Near infrared two-photon self-confinement in photopolymers for light induced self-written waveguides fabrication

Alberto Barsella, Honorat Dorkenoo, and Loïc Mager

Citation: Appl. Phys. Lett. **100**, 221102 (2012); doi: 10.1063/1.4722925
View online: https://doi.org/10.1063/1.4722925
View Table of Contents: http://aip.scitation.org/toc/apl/100/22
Published by the American Institute of Physics

Articles you may be interested in

Light-induced self-written three-dimensional optical waveguide
Applied Physics Letters **79**, 1079 (2001); 10.1063/1.1389516

Optically-induced growth of fiber patterns into a photopolymerizable resin
Applied Physics Letters **75**, 737 (1999); 10.1063/1.124498

A three-dimensional polymeric optical circuit fabrication using a femtosecond laser-assisted self-written waveguide technique
Applied Physics Letters **92**, 253302 (2008); 10.1063/1.2951598

PHYSICS TODAY
WHITEPAPERS

MANAGER'S GUIDE

Accelerate R&D with
Multiphysics Simulation

READ NOW

PRESENTED BY
COMSOL

Near infrared two-photon self-confinement in photopolymers for light induced self-written waveguides fabrication

Alberto Barsella, Honorat Dorkenoo, and Loïc Mager[a)]
Institut de Physique et Chimie des Matériaux de Strasbourg (IPCMS), UMR7504, CNRS-Université de Strasbourg, 23 rue du Loess, BP 43, 67034 Strasbourg CEDEX 2, France

(Received 16 March 2012; accepted 12 May 2012; published online 29 May 2012)

We present the fabrication of single mode light induced self-written waveguides using two-photon absorption in photopolymers. The measurements are compared to the finite element method simulation of the propagation and demonstrate that two-photon process leads to the confinement of light. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4722925]

The light induced self-written (LISW) waveguide build-up has been demonstrated in a large variety of photosensitive materials and especially in photopolymers.[1–4] These materials are very attractive as they are commercially available and as they offer the possibility of a simple fabrication of single mode waveguides and the possibility of their functionalization with optically active molecules.[5,6] Presently, the photoinitiation of the polymerization is performed using the UV-visible part of the spectrum, but there is an interest to shift to near-infrared (NIR) light to fit the operation at the telecom wavelengths. As the sensitivity of the photoinitiators dramatically drops in this spectral range, we have switched from one-photon (1P) to two-photon (2P) photoinitiation. In this paper, we present the experimental demonstration of the inscription of a LISW waveguide in an acrylate based photopolymer through two-photon photopolymerization. To guide the experimental approach, we have performed a simulation of the build-up process. The result of the calculations has been then used to analyse the experimental results obtained for 1P and 2P induced LISW waveguides.

The LISW waveguide fabrication process in photopolymer is induced by the quasi-solitonic propagation of a light beam[3] confining the light in a self-propagating optical channel that will remain permanently inscribed in the material.[7] The simulation of this process is made by implementing the paraxial wave equation[8–10] and the light induced refractive index variation law in the COMSOL4.0 software. Compared to Anderson and Peters,[10] we have preferred to use the simple partial differential equation (PDE) library instead of the electromagnetic wave library. Operating this way, it was simple to set the time dependent evolution of the LISW waveguides. We expected to be able to use a $\lambda/2$ meshing,[11] but we found out that accurate results were only obtained when the meshing resolution was below $\lambda/6$. This high resolution limits the field of the simulation to the first 100 μm which is enough to observe the complete construction of the LISW waveguide. Here, we have considered that the evolution of the refractive index follows the equation:

$$\frac{d\Delta n}{dt} = \eta I\left(1 - \frac{\Delta n}{\Delta n_s}\right),$$

where I is the light intensity, η is the photopolymerization efficiency, and Δn is the variation of the refractive index. The initial refractive index is 1.51 and the variation of the refractive index at saturation is $\Delta n_s = 10^{-2}$. The effect of the absorption has not been taken into account. A high absorption has been set on the edge of the computation region in order to avoid the reflections. The only change between 1P and 2P operation is in the dependence of the variation of the refractive index that shifts from a linear to a quadratic intensity dependence. Figure 1(b) shows the refractive index profiles of the 1P and 2P LISW waveguides 80 μm along the propagation direction. The variation of the refractive index across the core of the LISW waveguides shows that they can be considered as step index waveguides.[12] The full width at half maximum (FWHM) of the 2P LISW is half that of the 1P case, indicating that the confinement is more effective. Figure 1(a) shows the typical result of the simulation before the saturation. The source at left edge of the simulation domain is a gaussian illumination with a 4 μm width. For the simulation, we have arbitrarily chosen $\lambda = 1$ μm. When one wants to experimentally compare 1P and 2P LISW waveguide operations, it is necessary to switch to a higher wavelength and therefore to an adapted optical fiber for the injection. The third profile presented on Figure 1(b) corresponds to the 2P induced variation of the refractive index at 80 μm distance from the source for a 2 μm wavelength with a initial aperture of 8 μm. It demonstrates that for this larger wavelength the diameter of the 2P induced LISW waveguide is similar to this obtained for the 1P operations at the smaller wavelength.

