Monitoring of photopolymerization induced changes of self-written waveguides

Malallah, Ra'ed, Abdullah, Ali, Sheridan, John

Ra'ed Malallah, Ali Q. Abdullah, John T. Sheridan, "Monitoring of photopolymerization induced changes of self-written waveguides," Proc. SPIE 11358, Nonlinear Optics and its Applications 2020, 113581U (1 April 2020); doi: 10.1117/12.2554897

SPIE.

Event: SPIE Photonics Europe, 2020, Online Only, France

MONITORING OF PHOTOPOLYMERIZATION INDUCED CHANGES OF SELF-WRITTEN WAVEGUIDES

Ra'ed Malallah[a,b*], Ali Q. Abdullah[a], and John T. Sheridan[b]

[a] Physics Department, Faculty of Science, University of Basrah, Garmat Ali, Basrah, Iraq.
[b] School of Electrical and Electronic Engineering, UCD Communications and Optoelectronic Research Centre, College of Engineering and Architecture, University College Dublin, Belfield, Dublin 4, Ireland;
*Corresponding Author: raed.malallah@ucdconnect.ie

ABSTRACT

Photo-polymerization is the reaction between monomers to form polymer chains, and these polymer chains have a higher refractive index than the monomer in the photopolymer, and so it is higher in the polymerized areas. There are four main processes that occur during photo-polymerization in the photopolymer, which are Initiation, Propagation, Termination, and Inhibition. Self-written waveguides (SWWs) in photopolymers, and the process of self-focusing and self-trapping, has been seen that certain important areas which require further research. In this article, the effect a SWW has on the transmission of light through the photopolymer is further tested using a PVP as a media with Rhodamine 6G (R6G) as a dye. Simulations were focused on investigating the SWW mechanism, testing different quantities of beams entering the material. The SWW process was seen to be of most interest for the connection and splitting of multiple optical waveguides.

Keywords: Self-Written Waveguides; Photopolymer materials; Optical waveguides;

1. INTRODUCTION

Photopolymers are of interest as they are a low cost material, have very fast response times to exposure, and produce a large change in the refractive index. They are also sensitive to relatively low exposure intensity, meaning that a low power light can be used to achieve refractive index changes. The refractive index change has also been seen to be permanent in the literature, when stored in suitable conditions [1, 2]. The refractive index increase that takes place when photo-polymerization occurs can lead to light become self-focusing, self-trapping and self-written in the photo-sensitive material. This occurs when the higher refractive index causes the light to self-focus. The refractive index change is seen to be highest where the light intensity is strongest, and so the light is focused along the path of propagation of the beam. This self-focusing effect balances with the diffractive effects in the material to cause self-trapping of the light. This creates a channel through which light can propagate, and is referred to as a self-written waveguide (SWW) [3, 4]. After this structure has been formed in the photopolymer, it can be used as a waveguide for light to pass through the material, which has been shown by [5, 6]. This makes it of interest for the connection of optical fibers, as it provides a junction through which the light could propagate. The high refractive index area of the material, which is the SWW, acts as the core of an optical fiber would, with the light staying in the waveguide due to total internal reflection. This occurs as the high index SWW is surrounded by the lower index of the areas that have not undergone photo-polymerization [7, 8].
It has been seen that when beams are out of alignment when entering the photopolymer, the SWW's formed by them can bend towards each other, causing them to make a connection [9]. This is useful as it could allow for more tolerance with the alignment of optical fibers for connection, making for an easier process. This will only occur if the beams

Nonlinear Optics and its Applications 2020, edited by Neil G. R. Broderick, John M. Dudley, Anna C. Peacock,
Proc. of SPIE Vol. 11358, 113581U · © 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2554897

pass sufficiently close to each other for their SWW's to interact with one another. The bending takes place as a result of the changes in refractive index of the two SWW's interacting with each other, causing greater index in these overlapping areas [5, 6, 10]. Another form of SWW's seen in the literature was in the work by Mikami *et.al.* [11], in which a light curable resin is used. This resin requires ultraviolet (UV) or 405nm (Blue) light to cure. This method of forming waveguides does not use photosensitizing dyes to create a change in refractive index to form the SWW, but rather uses certain wavelengths of light to cure a resin with the same refractive index as the core, and then wash away any uncured resin. A clad resin is then added and cured to the outside of the cured core resin. This clad resin is of lower refractive index than the core resin, to keep the light in the core.

