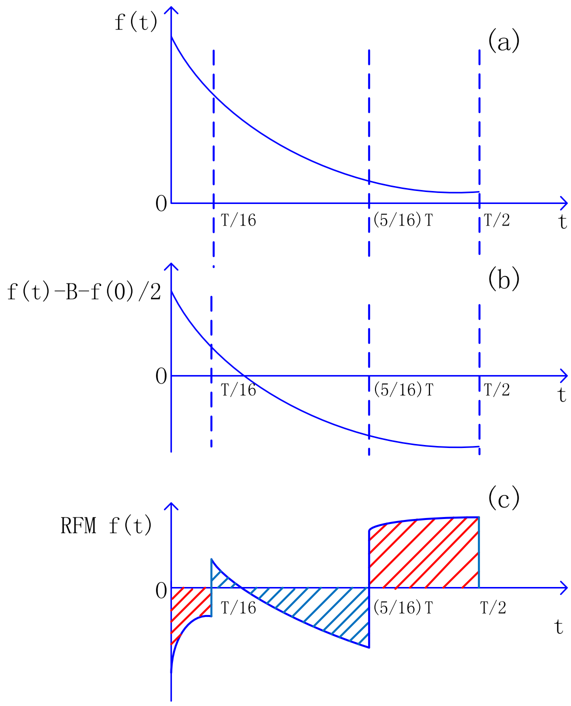

Fig. 1. Schematic illustration of the dynamic iterative algorithm with (a) the initial fluorescent decay curve (b) the fluorescent decay curve subtracted by half the initial intensity and background and (c) the reformed fluorescent decay curve for sum area computation.

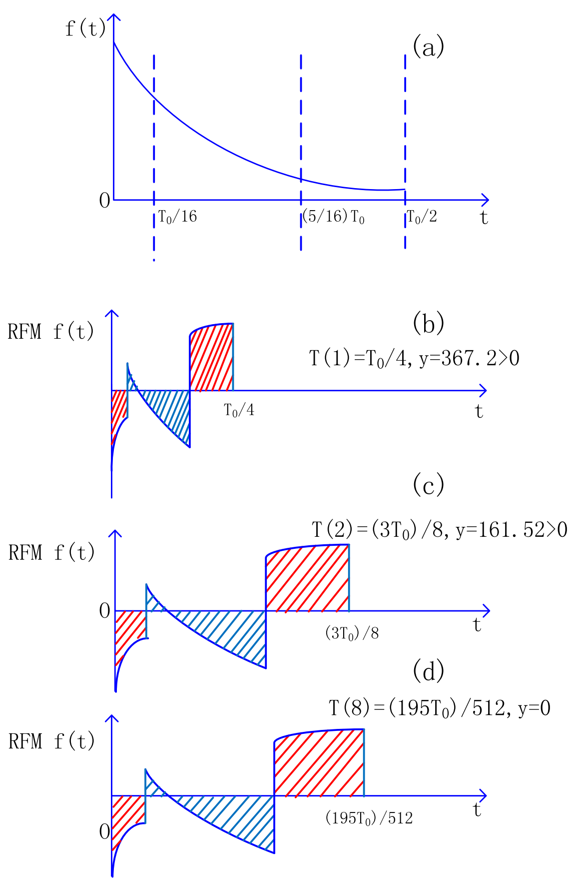

Fig. 2. The iteration process to determine the fluorescence lifetime of a ruby probe under working temperature of 25 °C at which FL should be 3.2 ms, (a) the initial fluorescence decay curve, (b) the 1st iteration computation using $T(1) = T_0/4$ (c) the 2nd iteration computation using $T(2) = 3T_0/8$, (d) the final iteration computation using $T(8) = (195T_0/512)$ when y is close to zero.

The FL measurement by sampling and fitting the FL decay curve is simple in system structure, especially in the circuit configuration. Many channels of FL decay signals can be simultaneously sampled by using only one exciting light source and single *A*/*D* converter, provided that an interconnect analog-switch chip could be applied before the *A*/*D* converter. However, the current available fitting methods normally require complicated iteration process, such as least square fitting method [15] and the fast Fourier transformation method (FFT) [14], and are thus always time-consuming.

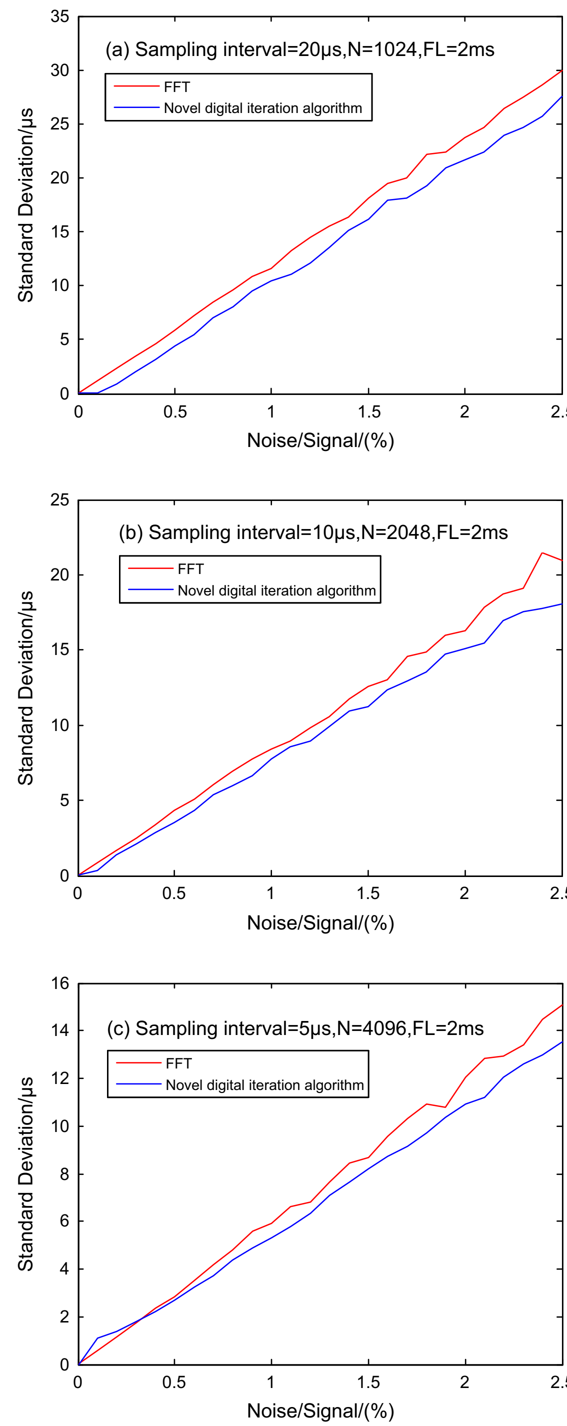

Fig. 3. Simulated standard error of FL under noisy signal condition for the proposed digital iteration algorithm and the FFT algorithm respectively. Sampling points of 1024, 2048 and 4096 were used for the total 20.48 ms measurement time respectively.

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