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Remote Temperature Sensor Based on the Up-Conversion Fluorescence Power Ratio of an Erbium-Doped Silica Fiber Pumped at 975 nm

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Abstract  This article presents experimental results demonstrating the performance of an erbium-doped silica fiber as a remote temperature sensor in the interval from \(20^\circ\text{C}\) to \(200^\circ\text{C}\). The sensor is based on the change in the fluorescence intensity ratio of two spectral bands as a function of temperature. The green fluorescence signal was generated by up-conversion processes in the erbium-doped fiber pumped at 975 nm. A radiometric analysis was applied to the erbium-doped fiber to evaluate its performance as a temperature sensor, and the results from this analysis were compared against other rare-earth-doped fiber sensors that utilize the intensity ratio technique.

Keywords  erbium-doped silica fiber, temperature sensor, up-conversion fluorescence

1. Introduction

A rare-earth-doped optical fiber (laser fiber) undergoes processes of absorption and spontaneous and stimulated emission of radiation when it is excited with photons of a particular energy. An investigation of these processes were conducted to improve the development of an erbium-doped fiber amplifier (EDFA) with the goal of extending the distance of transmission in optical communication systems [1]. The investigation of non-linear processes in laser fibers has allowed for the development of new optical fiber lasers by up-conversion [2–4]. Currently, laser fibers are being investigated to develop new temperature sensors, as their properties of emission and absorption are dependent upon the temperature [5–21].

In general, radiative methods of temperature measurement are highly advantageous because they do not require physical contact or temperature equilibrium between different objects with distinct thermal masses. Also, frequently, the temperature can only be measured indirectly at a distance from the object to be measured. Fiber optic sensors have proven to be very efficient due to their small thermal mass, their mechanical...
flexibility allowing access to small remote volumes, and their ability to transmit light efficiently.

Erbium-doped fibers have been investigated to develop new fluorescent sensors of temperature. Recently, a new method based on the analysis of radiometric figures of merit as signal-to-noise ratio (SNR), noise equivalent power (NEP), sensitivity, and temperature resolution ($\Delta T_{\text{res}}$) has been proposed to evaluate the performance of these optical sensors. In order to select the optimum sensor for the monitoring of temperature in situ, this radiometric analysis allows setting up the limits of detection of these fluorescent sensors. In most practical cases, compact optical fiber sensors with high SNR and sensitivity are desirable. Therefore, this article presents experimental results characterizing the performance of an erbium-doped silica fiber as a remote temperature sensor. In this case, the laser fiber is pumped by a pigtail laser diode at 975 nm, improving its performance as a fluorescent optic sensor. The sensor is based on the change in the fluorescence intensity ratio of two spectral bands as a function of temperature. The green fluorescence signal was generated by up-conversion processes in the erbium-doped fiber pumped at 975 nm.

A detection system was implemented to interpret the temperature information encoded in the measured fluorescence spectrum. The detection system incorporates two optic channels to select the fluorescence spectral bands emitted from the $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$ levels of the erbium-doped fiber. From a radiometric analysis, the photo-current generated at the end of the photo-detector (PD) for the two channels by the incident fluorescence signal as a function of temperature was evaluated, and the SNR for different spectral bands of fluorescence in the interval from 515 nm to 570 nm was examined. Next, the fluorescence spectral bands for optimal performance of the erbium-doped fiber as a temperature sensor were identified. Finally, the sensitivity of the sensor was evaluated, and its performance was compared to other rare-earth-doped fiber sensors that utilize the intensity ratio technique.

2. Erbium-Doped Silica Fibers

Rare-earth-doped low-loss silica fibers are of interest for temperature sensing applications because their absorption and emission spectrum are temperature dependent. This behavior is due to the homogeneous broadening of line widths and the changing population of energy levels with temperature.

When an erbium-doped fiber is pumped with a photon energy of $2.028 \times 10^{-19}$ J ($\lambda = 980$ nm), the $^4\text{I}_{11/2}$ erbium level is excited through ground state absorption (GSA), and the $^4\text{I}_{13/2}$ metastable level is quasi-instantaneously populated due to non-radiative transitions. In the $^4\text{I}_{13/2}$ level, an emission to the ground state is observed around 1,530 nm (near-IR). The $^4\text{I}_{11/2}$ level absorbs pump photons and excites the $^4\text{F}_{7/2}$ level through excited state absorption (ESA). The latter process populates levels $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$, which are responsible for emission around 530 nm and 545 nm, respectively (see Figure 1). The latter levels are said to be in quasi-thermal equilibrium because of the small energy gap between them (about 800 cm$^{-1} = 1.59 \times 10^{-20}$ J), in contrast to the relatively large energy difference between them and the next lower level (about 3,000 cm$^{-1} = 5.9636 \times 10^{-20}$ J). In silica, a fast thermal coupling between these two levels has been studied theoretically [7, 8] and observed experimentally [9–11].

