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Two-photon luminescence thermometry: towards 3D high-resolution thermal imaging of waveguides

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Abstract. We report on the use of erbium-based luminescence thermometry to realize high resolution, three dimensional (3D) thermal imaging of optical waveguides. Proof of concept is demonstrated in a 980-nm laser pumped ultrafast laser inscribed waveguide in an Er:Yb phosphate glass platform. Multi-photon microscopy images revealed the existence of well confined intra-waveguide temperature increments as large as 200 °C for moderate 980 nm pump powers of 120 mW. Numerical simulations and experimental data reveal that thermal loading can be substantially reduced if pump events are separated more than the characteristic thermal time that for the waveguides investigated is in the millisecond time scale.

1. Introduction

Optical waveguides (WGs) are building blocks in modern integrated photonics as they provide full control over light propagation in the micrometric scale in an analogous way that microwires do in electrical circuits [1]. WGs are based on the controlled refractive index modulation at the micron and sub-micron scales designed for light confinement in an active volume of an enhanced refractive index and/or surrounded by low refractive index media. The requirements of integrated photonics restrict the typical dimensions of active volumes down to few microns. Under those conditions, large photon densities could be achieved inside waveguides and, hence, inside photonic circuits. Such large photon densities could be beneficial for some applications (e.g., those involving nonlinear processes [2]) but could also lead to the appearance of adverse effects [3-5]. Among all of the potential arising adverse effects, local heating has been well known to be of special relevance [3]. Intra-waveguide local heating arises from the partial absorption of propagating light by the material and its subsequent re-emission in the form of heat that could lead to relevant temperature increments at the waveguide's volume and its surroundings. These local light-induced heating could lead to the appearance of a variety of adverse effects. For instance, the optical performance of any optical WG is determined by the refractive index contrast between waveguide's active volume and its surroundings [4]. In most of the cases, refractive index is temperature-dependent so that intra-waveguide heating could modify the refractive index of waveguide's active volume and the refractive index contrast. This would lead to

deterioration in the confinement ability of the optical WGs. In addition, the appearance of relevant thermal gradients in integrated photonic circuits could give place to the creation of no negligible stress fields that could affect both the performance and lifetime of those integrated circuits [5]. Control over heat generation processes inside WGs therefore becomes essential. Thermal control requires, as a first step, a detailed knowledge of the temperature patterns created by the propagating radiation inside WGs. The acquisition of thermal images of active WGs with sub-micrometric resolution is not an easy task at all. Thermal imaging of WGs should be obtained in a contact-less mode so that the optical performance of the WG would be non-affected by the measuring performance. Additionally, as WGS are three dimensional (3D) structures, full characterization would require the acquisition of 3D thermal images. Classical methods, such as Scanning Thermal Microscopy or Thermal Lens based interference methods failed to satisfy these two requirements simultaneously. Thus, the development of new thermal imaging techniques should be developed for thermal imaging of integrated optical WGs.

Luminescence Thermometry (LT) [6,7] is a relatively new thermal imaging technique that has been demonstrated to be a simple, flexible and sensitive approach capable of providing contact-free, three dimensional images of a great variety of systems. LT is based on the extraction of thermal information from an appropriate analysis of fluorescence images. Very recent works have demonstrated the suitability of LT for three dimensional thermal imaging of optical WGs, in particular of Nd:YAG waveguides [8]. In that case, the Neodymium ions were used as thermal probes and the three dimensional capacity was provided by using a confocal architecture. In these conditions thermal sensitivity of obtained images was limited to 2 °C. Thermal sensitivity improvement would require the use of other luminescence probes with a superior thermal sensitivity. Among the different luminescent ions used in recent years as thermal sensors, Erbium ions emerged of special relevance as they provide, based on their visible emission bands, thermal sensitivities in a large variety of materials larger than 0.01 °C⁻¹ (one order of magnitude larger than those provided, for example, by Neodymium ions) [9,10]. In addition, when combined with appropriate donor ions (such as Ytterbium), the thermal sensitive visible band of Erbium ions can be efficiently excited by infrared (980 nm) via a two-photon excitation process [11,12]. This would provide the LT with a superior spatial resolution via multi-photon microscopy without requiring the use of confocal apertures, i.e. with an improved acquisition times and signal-to-noise ratio. Erbium ions have been used in the past as thermal sensors in fibers and lasers but its application for the acquisition of high spatial and thermal resolution 3D thermal images of integrated optical WGs has not been yet explored.