The experiments have been performed using Petia/MDEA/Eosin 92.4/7.4/0.2 % wt.[13] The LISW waveguide is generated by injecting the light in the phopolymerizable solution via a single mode optical fiber at 1μm (Fibercore SM980G80). Its propagation is made in a 1×1 cm^2 glass cell with a thickness of 125 μm allowing the insertion of the optical fiber. The solution is filtered (0.7 μm) and injected in the cell using a syringe. An exit glass window has been added to measure the intensity profile of the propagating mode. The use of a well defined diopter as exit window prevents alteration from the roughness at the air/photopolymer interface. The refractive index variation induced by the photopolymerization of the present mixture is too high to allow the single mode propagation of the LISW waveguide[9] and

[a)]Electronic mail: loic.mager@unistra.u-strasbg.fr.

 © 2012 American Institute of Physics

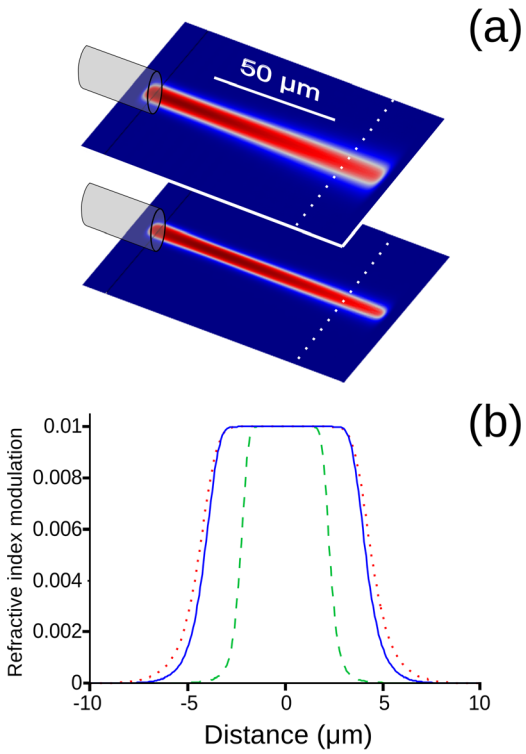

FIG. 1. Simulation of the propagation of LISW refractive index profile. (a) 2D refractive index modulation profiles, top, for 1P process, bottom, for 2P process. The dotted white line corresponds to the cut at 80 μm from the light source presented on the graph. (b) Refractive index modulation profile, full blue line 2P process at 2 μm, red dotted line 1P process at 1 μm, green dashed line 2P process at 1 μm