The ratio $R$ of the intensities $I$ radiating from two respective levels ($^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$) is proportional to their frequency ratio ($\nu$), their emission cross-section ratio ($\sigma$),
and the population distribution

\[ R = \frac{I(\Delta \lambda, T; {^2}H_{11/2})}{I(\Delta \lambda, T; {^4}S_{3/2})} = \frac{\nu({^2}H_{11/2})}{\nu({^4}S_{3/2})} \times \frac{\sigma({^2}H_{11/2})}{\sigma({^4}S_{3/2})} \exp \left[ -\frac{\Delta E}{k \times T} \right]. \] (1)

### 3. Measurement Setup

Figure 2 shows the experimental setup to evaluate the performance of the erbium-doped silica fiber sensor for remote temperature measurements. The optical radiation of a pigtail laser diode with emission at 975 nm (near-IR) and regulated by a current controller (LCD220, 2A, Thorlabs, Inc., Newton, New Jersey, USA) passes through a dichroic mirror into a standard telecommunication fiber (monomodal at 1.55 μm). An erbium-doped (960-ppm) fiber of 20 cm length and core diameter of 3.2 μm is located inside an enclosure whose temperature \( T \) is additionally monitored with a thermocouple. The green fluorescence power measured is 50 μW at 20°C for 60 mW of pump power, considering a pump power coupling efficiency to the fiber core of about 30%. The fluorescence spectrum is measured with a spectrometer (Ocean Optics, Dunedin, Florida, USA). A dichroic mirror transmits the pumping infrared laser radiation and reflects the green fluorescence radiation. In the detection system, a dichroic mirror, wavelength division multiplexing (WDM) is used to separate different spectral lines of the fluorescence-spectrum toward the two optical channels of the sensor. Interference filters with a 10-nm transmission spectral width centered on the maximum peak of transmission were employed to isolate the fluorescence spectral bands of the beam in each channel. A transducer is placed in each channel to interpret the temperature information encoded in the optical signal. Finally, the integrated radiation over different wavelength intervals is detected and divided to give the spectral band power ratio.
The detection system converts the measured fluorescence spectrum of two thermally coupled energy levels ($^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$) of the erbium-doped fiber into temperature information.

4. Experimental Results

Figure 3 shows the normalized fluorescence spectrum of the erbium-doped silica fiber as a function of wavelength in the temperature interval from 20°C to 200°C. The fluorescence signal was recorded with a spectrometer (Ocean Optics) to obtain the spectral power data. The power of the fluorescence spectrum centered at 530 nm ($^2\text{H}_{11/2}$ transition) increases with temperature, while the fluorescence spectrum centered at 545 nm ($^4\text{S}_{3/2}$ transition) decreases over the same temperature interval (see Figure 3). The abscissa was changed to show the spectral power in microwatts per nanometer rather than intensity. The power and the intensity are related through common factors that cancel out in any ratio technique.

4.1. Fluorescence Signal Integrated over Wavelength Intervals

The detection system that interprets the temperature information encoded in the fluorescence signal $P_f(\Delta \lambda, T)$ integrated over wavelength intervals of the erbium-doped fiber sensor is shown in Figure 2. The optical transmission losses at the beam-splitter, $\tau_1$, lens ($L$), $\tau_2$, filters ($F$), and $\tau_3$ in each channel of the detection system diminish the fluorescence signal. For this analysis, commercially available filters with a transmission spectral width of 10 nm and a transmittance of 60% were employed. Therefore, $P_0(\Delta \lambda, T)$ is the power incident on the PD integrated over the spectral bands as a function of temperature:

$$ P_0(\Delta \lambda, T) = \tau_1 \times \tau_2 \times \tau_3 \times P_f(\Delta \lambda, T) \quad \text{(W)}. $$

A transducer is placed in each channel at the output of the detection system to interpret the temperature information encoded in the optical signal integrated over the spectral bands.
The desired attributes of the detection system are high sensitivity in the spectral interval 515 nm–570 nm, low dark current, and compatibility with the optical fiber. A p-i-n silicon PD meets these performance requirements. This is a low-frequency and low light level application. Therefore, the detector is used in a photo-voltaic mode of operation with no bias voltage. The non-linearity of a planar diffusion silicon photo-diode is less than ±1% over six decades.