In this work we report on the acquisition of two-photon and 3D thermal images of ultrafast laser inscribed waveguides (ULI-WGs) in an Ytterbium and Erbium co-doped phosphate glass by LT. “Pump and probe” experiments in combination with two-photon microscopy have been used to elucidate the 3D spatial extension and magnitude of the 980 nm laser-induced thermal loading in both the WG active volume and surroundings. Time modulation of the 980 nm pump radiation has been used to investigate the

dynamics of thermal loading processes inside the WG. Results have been compared to numerical simulations, being in good agreement.

2. Experimental.

The Er:Yb: phosphate glass (doped with 1.5 wt.% Er_2O_3 and 4.5 wt.% Yb_2O_3) used in this work is a $17 \times 9 \times 2 \text{ mm}^3$ wafer with all the faces polished to optical quality. An amplified Ti:Sapphire laser system operating at a wavelength of 800 nm, which produced pulses of 120 fs duration, 1 mJ maximum pulse energy at a repetition rate of 1 kHz, was utilized to fabricate surface cladding structures in the glass sample. For doing so the sample was placed in a 3-axes motorized stage with a spatial resolution better than 100 nm. The laser beam was focused through the sample surface by a $40\times$ microscope objective (N.A. = 0.65). Pulse energy of $0.36 \mu\text{J}$ was found as the optimum value to produce filaments while scanning the sample at a constant velocity of 0.5 mm/s. By inscribing parallel filaments with a lateral separation of $3 \mu\text{m}$ at different depths, surface cladding structures were inscribed. Figure 1a shows the cross sectional optical microscope image of the surface cladding waveguide. The waveguide consists on a $17 \mu\text{m}$ in diameter semi-circle constituted by seven filaments and the glass/air interface. By using an end-coupling arrangement, a single mode fiber was pigtailed into the end-face of the waveguide, as shown in Fig. 1c. Figure 1b shows the near-field spatial modal distribution at 800 nm collected from the opposite end-face of the waveguide, showing well-confined propagation.

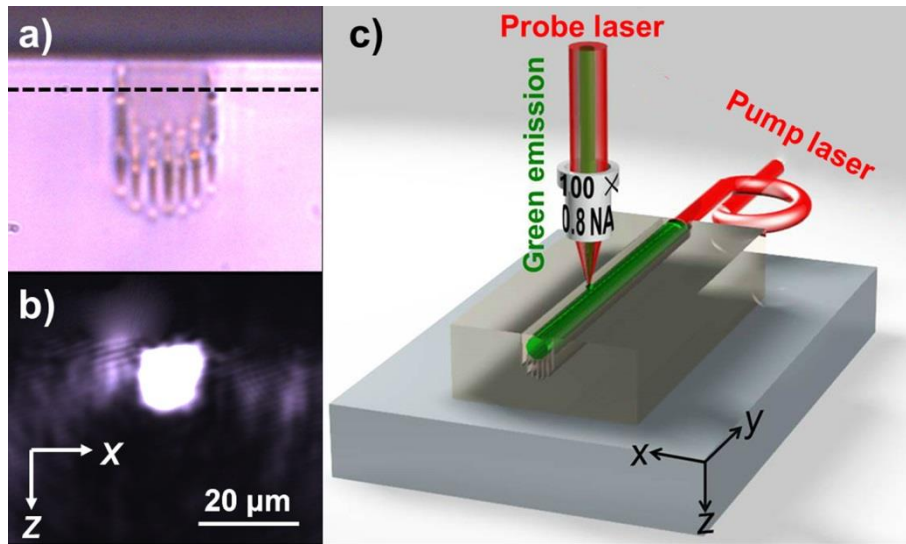


Figure 1. a) Cross-sectional optical microscope image of the surface cladding waveguide. b) Near-field spatial modal distribution at 800 nm. The scale bar is $20\mu\text{m}$ for both a) and b). c) Schematic of the “pump and probe” experimental setup.