leads to the filamentation of the guide. In order to ensure the single-mode propagation regime, we lower the index contrast by partial photopolymerization of the entire sample, which is performed prior to starting the LISW waveguide inscription. This is done by using a halogen lamp for 20 min, typically 25 $\text{mW} \cdot \text{cm}^{-2}$. The light source for the LISW waveguide fabrication is a femtosecond laser Fianium FP1060-2-fs, (1064 nm, 80 MHz, <300 fs) directly injected in the optical fiber. The 2P fluorescence of the eosin appears for a power of about 10 mW at the fiber exit. This corresponds to a power density of 50 $\text{MW} \cdot \text{cm}^{-2}$. Using IR light, we consider that the apparition of the fluorescence corresponds to the threshold of the 2P initiation of the polymerization. This fluorescence allows observation of the LISW by simple optical microscopy. The images are acquired using a CCD camera, Thorlabs DCU224C with Sony ICX205AK sensor, exhibiting some sensitivity in the near IR range. The propagation over $\approx$5 mm is made in about 1 h, progressively increasing the input power to 35 mW to compensate for the 2P absorption losses of the unreacted eosin. The Figure 2(a) shows the 2P written waveguide by the yellowish fluorescence of the eosin. At the center of the figure, some diffraction rings appear due to the diffusion of IR light on a defect in the material. Otherwise, one does not observe any IR diffusion through the LISW waveguide indicating the efficiency of the light confinement. After the full construction of the LISW waveguide, the refractive index modulation is visualized using differential interferometric contrast (DIC) miscroscopy (see Figure 2(b)). The characteristics of the LISW waveguides have been deduced from the intensity profile of the exit mode. Figure 3 shows the image of the exit mode for a 2P polymerization. The intensity profile presents a gaussian shape with a beam width $\omega_0 = 10\,\mu$m. Some small variations of the diameter between the different experiments have been observed depending on the prepolymerization step and the light intensity during the build-up. It is to note that the material can withstand very high power density. After the full LISW build-up, we have risen the power up to 60 mW (300 $\text{MW} \cdot \text{cm}^{-2}$) for an hour without experimenting any degradation of the guide. We have also checked the integrity of the LISW waveguide four months after its construction and no variation of the guiding properties has been noted. From the measurement of the mode diameter, the numerical aperture of the waveguide is $\text{NA} = \sin(\lambda/\pi\omega_0) = 0.03$ for $\lambda = 1064$ nm. This value is confirmed by the direct measurement of the beam divergence. As the simulation shows that the LISW process leads to step index waveguides and knowing that the refractive index of the core of the guide is $n_{core} = 1.52$, the refractive index step between the core and the cladding n_{clad} is deduced from the relation $\text{NA} = \sqrt{n_{core}^2 - n_{clad}^2} = 0.03$ and is $\Delta n = 4 \times 10^{-4}$. Considering the 2P process, the photopolymerization is not initiated on the full extent of the light beam, but on the high intensity regions only. It appears that the 2P process does not affect the self-guiding properties as the LISW waveguide construction is observed.

For comparison, we have inscribed a LISW waveguides using 1P photopolymerization in the same material and observed similar results. The exit mode of the guide built using 514 nm actinic light and a single mode injection fiber (Nurfen 460HP) shows a $\omega_0 = 6\,\mu$m width. Considering the variation of the wavelength, the calculated numerical aperture is the same that this obtained in 2P process, NA = 0.03 and then to the same $\Delta n = 4 \cdot 10^{-4}$. From these results, the

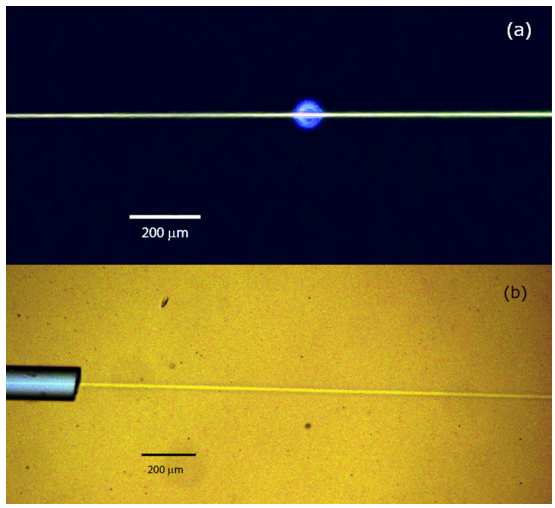

FIG. 2. (a) Micrograph image of the 2P fluorescence coming from the remaining eosin that reveals the LISW waveguide trajectory. The bright circle at the center of the image is due to the IR light diffusion on a defect (dust) in the material. (b) LISW image obtained by DIC microscopy.

