

Comparative Study of 10-mm Length Commercial Erbium Doped Optical Fibers for Temperature Sensing with a Fluorescence Decay Method

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Abstract

This paper shows the experimental results on the temperature sensitivity of the fluorescence decay time in commercial rare-earth-doped silica fibers within the ambient temperature range from 0°C to 60°C by pumping with a laser diode at 976 nm. The average temperature sensitivity of the 10-mm fiber length sensors defined as a slope of a linear regression over the measured temperature range has achieved 2.51 $\mu\text{s}/^\circ\text{C}$ and 1.54 $\mu\text{s}/^\circ\text{C}$ for Er^{3+} -doped fibers with low and high ions concentration respectively. The average sensitivity of 1.99 $\mu\text{s}/^\circ\text{C}$ has been achieved with $\text{Yb}^{3+}/\text{Er}^{3+}$ -codoped fiber. A short-term precision calculated as an overall standard deviation of the measured fluorescence decay time within the ambient temperature range was 0.88 μs and 0.64 μs for Er^{3+} -doped fibers with low and high ions concentration; and 4.04 μs for $\text{Yb}^{3+}/\text{Er}^{3+}$ -codoped fiber respectively.

Keywords: Fiber-optic sensor, temperature sensing, rare-earth-doped fiber, fluorescence.

Introduction

Employing fiber-optic sensors for temperature monitoring ensures a precise measurement while withstanding harsh environments. Due to its small thermal mass, mechanical flexibility, electrical insulation and low loss, an optical fiber can be advantageous for temperature sensing in remote, hard accessible physical spaces. Well-established approaches for distributed and point sensing are mainly based on scattering methods, fiber Bragg gratings and fluorescence techniques [1]. The various rare-earth-doped waveguides and fibers are often applied as an intrinsic probe for temperature sensing, where the fluorescence intensity ratio (FIR) of two radiative transitions is analyzed or the fluorescence decay time is measured [2, 3]. Typical length of the sensing rare-earth-doped fibers may vary from a few centimeters to several tens of centimeters to provide appropriate fluorescence power as well as adequate pump absorption [2-4].

In this work we analyze and compare the temperature sensitivity of the fluorescence decay time in commercial rare-earth-doped silica fibers (LIEKKI® Er30-4/125, LIEKKI® Er110-4/125, Fibercore® DF1500Y) within the ambient temperature range from 0°C to 60°C by pumping with a laser diode at 976 nm. The length of the sensing fibers has been chosen as short as 10 mm allowing a single-point

probe implementation. These results aim to determine the potential of commercial fibers that are commonly used in telecommunication infrastructure for fluorescence-based thermometry at ambient temperatures, requiring higher sensitivity and precision as for reported high-temperature applications [4, 5].

Measurement Setup

The schematic diagram of the setup to measure the fluorescence decay time is shown in Fig. 1.

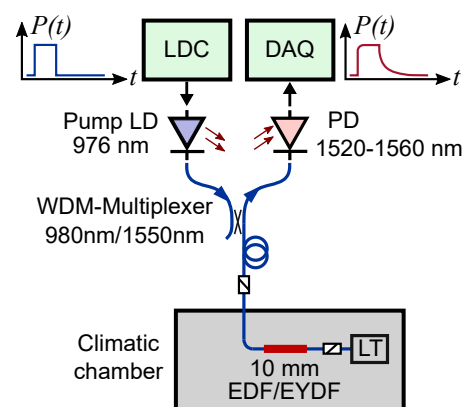


Fig.1: Schematic diagram of the experimental setup to measure a temperature dependent fluorescence decay time.

Tab. 1: Parameters of the rare-earth-doped silica fibers under test.

Fiber	LIEKKI® Er30-4/125 (Er ³⁺ -doped)	LIEKKI® Er110-4/125 (Er ³⁺ -doped)	Fibercore® DF1500Y (Yb ³⁺ /Er ³⁺ -codoped)
Parameter			
Mode Field Diameter @ 1550 nm, [μm]	6.5 ± 0.5	6.5 ± 0.5	5.3 - 6.8
Numerical Aperture (nominal)	0.2	0.2	0.2 - 0.24
Peak Core Absorption @ 1530 nm, [dB/m]	30 ± 3	110 ± 10	20
Concentration Er ³⁺ , [ions/m ³]	1.94 · 10 ²⁵	6.6 · 10 ²⁵	-
Concentration Er ³⁺ , [ppm wt]	2450	8320	-

Three types of single mode silica fibers doped with Er³⁺ ions (EDF) and Yb³⁺/Er³⁺ ions (EYDF) were tested in a climatic chamber (see Table 1).