The photo-current $I_p(\Delta \lambda, T)$, generated at the end of the PD by the incident fluorescence signal and integrated over a spectral width as a function of temperature, was evaluated. The photo-current $I_p(\Delta \lambda, T)$, resulting from the absorption of the optical radiation in the detector, is given by

$$I_p(\Delta \lambda, T) = \frac{q \times \lambda \times P_0(\Delta \lambda, T) \times \eta(\lambda)}{h \times c} \quad (A).$$

$P_0(\Delta \lambda, T)$ (W) is the temperature-dependent power integrated over the spectral bands incident on the detector, $q$ is the charge of the electron, $1.60 \times 10^{-19}$ C; $h$ is the Planck constant, $6.6256 \times 10^{-34}$ Js; $c$ is the speed of light in vacuum, $2.9979 \times 10^8$ m/s; $\lambda$ (nm) is the wavelength of the peak emission for each fluorescence spectral band; and finally, $\eta(\lambda)$ is the photo-diode efficiency, approximately equal to 0.9.

Figure 4 shows the photo-current $I_p(\Delta \lambda, T)$ generated at the end of the PD for the two channels of the detection system as a function of wavelength for the levels $^2H_{11/2}$ and $^4S_{3/2}$. It is observed that the photo-current obtained for the spectral bands (520 nm–530 nm) and (525 nm–535 nm), corresponding to the $^2H_{11/2}$ transition of the erbium-doped fiber, increases from 6 $\mu$A to 11 $\mu$A as a function of temperature. The photo-current for the spectral band (540 nm–550 nm) corresponding to the $^4S_{3/2}$
transition of the erbium-doped fiber decreases from 19 $\mu$A to 14 $\mu$A as a function of temperature, whereas the photo-current for the spectral band (545 nm–555 nm) changes from 13 $\mu$A to 10 $\mu$A as a function of temperature. When we use filters to isolate the fluorescence spectral bands instead of spectral lines, an increment of the signal output is noted; likewise, the SNR of the sensor is increased.

5. Evaluation of the SNR of the Fluorescence Spectral Bands

The SNR is very important on the evaluation the performance of fiber-optic sensors. This figure of merit is relevant because they allow the deduction of the detection limits of the sensor. The noise is the principal factor degrading the SNR. Therefore, the noises considered for the radiometric evaluation of sensor are thermal noise $I_f$, shot noise $I_{sn}$, and amplifier noise $I_a (\approx 10^{-13}$ A/Hz$^{1/2}$).

Employing Eq. (4), and considering the photo-current evaluated in the channels of the sensor (Eq. (3)), the SNR for the erbium-doped fiber sensor was determined.

The SNR for this sensor, $SNR(\Delta \lambda, T)$, evaluated in each channel for different fluorescence spectral bands as a function of temperature is given by

$$SNR(\Delta \lambda, T) = \frac{I_p(\Delta \lambda, T)}{\left\{\left\{\frac{4 \times k \times T_d}{R_T}\right\} + 2 \times q[I_p(\Delta \lambda, T) + I_d(T_d)]\right\} \Delta f + (Ia)^2}^{1/2} \text{ (dB).}$$ (4)
Figure 5 shows \( SNR(\Delta \lambda, T) \) at the detector, including the transmission losses due to different optic components and fluorescence spectral bands integrated over wavelength intervals that are proposed to use for the erbium-doped fiber temperature sensor.

Figure 5a shows the SNR evaluated for different spectral bands of fluorescence in the wavelength interval of (515 nm–565 nm), with temperature as a parameter. Likewise, the SNR for different spectral bands related to the two channels of the sensor (\(^2\)H\(_{11/2}\) and \(^4\)S\(_{3/2}\) transitions) are shown as a temperature function in Figure 5b.

For this sensor, three filters were selected for the \(^2\)H\(_{11/2}\) transition (channel 1), and four filters were selected for the \(^4\)S\(_{3/2}\) transition (channel 2), based on the commercially available filters that were proposed to use for this sensor. The spectral band at (540 nm–550 nm), which is the maximum peak of fluorescence corresponding to transition \(^4\)S\(_{3/2}\), has a maximum SNR of 120 dB at 20\(^\circ\)C. The SNR decreases to 117 dB at 200\(^\circ\)C. However, the spectral band at (525 nm–535 nm), which is the maximum peak of fluorescence corresponding to transition \(^2\)H\(_{11/2}\), has a SNR of 111 dB at 20\(^\circ\)C, and it increases to 115 dB at 200\(^\circ\)C.