A schematic plot of the experimental setup used for two-photon fluorescence measurements and thermal imaging is included in Figure 1c. The Er:Yb phosphate glass was mounted on an XYZ motorized stage that allows the three dimensional scanning. The sample was optically excited by means of a single-mode fiber-coupled 980 nm laser

diode. The “probe” laser beam was tightly focused into the sample by using a 100× (NA = 0.80) near-infrared long working distance microscope objective. The 980 nm laser radiation is absorbed by the Yb³⁺ ions (²F_{7/2}→²F_{5/2} transition), and then the energy is transferred from Yb³⁺ ions to Er³⁺ ions, leading to the excitation of Erbium ions up to ²H_{11/2}, and ⁴S_{3/2} level, from which the subsequent green luminescence is generated (Fig. 2a). The two-photon green luminescence signal was collected by the same microscope objective and spectrally analyzed by a high-resolution spectrometer (Horiba Jobin Yvon iHR320). The micro-luminescence spectrum obtained in our experiment is shown in Fig. 2b. In this work, we focused on the two thermal sensitive emission lines (525 nm and 545 nm, as depicted in Fig. 2b) as they can be used to detect the temperature modifications in the ULI Er:Yb:phosphate glass WGs. As commented in the introduction, several works have revealed that the intensity ration between these two emission lines can be used for high resolution thermal sensing. Such thermal sensitivity arises from the fact that these two lines are originated from the thermally coupled ²H_{11/2}, and ⁴S_{3/2} states. As temperature changes, population redistribution among these states takes place, leading to remarkable change in the intensity ratio between these bands, in such a way that this intensity ratio can be used as a temperature indicator. Figure 2b includes the micro-luminescence spectra obtained by coupling the 980 nm “pump” laser beam into the waveguide’s volume at two different powers, which induce different temperature increments in the WG. The remarkable ratio increment between the two emission lines as the temperature increases is observed. The intensity ratio R between the two visible bands, obtained as a function of the sample temperature, is shown in Fig. 2c. The emission intensities were measured under only “probe” laser excitation when the glass sample was placed at a heating plate with temperature control from 10 to 60 °C. As can be observed, the intensity ratio varies in a pseudo-linear way in the temperature range under this study. From the linear fit of experimental data, we can extract a relative ratiometric thermal sensitivity, defined as $S = \frac{1}{R} \frac{dR}{dT}$ [13], to **0.9% °C⁻¹**.

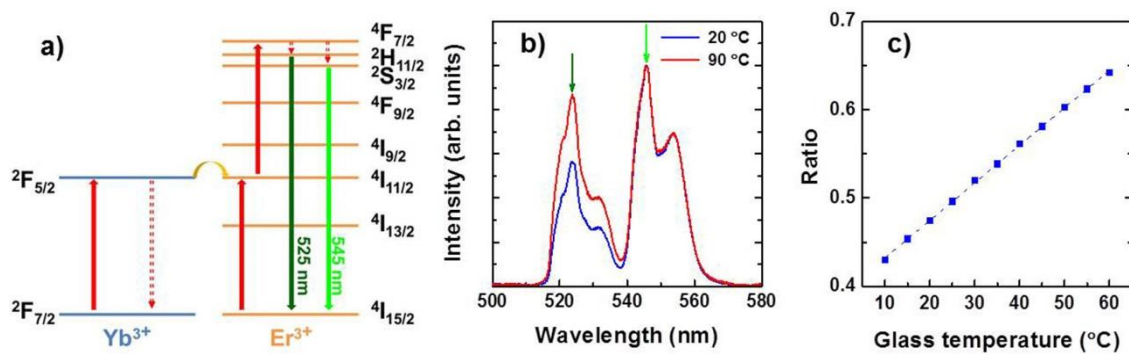


Figure 2. a) Energy level diagram showing the relevant states of the Yb³⁺ and Er³⁺ ions and the two-step up conversion excitation mechanism. b) Normalized micro-luminescence emission spectra obtained at two different “pump” laser powers. The two emission lines used for ratiometric thermal sensing are indicated. c) Ratio increment as a function of the glass temperature. The dashed line indicates the linear fit of the experimental data.