An FBG-stabilized pump laser diode (LD) emitting at 976 nm with a maximum power of

300 mW was modulated directly through an external analog modulation input of the laser diode controller (LDC). The duration and period of the rectangular modulation pulses were set to 20 ms and 100 ms respectively. A 10-mm length rare-earth-doped silica fiber was spliced to the lead-in HI1060 fiber, while the far end of the sample was spliced to an FC/APC fiber pigtail and secured with a fiber optic light trap (LT). The length of the fiber under test is reasonable for the point sensor implementation, and still provides a sufficient fluorescence emission. A fused fiber optic wavelength division (WDM) multiplexer 980 nm / 1550 nm was required to launch a pump light into the rare-earth-doped fiber and split a backward fluorescence decay signal to an InGaAs photodetector (PD) operating in a photoconductive mode. The output signal, amplified by a transimpedance amplifier, was then acquired by an oscilloscope with an averaging over 10 waveforms.

Calibration of probes

First, the spectral fluorescence intensity profiles have been measured with an optical spectrum analyzer (OSA) Yokogawa AQ6370D in a backward propagation direction with respect to temperature and pump power P_p (see Fig. 2, a-c).

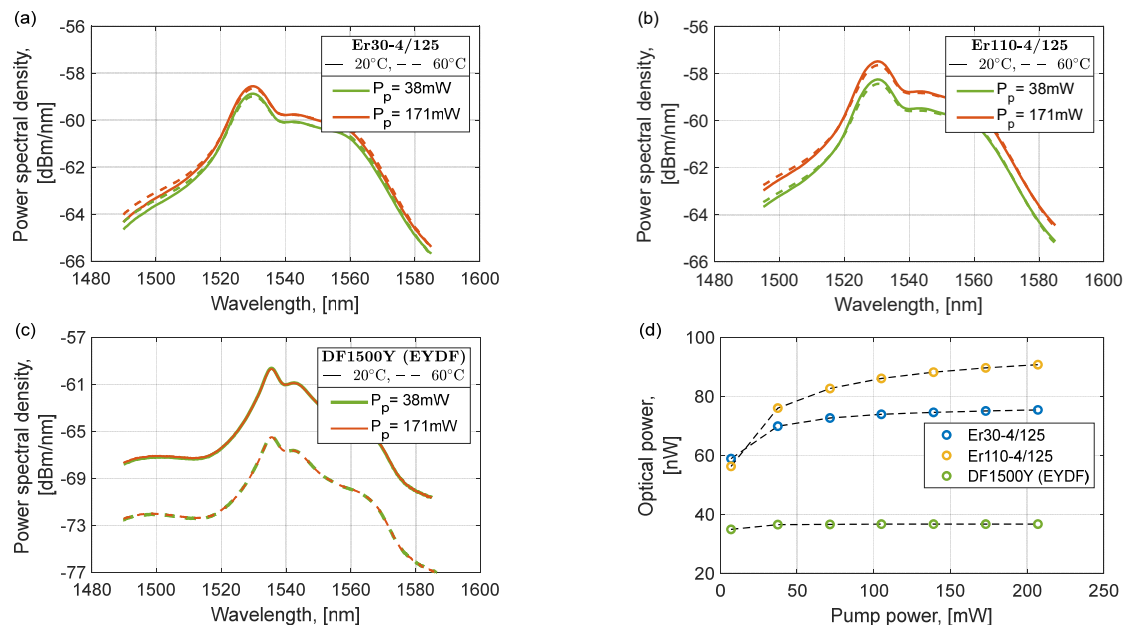


Fig. 2: Spectral fluorescence intensity profiles of the rare-earth-doped fibers by pumping at 976 nm (a-c); Fluorescence intensity near 1550 nm as a function of the pump pulse power measured at a temperature of 20 °C (d).

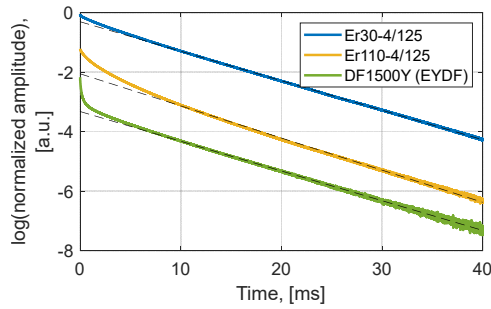


Fig. 3: Normalized fluorescence decay signals measured at a temperature of 20 °C and pump pulse power of 58 mW.