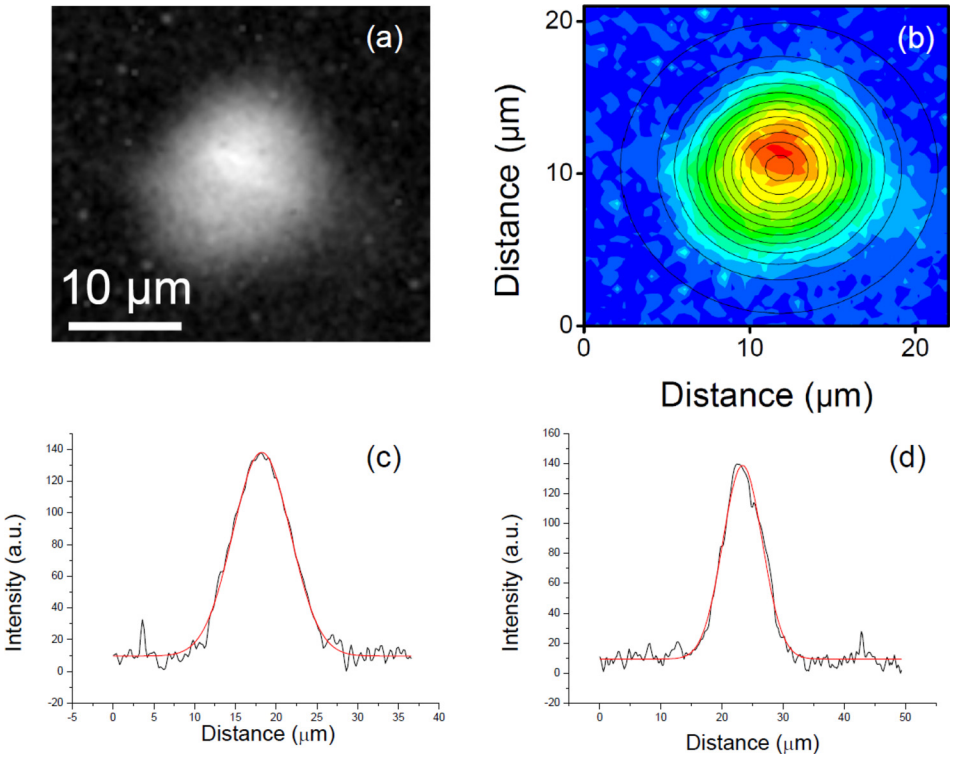

FIG. 3. Exit mode from the 2P LISW waveguide. (a) Micrograph image of the exit mode. (b) Intensity 2D map of the exit mode. The circles correspond to the isointensities of the 2D gaussian fit. (c) Intensity horizontal profile and (d) intensity vertical profile, the red lines correspond to the gaussian fit.

width of the 2P LISW waveguide fabricated at $\lambda = 1.064\,\mu$m is larger than expected from the simulation. This may be explained by the diffusion of the polymerization that has not been considered in the model.

We have demonstrated the LISW waveguide build-up process in photopolymers inscribed by two-photon polymerization in the near IR. The light is efficiently confined in the inscribed single-mode waveguide, but the size of the IR propagating mode is larger than this expected from the simulation. Finally, the numerical aperture was found to be very low as the refractive index variation between the core and the cladding of the waveguide is very small. The demonstration of the 2P LISW waveguide extends the available materials for their fabrication. It allows the use of photopolymers for applications in the near infra-red region and opens the path for the use of 1.3 μm and 1.5 μm wavelength for the telecom applications.

[1]C. Meneghini and A. Villeneuve, J. Opt. Soc. Am. B **15**, 2946 (1998).
[2]T. M. Monro, D. Moss, M. Bazylenko, C. Martijn de Sterke, and L. Poladian, Phys. Rev. Lett. **80**, 4072 (1998).
[3]S. J. Frisken, Opt. Lett. **18**, 1035 (1993).
[4]K. Dorkenoo, O. Crégut, L. Mager, F. Gillot, C. Carre, and A. Fort, Opt. Lett. **27**, 1782 (2002).
[5]K. Yamashita, E. Fukuzawa, A. Kitanobou, and K. Oe, Appl. Phys. Lett. **92**, 051102 (2008).
[6]O. Sugihara, S. Yasuda, B. Cai, K. Komatsu, and T. Kaino, Opt. Lett. **33**, 294 (2008).
[7]A. Zohrabyan, A. Tork, R. Birabassov, and T. Galstian, Appl. Phys. Lett. **91**, 111912 (2007).
[8]S. Shoji, S. Kawata, A. A. Sukhorukov, and Y. S. Kivshar, Opt. Lett. **27**, 185 (2002).
[9]K. D. Dorkenoo, F. Gillot, O. Crégut, Y. Sonnefraud, A. Fort, and H. Leblond, Phys. Rev. Lett. **93**, 143905 (2004).
[10]A. Anderson and K. Peters, J. Lightwave Technol. **27**, 5529 (2009).
[11]J. E. Toney, in *Proceedings of the COMSOL Conference*, Boston, 2009.
[12]G. Keiser, *Optical Fiber Communications*, 2nd ed. (McGraw-Hill, 1991).
[13]M. Farsari, G. Filippidis, K. Sambani, T. S. Drakakis, and C. Fotakis, J. Photochem. Photobiol., A **181**, 132 (2006).