It is observed that for the spectral bands corresponding to the transition \(^2\)H\(_{11/2}\), the SNR is more dependent on the temperature. However, it is also seen that the SNR depends on the spectral band selected and on the temperature in the erbium-doped fiber. The spectral bands analyzed and determined using the interference filters with a 10-nm spectral width and 60% transmittance performed best in the temperature sensor, as is clearly seen in Figures 4 and 5. It is observed that the SNR of the sensor of erbium-doped silica fiber pumped with 975 nm is improved in comparison with previous works.

6. Fluorescence Spectral Bands Ratio and Sensitivity of the Sensor

Figure 6 shows the measured power ratio as a function of temperature for different fluorescence spectral bands integrated over the 10 nm width determined by the interference filters. The power ratio varies roughly linearly with temperature in the interval from 20\(^\circ\)C to 200\(^\circ\)C with different slopes and a nearly linear increase in the y-intercepts.

The power ratio is shown for a number of possible different fluorescence spectral bands considered for use in the erbium-doped fiber as remote temperature sensors (see Figure 6). The power ratio for the spectral bands (520 nm–530 nm)/(540 nm–550 nm) has a slope of 2.27 \(\times\) \(10^{-3}\)/\(^\circ\)C, and the power ratio for the spectral bands (525 nm–535 nm)/(550 nm–560 nm) has a slope of 6.45 \(\times\) \(10^{-3}\)/\(^\circ\)C. For the spectral bands (515 nm–525 nm)/(555 nm–565 nm), (520 nm–530 nm)/(555 nm–565 nm), and (525 nm–535 nm)/(555 nm–565 nm), the power ratio has slopes of 10.35 \(\times\) \(10^{-3}\)/\(^\circ\)C, 15 \(\times\) \(10^{-3}\)/\(^\circ\)C, and 15.3 \(\times\) \(10^{-3}\)/\(^\circ\)C, respectively.

It is shown that the sensitivity of the sensor \( S(R) \), evaluated as the ratio of the change in intensity integrated over spectral bands \( \Delta R(I_1/I_2) \), increases its temperature signal input \( \Delta T_{fiber} \). An expression is presented to evaluate the sensitivity of the sensor as follows:

\[
S(R) = \frac{\Delta R}{\Delta T_{fiber}} \left[ \frac{I_{p1}(\Delta \lambda_1, T)}{I_{p2}(\Delta \lambda_2, T)} \right] \quad (1/\degree C),
\]
Figure 5. (a) SNR evaluated at the detector output from 515 nm–565 nm with temperature as a parameter; (b) SNR for different fluorescence spectral bands as a function of temperature.
where $I_{p1}(\Delta \lambda_1, T)$ is the photo-current of channel 1 ($^2H_{11/2}$ transition) for different spectral bands as a function of temperature, and $I_{p2}(\Delta \lambda_2, T)$ is the photo-current of channel 2 ($^4S_{3/2}$ transition) for different spectral bands as a function of temperature. $\Delta T_{fiber}$ is the temperature change in the erbium-doped fiber.

Figure 7 illustrates the sensitivity of the erbium-doped fiber optic temperature sensor as a function of temperature for different spectral bands.

The sensor sensitivity with the spectral bands (525 nm–535 nm)/(555 nm–565 nm) and (520 nm–530 nm)/(555 nm–565 nm) changed from approximately $35 \times 10^{-3} / ^\circ C$ to $9 \times 10^{-3} / ^\circ C$ and $33 \times 10^{-3} / ^\circ C$ to $8 \times 10^{-3} / ^\circ C$, respectively. Besides, the sensitivities for the spectral intervals (515 nm–525 nm)/(555 nm–565 nm) and (525 nm–535 nm)/(550 nm–560 nm) changed from about $21 \times 10^{-3} / ^\circ C$ to $6 \times 10^{-3} / ^\circ C$ and $15 \times 10^{-3} / ^\circ C$ to $4 \times 10^{-3} / ^\circ C$, respectively.

It is concluded that the sensor sensitivity exponentially decreases with an increase in temperature (Figure 7). Nevertheless, the sensitivity of the sensor of erbium-doped silica fiber pumped with 975 nm is greater than that obtained in previous works (see Table 1).

Table 1 summarizes the performance of some optical fibers and materials doped with rare-earths that are employed as temperature transducers, based on the fluorescence intensity ratio technique; it can be clearly seen that the results obtained for the erbium-doped fiber pumped at 975 nm are more sensitive to the temperature in comparison with them.