Both EDF demonstrated a similar behavior. The spectral change with temperature is related to the temperature dependent nonradiative relaxation of erbium ions [2] as well as the thermal distribution of populations between the components of the $^4I_{15/2}$ and $^4I_{13/2}$ levels [6]. The overall fluorescence intensity in EDF rises with a pump power indicating that the fibers are not saturated yet (see Fig. 2, d). The EYDF spectra demonstrated a stronger temperature dependence of the spectral fluorescence profile, and at the same time, the fiber was saturated by the pump power above 40 mW. The $\text{Yb}^{3+}/\text{Er}^{3+}$ -dopant system results in a dual-band fluorescence (Fig. 2, c shows the spectral fluorescence profile of erbium ions only).

The ratio between emission intensities in two bands varies with temperature, since the energy transfer between erbium and ytterbium ions is thermally dependent [2]. Thus, the EYDF can be potentially used for FIR thermometry.

Fig. 3 shows an example of the fluorescence decay signals for three fiber samples measured at a temperature of 20 °C after the pumping pulse has been turned off. The logarithmic scaling of the amplitude axis makes it clear that the decay signals cannot be described with a single exponential function (shown by the dashed lines in Fig. 3) since an additional faster fluorescence process is noticeable within the first 2-4 ms. This rapid initial decay may be attributed to stimulated emission. Additionally, a wide emission spectrum of ytterbium ions in EYDF may affect the decay signal by leakage through a WDM multiplexer.

The time constant related to the radiative transition from level $^4I_{15/2}$ to ground level $^4I_{13/2}$ has been estimated with the nonlinear least squares method by fitting a single exponential model to the decay curve captured by an oscilloscope and averaged over 10 consecutive waveforms with a period of 100 ms. The application of the fitting interval starting 2 ms after the pumping pulse had been turned off allows to exclude the rapid initial fluorescence decay from the evaluation, and thus ensures the simplicity of the model.

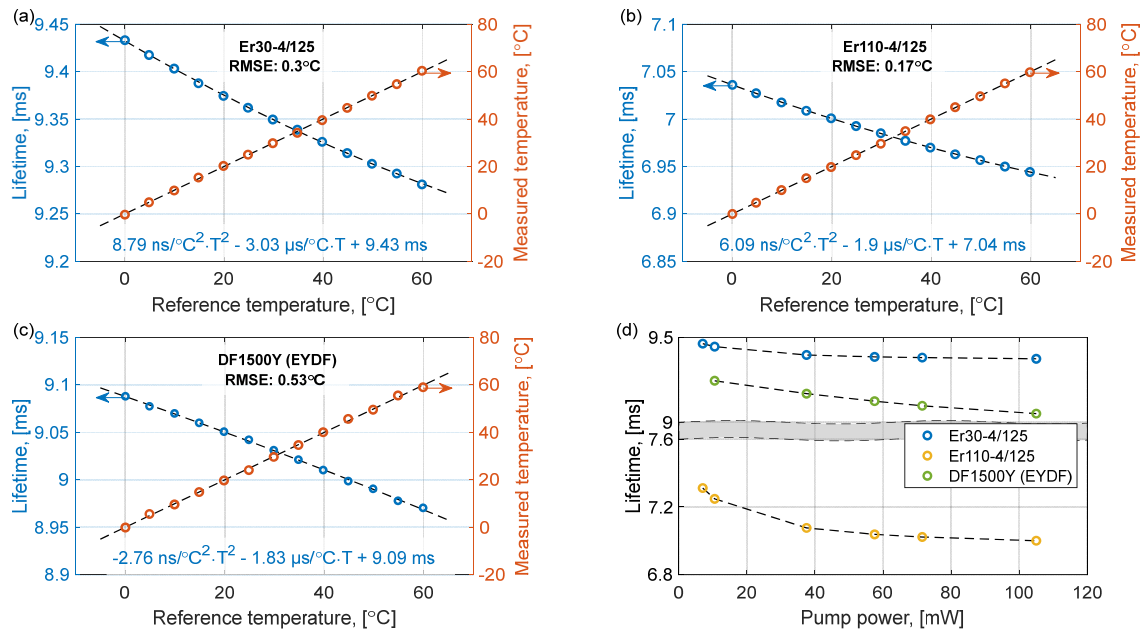


Fig. 4: Calibration curves of the rare-earth-doped fibers as a temperature sensor by the pump pulse power of 105 mW within the ambient temperature range from 0 °C to 60 °C (a-c); Fluorescence decay lifetime as a function of the pump pulse power measured at temperature of 20 °C (d).