3. Results and discussion.

3.1. Thermal loading under continuous wave excitation.

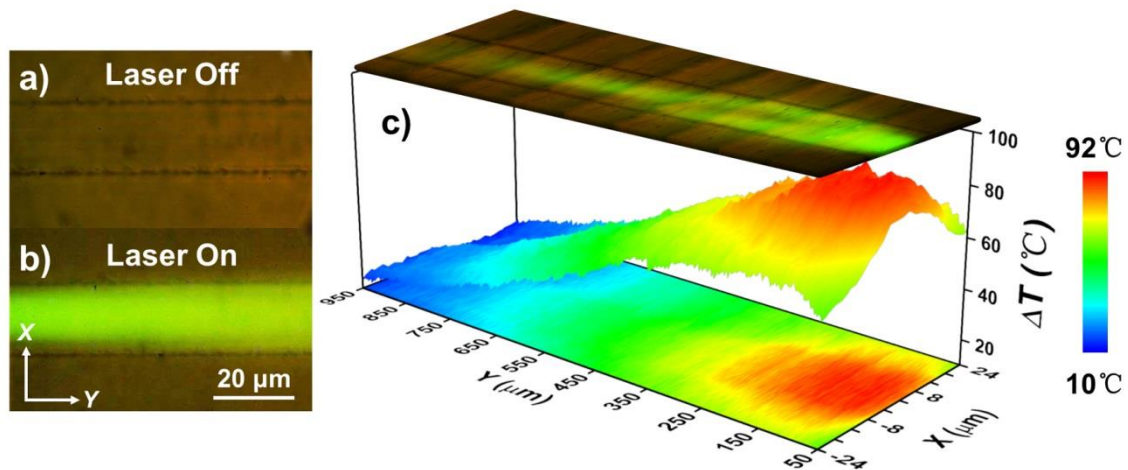


Figure 3. Microscope images of the waveguide surface: a) “pump” laser off and b) “pump” laser on, in which the confined green emission generated by the “pump” 980 nm laser is clearly shown. c) 2D temperature image obtained along the waveguide propagation direction (Y). Position $Y = 0 \mu\text{m}$ corresponds to the input face of the waveguide. The horizontal scan path (X) is indicated by the dashed line in Fig. 1a. The top view shows the green emission along the waveguide.

The large ratiometric thermal sensitivity of Erbium ions (Fig.2c) allows us to obtain 3D thermal images from the proper calibration of the 3D micro-luminescence images obtained in terms of the intensity ratio R . In order to get rid of the possible self-heating created by the 980 nm “probe” beam, we have measured the “ratio maps” in presence and absence of the 980 nm “pump” beam with the same “probe” beam. The net variation induced by the “pump” beam in the intensity ratio was obtained by subtracting the ratio map obtained in absence of pump radiation (here considered as a background contribution) from that in presence of pump radiation.

Following the above explained procedure we firstly obtained the temperature patterns created by the 980 nm pump radiation in the XY plane (top thermal images). Figures 3a and 3b depict the microscope top images of the waveguide. When the 980 nm “pump” laser was switched off, optical image reveals the presence of the parallel ULI damage tracks constituting the waveguide. On the other hand, in presence of 980 nm “pump” radiation propagating along the waveguide, the up-converted green emission generated by Erbium ions is clearly observed, being well confined within the waveguide volume (i.e. between damage tracks). The XY (top) thermal image was obtained by scanning the “probe” beam in the XY plane at a fixed depth ($Z = 5 \mu\text{m}$) while keeping the “pump” laser power fixed. Figure 3c shows the experimentally obtained XY imaged as obtained for a “pump” 980 nm laser power of 60 mW. From this XY temperature image, several conclusions can be extracted:

- i) The “pump” laser induced intra-waveguide heating decreases along the waveguide propagation direction Y , being mainly concentrated in the first

millimeter. This fact is attributed to the strong absorption of the 980 nm “pump” radiation along the waveguide by the Ytterbium ions. Indeed the absorption coefficient of our Er:Yb codoped phosphate glass has been measured to be $\alpha_{\text{abs}} = 8.2 \text{ cm}^{-1}$ at 980 nm, so that the propagation length of “pump” radiation is expected to be $L_{\text{abs}} = 1.2 \text{ mm}$, defined as the length at which the laser power is declined to $1/e$ of the input power. The absorption of pump radiation during the first 1 mm is further proved by the optical image included in Fig. 3c from which it is clear that green emission is almost completely attenuated along the first 1 mm of propagation length.

- ii) Secondly, thermal images revealed the presence of laser-induced thermal loadings as large as 90 °C for a moderate 980 nm “pump” power of 60 mW. This fact suggests that pump-induced thermal effects in Er:Yb glass waveguides cannot be neglected at all and should be seriously considered during design and operation of such devices. These pump-induced thermal loadings have been, indeed, found to be comparable [14] in a Er:Yb phosphate glass microchip laser, and much larger than lasers in Yb doped crystals [15,16] and Er:Yb codoped fibers [17-20]. This large pump induced thermal loading could be due to the large pump laser densities achieved in our waveguides in which 980 nm pump radiation is confined between damage tracks separated only 17 μm .
- iii) Finally, although the 980 nm pump radiation is well confined within WG’s volume, the temperature pattern clearly extends over the surroundings of the WG due to thermal diffusion.

In order to get additional information about the confinement of the pump induced temperature pattern in the WG, we have also measured the cross sectional thermal image of the WG by scanning the 980 nm “probe” spot along the XZ plane. Figure 4a shows a waveguide cross sectional thermal image obtained at a distance of 50 μm from the input face with a CW 980 nm pump laser at a power of 120 mW. From this thermal image it is clear that, although some heating is also produced in the surroundings of the WG, it is mostly localized within the WG’s area. Indeed, the ULI filaments (indicated by the dashed lines in Fig. 4a) seem to be producing an efficient thermal confinement that results in a high temperature increment inside the waveguide volume, reaching a maximum temperature increment around 215 °C. This suggests that damage filaments could act as “thermal barriers”. This behavior is further supported by the fact that the observed “temperature spreading” in the surroundings of WG’s volume is highly anisotropic. Along the Z direction, parallel to the filaments, temperature gradients in the surroundings of WG are found to be close to 1.5 °C/ μm whereas along the horizontal X direction (perpendicular to damage filaments) thermal gradients increase up to 1.9 °C/ μm . These facts indicate that ULI damage filaments are behaving as anisotropic thermal barriers. This is, indeed, in agreement with the results published by Belloudard *et al.* [21] which concluded that ULI damage produced in transparent materials is characterized by a reduced thermal conductivity.

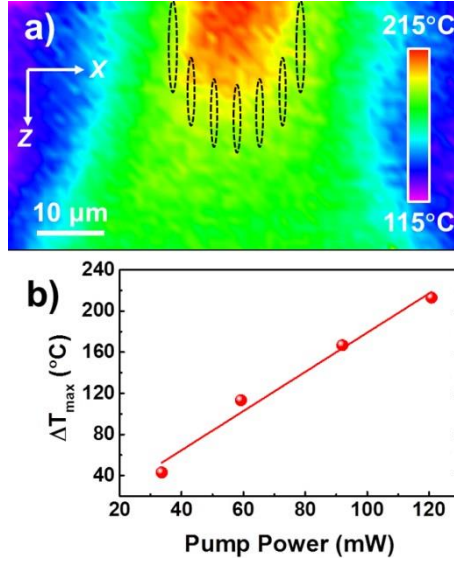


Figure 4. a) The cross sectional thermal image obtained at a distance of 50 μm from the input waveguide face with a CW 980 nm pump laser at a power of 120 mW. Dashed lines indicate the position of damage tracks. b) Maximum temperature increments induced by different pump powers.