Nevertheless, considering that the main characteristics for the best performance of any fiber optic sensor are a high SNR and excellent sensitivity, it was also proposed to use the ratio of powers of spectral bands (520 nm–530 nm)/(540 nm–550 nm) with
sensitivities from approximately $4 \times 10^{-3}/\degree C$ to $2 \times 10^{-3}/\degree C$ in the temperature interval of 20°C–200°C. These spectral bands showed smaller sensitivities and power ratio slopes than others. However, they have a very high SNR and responsivity because these spectral bands correspond with the maximum peaks of fluorescence for the $^2H_{11/2}$ and $^4S_{3/2}$ transitions (channels of the sensor). Therefore, radiometric analysis is a powerful tool for predicting and comparing the performance of fiber optic sensors, which allows for the determination of the optimum sensor for specific applications.

**Figure 7.** Sensitivity of the erbium-doped fiber sensor for different spectral bands as a function of temperature.

<table>
<thead>
<tr>
<th>Sensing material</th>
<th>$\lambda$ pump</th>
<th>Fluorescence intensity ratio technique (FIR)</th>
<th>Temperature range</th>
<th>Sensitivity at 20°C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er: silica fiber</td>
<td>800 nm</td>
<td>530 nm/555 nm</td>
<td>23–600°C</td>
<td>$13 \times 10^{-3}/\degree C$</td>
<td>[9]</td>
</tr>
<tr>
<td>Yb: silica fiber</td>
<td>810 nm</td>
<td>910 nm/1,030 nm</td>
<td>20–600°C</td>
<td>$9.5 \times 10^{-3}/\degree C$</td>
<td>[12]</td>
</tr>
<tr>
<td>Pr: ZBLAN glass</td>
<td>450 nm</td>
<td>877 nm/906 nm</td>
<td>-45–255°C</td>
<td>$4.8 \times 10^{-3}/\degree C$</td>
<td>[13]</td>
</tr>
<tr>
<td>Nd: silica fiber</td>
<td>807 nm</td>
<td>820–840 nm/895–915 nm</td>
<td>-50–500°C</td>
<td>$16.8 \times 10^{-3}/\degree C$</td>
<td>[14]</td>
</tr>
<tr>
<td>Er and Er/Yb: chalcogenide glasses</td>
<td>1,540 µm and 1,064 µm</td>
<td>530 nm/555 nm</td>
<td>20–220°C</td>
<td>$10.2 \times 10^{-3}/\degree C$ at 220°C and $5.2 \times 10^{-3}/\degree C$ at 220°C</td>
<td>[15]</td>
</tr>
<tr>
<td>Er: silica fiber</td>
<td>800 nm</td>
<td>515–525 nm/555–565 nm</td>
<td>300–500 K</td>
<td>$10 \times 10^{-3}/K$</td>
<td>[20]</td>
</tr>
<tr>
<td>Er: silica fiber</td>
<td>785 nm</td>
<td>527–537 nm/545–555 nm</td>
<td>21–96°C</td>
<td>$6 \times 10^{-3}/\degree C$</td>
<td>[21]</td>
</tr>
<tr>
<td>Er: silica fiber</td>
<td>975 nm</td>
<td>525–535 nm/555–565 nm</td>
<td>20–200°C</td>
<td>$35 \times 10^{-3}/\degree C$</td>
<td>This work</td>
</tr>
</tbody>
</table>

**Table 1**

Summary of the performance of rare-earth doped fibers and materials as temperature-sensing elements based on the fluorescence intensity ratio technique.
7. Conclusions

This article has presented experimental results demonstrating the performance of an erbium-doped-silica fiber as a remote temperature sensor using the fluorescence intensity ratio technique. The green fluorescence signal is generated by up-conversion processes in the erbium-doped fiber pumped by a pigtail laser diode at 975 nm.

It is concluded that the optimal spectral bands to use in the sensor are (520 nm–530 nm) and (525 nm–535 nm) ($^2\text{H}_{11/2}$ transition) of the erbium doped fiber with a SNR of 110 dB and 111 dB, respectively, at 20°C; while for the spectral bands (540 nm–550 nm) and (555 nm–565 nm) ($^4\text{S}_{3/2}$ transition) of the erbium doped fiber, the SNR is 120 dB and 104 dB, respectively, at 20°C. The highest sensitivity obtained for the sensor is from approximately $35 \times 10^{-3}/$°C to about $10 \times 10^{-3}/$°C for the temperature interval of 20°C–200°C. The SNR and sensitivity of the sensor of erbium-doped fiber pumped at 975 nm is greater than that obtained with other rare-earth-doped fibers that utilize the intensity ratio technique.

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References

Remote Temperature Sensor Based on Up-Conversion


Biographies

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