The calibration of the fibers as a temperature sensor shown in Fig. 4 has been performed by measuring the fluorescence lifetime as a function of temperature within the range from 0°C to 60°C by the pump pulse power of 105 mW. The lifetime measurements at every temperature level have been repeated 10 times with a one minute interval allowing an estimation of a short-term precision. The curves have then been fitted with a 2nd degree polynomial whose coefficients are also shown in the figure. The root mean square error (RMSE) for 2nd degree calibration polynomials was as low as 0.3°C, 0.17°C and 0.53°C for EDF Er30-4/125, Er110-4/125 and EYDF DF1500Y respectively. The average temperature sensitivity of the probes (S_T) calculated as a slope of a linear regression over the range from 0°C to 60°C achieved 2.51 $\mu\text{s}/^\circ\text{C}$, 1.54 $\mu\text{s}/^\circ\text{C}$ and 1.99 $\mu\text{s}/^\circ\text{C}$ respectively. A short-term precision defined as an overall standard deviation of the measured fluorescence decay time and computed over the total number of trials and temperature levels was 0.88 μs , 0.64 μs and 4.04 μs respectively.

By repeating the calibration measurements with a pump pulse power ranging from 10 mW to 105 mW the variation of the average temperature sensitivity for EDF probes remained below 1 %; and for EYDF probe it was 5 %. All fibers under test have demonstrated a similar behavior of the fluorescence lifetime depending on a pump power that is approaching an asymptotic value (see Fig. 4, d). The minimal lifetime variation with a pump power was observed for EDF Er30-4/125.

Conclusion

Characterization and comparison of the temperature behavior of commercial Er^{3+} -doped and $\text{Yb}^{3+}/\text{Er}^{3+}$ -codoped fibers within the ambient range from 0°C to 60°C has been reported in the paper. The measurements have been carried out with 10-mm fiber length samples enabling the design of the compact, intrinsic probes for point temperature sensing. It has been shown that the fluorescence lifetime as well as the fluorescence intensity depend on temperature and pumping power. At the same time, the average temperature sensitivity of the probes has been remained nearly constant within the wide range of the pump power. The fiber Er30-4/125 with a lower Er^{3+} -concentration has demonstrated higher average temperature sensitivity of 2.51 $\mu\text{s}/^\circ\text{C}$ with an overall standard deviation of the measured fluorescence decay time of 0.88 μs and the considerably weaker dependency of

the fluorescence lifetime on the pump power. The fiber calibration curves have been fitted with 2nd degree polynomials with RMSE of 0.3°C, 0.17°C and 0.53°C for EDF Er30-4/125, Er110-4/125 and EYDF DF1500Y respectively.

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References

- [1] P. Lu, N. Lalam, M. Badar, B. Liu, B. T. Chorpining, M. P. Buric, P. R. Ohodnicki, “Distributed optical fiber sensing: Review and perspective,” *Appl. Phys. Rev.*, 6(4), 041302 (2019); doi: 10.1063/1.5113955
- [2] S. Baek, Y. Jeong, J. Nilsson, J.K. Sahu, B. Lee, “Temperature-dependent fluorescence characteristics of an ytterbium-sensitized erbium-doped silica fiber for sensor applications,” *Optical Fiber Technology*, 12(1), 10-19 (2006); doi: 10.1016/j.yofte.2005.04.002
- [3] G. Paez, V. Lopez, M. Strojnik, “Variable time constant of erbium-doped temperature sensor,” *Proc. SPIE 5152, Infrared Spaceborne Remote Sensing XI*, (2003); doi: 10.1117/12.506862
- [4] D. I. Forsyth, T. Sun, K. T. V. Grattan, S. A. Wade, S. F. Collins, “Characteristics of doped optical fiber for fluorescence-based fiber optic temperature systems,” *Rev. Sci. Instrum.*, 74(12), 5215-5218 (2003); doi: 10.1063/1.1623624
- [5] Z. Y. Zhang, K. T. V. Grattan, A. W. Palmer, B. T. Meggitt, T. Sun, “Fluorescence decay-time characteristics of erbium-doped optical fiber at elevated temperatures,” *Rev. Sci. Instrum.*, 68(7), 2764-2766 (1997); doi: 10.1063/1.1148192
- [6] N. Kagi, A. Oyobe, K. Nakamura, “Temperature dependence of the gain in erbium-doped fibers,” *J. of Lightw. Technol.*, 9(2), 261-265 (2002); doi: 10.1109/50.65884