Finally, by measuring thermal images for different “pump” powers we were able to determine the variation of temperature increment induced at WG’s volume (ΔT_{\max}) as a function of the 980 nm “pump” power. Results obtained at a fixed distance (50 μm) from the waveguide input end-face are shown in Fig. 4b. Note that in the “pump” power range under study in this work, the induced temperature increment has been found to follow a linear trend with the 980 nm “pump” power. This fact reveals that, despite the large temperature increments induced in the WG’s volume (in excess of 200 °C), those are not causing relevant leaking of 980 nm “pump” radiation out of the waveguide, which would be detected by the appearance of sublinear behaviors in the temperature versus pump power curve.

3.2. Thermal loading under pulse excitation: Thermal accumulation effects.

Data included in previous section reveal that 980 nm pump induced thermal loading in Er:Yb ULI glass WGs cannot be neglected at all and it could lead to the appearance of adverse effects that could result, in the long term scale, to severe deterioration in their optical performance. In this sense, new strategies have to be developed to reduce this large thermal loading to avoid undesired deterioration. It has been proposed and experimentally demonstrated in previous works that time modulation of pump radiation could be used for efficient reduction of thermal loading. When the time distance between consecutive pump pulses (i.e., pulse separation) is larger than the characteristic thermal relaxation time (τ_{thermal}), thermal accumulation between consecutive laser pulses is minimized resulting on a reduced average heating [14,19]. This possibility has been demonstrated to be especially suitable for the optimization of the laser performance of microchip lasers that are also characterized by large pump-induced thermal loadings of the active volume [xx]. Nevertheless, up to the best of our knowledge, this possibility has not been yet demonstrated in laser excited WGs. In this

section we have systematically studied the average heating induced in our ULI Er:Yb glass WGs by time-modulated pump radiation. The 980 nm “pump” laser was time-modulated to generate a train of square laser pulses with a fixed pulse width of 2 ms, a peak power of 60 mW and a pulse separation ranging from 0.1 ms to 10 ms. The waveform of the pulse laser is schematically illustrated in Figs. 5a and 5b for pulse separations significantly larger and shorter than the thermal relaxation time, respectively. In Fig. 5a, when the pulse separation was significantly larger than τ_{thermal} , almost complete heat dissipation occurs between pump pulses, in such a way that thermal accumulation does not take place. On the other hand, when the pulse separation is below τ_{thermal} , thermal relaxation between consecutive pump pulses does not occur and, as a result, thermal accumulation takes place, leading to a larger average temperature increment (Fig. 5b). This was experimentally verified by measuring the intra-waveguide temperature increment as a function of the pulse separation. Experimental data are included in Fig. 5c as solid circles. It has been observed that the intra-waveguide temperature increment decreases monotonously with the pulse separation. Indeed, the temperature increment vs time data can be nicely fitted to a single exponential decay. From the fitting, a characteristic time constant close to 2 ms is found. Thus we conclude that the observed decrease in the average temperature increment is, indeed, caused by a reduction in the thermal accumulation between pump pulses.

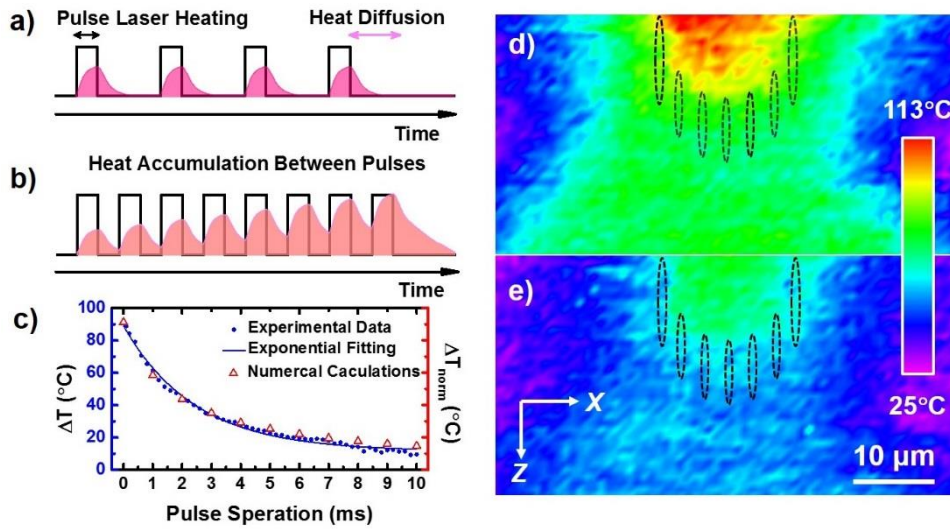


Figure 5. Schematic representation of the heating and diffusion processes induced by a train of square laser pulses. a) The pulse separation is long enough that the thermal diffusion has carried the heat away from the sample before the next pulse arrives. b) The time between laser pulses is less than the time for heat to diffuse away, resulting in an accumulation of heat. c) The experimental (solid circles) and numerical calculation (triangles) of temperature increment as a function of the pulse separation. The peak power was fixed to 60 mW, and the pulse width was fixed to 2 ms. d) and e) show the cross sectional thermal images obtained at a distance of 50 μm from the input face. d) CW laser. e) Square pulse laser with a pulse separation of 2 ms. Dashed lines indicate the position of damage tracks.

The advantage of using time-modulated pump radiation is further evidenced in Figs. 5d and 5e. In these figures we show the cross sectional thermal images obtained when the pump beam had a constant power of 60 mW and when the pump beam was constituted by a train of 2 ms width pulses with a pulse separation of 2 ms. In this last case, the pulse energy was set to 120 nJ that corresponds to a peak power of 60 mW (same as the power used under CW excitation). The thermal images show similar temperature distributions. In both cases, the thermal pattern is characterized by a remarkable thermal confinement inside the waveguide area. This unequivocally indicates that time modulation of the heat generation source has not effect on the spatial distribution of heat that it is mainly determined by the spatial confinement of pump radiation and the existence of thermal barriers (damage tracks). On the other hand, the magnitudes of the temperature increments are quite different. Indeed, time modulation of pump beam leads to a significant reduction in the maximum temperature increment inside the WG from 113 °C down to 60 °C. Figure 5 demonstrates the advantages of using modulated pump radiations for the minimization of undesirable thermal effects in integrated optical devices.

3.3. Numerical simulation.

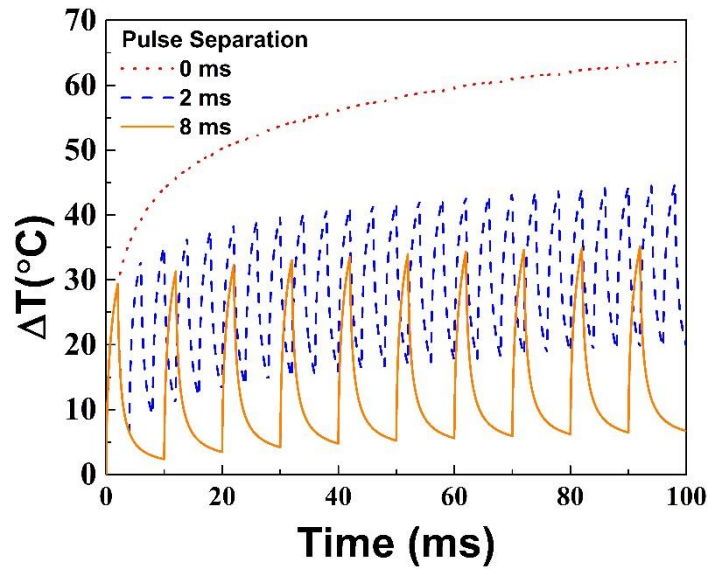


Figure 6. Time evolution of pump induced temperature increment inside the waveguide for three different time configurations of the 980 nm pump radiation. The pulse separations are 0 ms (i.e. CW laser, dot), 2 ms (dash), and 8 ms (solid), from top to bottom, respectively.

In order to corroborate the correctness of our measurements and the validity of our conclusions, numerical simulations of the thermal diffusion equation have been carried out by applying a finite difference approach. Thermal and spectroscopic properties assumed in our calculations were extracted from previous works describing Erbium and Ytterbium codoped phosphate glasses [xxx]. Figure 6 shows the time evolution of the temperature inside the waveguide for three different time configuration of the 980 nm pump radiation. The dot line in Fig. 6 shows the calculated temperature when the pump beam was assumed to be a CW beam with a constant pump power of 60 mW. In this

case, temperature increases monotonously stabilizing for times larger than 20 ms. Saturation is achieved when the heating rate caused by the absorption of pump radiation is equal to the heat dissipation due to temperature differences between environment and phosphate glass. When the pump beam was constituted by 2 ms pulses with a pulse separation of 2 ms, the time evolution of intra-waveguide temperature increment is shown in Fig. 6 (dash line). In this case, temperature increases during the laser pulse and relaxes during the time interval between pulses. Particularly, simulations reveal that complete thermal relaxation does not occur between consecutive pulses and thus heat accumulation takes place. As a consequence, waveguide's temperature increases, on average, with time. It should be noted that the partial thermal relaxation between pulses leads to an average waveguide's temperature smaller than that achieved under CW excitation. Finally, the solid curve in Fig. 6 shows the time evolution of waveguide's temperature when the pulse separation was set to 8 ms that is larger than the characteristic thermal relaxation time. Again, waveguide's temperature increases during the pump pulse but, at variance with previous cases, almost complete thermal relaxation occurs between pulses. In this case thermal accumulation between consecutive pulses is almost negligible and, consequently, the average waveguide's temperature increment is almost negligible. The average temperature increment normalized to the temperature increment induced under CW excitation (ΔT_{norm}) as a function of the time distance between pulses extracted from numerical calculations (triangles) has been included together with experimental data (solid circles) in Fig. 5c. As can be observed, an excellent agreement between experimental data and numerical calculations has been obtained revealing the correctness of our calculations as well as the role played by thermal accumulation in the observed minimization of thermal loading when using time-modulated pump radiations.

4. Conclusions

In summary, we have demonstrated how the high thermal sensitivity of the two-photon excited luminescence of Erbium ions, in combination with high resolution multiphoton fluorescence imaging, constitutes an accurate, reliable and flexible three dimensional, contact-free technique for thermal imaging of photonic devices. In particular, we have provided high resolution three dimensional thermal images of 980 nm laser pumped Ultrafast Laser Inscribed channel waveguide in an Erbium and Ytterbium doubly doped phosphate glass. Thermal images have revealed that in these structures laser induced thermal loading cannot be neglected at all. Temperature increments at waveguide's volume as large as 200 °C have been found for moderate pump powers of 120 mW. Furthermore, thermal images have also revealed a strong confinement of the pump induced thermal load at the waveguide's volume revealing the thermal impedance caused by the damage tracks that simultaneously behave as thermal and optical barriers.

Thermal images have also indicated that such relevant pump induced intra-waveguide thermal loading can be substantially reduced by time modulation of the pump beam. Experimental and numerical simulations have concluded that intra-waveguide thermal

relaxation times are in the millisecond time scale in such a way that heat accumulation can be minimized by using pulse pump beams with time separation between pulses of few milliseconds.

This work introduces to the scientific community a high resolution, flexible, simple and versatile tool for the acquisition of three dimensions, high resolution and time resolved thermal images of active photonic devices that would be essential for the complete understanding of their optical performance as well as for the optimization of their optical performance.

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