Furthermore that Jradi *et.al.* has shown in their work that it is possible to create a connection between two single mode optical fibers by using a photo-polymerizable liquid between them. This resulted in perfectly aligned connections between the optical fibers, and they were securely anchored to the ends of each other [12]. These interactions between multiple beams in photo-polymerizable materials have been shown previously [13]. This work studied the effects input beams had on photo-polymerizable resins, with different angles of entry be different beams being studied. Numerical solutions of the refractive index changes in the resin were shown, and waveguides were shown not to merge in the material if their collision angle was greater than 9 degrees [14, 15].

In this work the investigation of using the photosensitive materials, photopolymers, is studied for creating the optical trajectories. Polymerization can occur upon exposure to light, causing a refractive index change. This leads to the exposing light being focused into a channel, known as a self-written waveguide (SWW). Multiple beams entering the material have also been seen to merge when in close proximity, which is referred to as self-branding and self-healing. It is seen that the material that looks to be the most promising in the applications of developing optical interconnects by use of SWW's is the dry photopolymer media (PVP) with using a Rhodamine 6G (R6G) as a dye. This is due to the simpler processes of writing SWW's inside this material during photo-polymerization process.

2. MODELLING SELF-WRITTEN WAVEGUIDE FORMATION:

The process by which the refractive index change takes place in photopolymers is photo-polymerization. This is polymerization triggered by light exposing the material [1, 2]. In the case of a Polyvinyl-Pyrrolidone (PVP) is made up with a photo-absorptive dye, Rhodamine 6G (R6G), which is sensitive to a wavelength of 532nm. The process of polymerization that takes place in the material is known as free radical photo-polymerization. This involves the creation of radicals when the electron donor reacts with an excited state of the dye, which leads to the generation of chain initiators when the radicals react with the monomers.

Numerically the SWW's in the photopolymer can be performed by use of a suitable model and a numerical algorithm [1, 2, 5]. The SWW formation can be modelled by the paraxial wave equation, to calculate the light intensity as the photopolymer is exposed [5]. This equation is solved by use of the split step Fourier method, allowing it to be used in a numerical algorithm. The form of this used in modelling of SWW formation is:

$$\frac{\partial E}{\partial z} = \frac{i}{2k_0 n_0}\nabla_{\perp}{}^2 E + ik_0 \Delta n E - \frac{1}{2}\alpha E. \tag{1}$$

In this equation, E is the electric field amplitude, z is the direction of light propagation, n_0 is the average initial refractive index of the material, k_0 is the free space wave number $2\pi/\lambda$. $\nabla_{\perp}^2$ is the 2D Laplace operator $\partial^2/\partial x^2 + \partial^2/\partial y^2$, $\Delta n(x, y, z, t)$ is the change in refractive index, and $\alpha(x, y, z, t)$ is the coefficient that governs light loss in the material. This coefficient is made of the sum of the linear and nonlinear loss coefficients. In this model, the refractive index evolution during the self-writing process is approximated using a simple phenomenological model [5, 16]:

$$\frac{\partial \Delta n(x,y,z,t)}{\partial t} = AI(x,y,z,t)^p \left(1 - \frac{\Delta n(x,y,z,t)}{\Delta n_s}\right), \tag{2}$$

where t is the exposure time, Δn_s is the fixed saturation value of the refractive index change, and $I(x, y, z, t)$ is the local light intensity [5, 16, 17] where $I(x, y, z, t) = |E(x, y, z, t)|^2$. The coefficient, A, is a real coefficient that depends on the material properties, the number of photons p, and the wavelength of the exposure light. In the photo-polymerization process, the number of photons involved in the process is typically assumed to be $p = 1$, (i.e. one-photon photosensitivity during photo-polymerization process) [5, 18]. This equation typically employed to calculate the index change because it can be relatively easily combined with the paraxial wave equation to give useful predictions. The light intensity in the material can model the formation of the SWW as the light is most strongly focused along the path of propagation of the beam, which is where the light intensity is highest. This occurs due to the fact that the refractive index change is proportional to the light intensity. Therefore the areas of higher light intensity in the material are where the SWW has formed.

3. NUMERICAL RESULTS

Photopolymers are of interest as they are a low cost material, have very fast response times to exposure, and produce a large change in the refractive index. They are also sensitive to relatively low exposure intensity, meaning that a low power light can be used to achieve refractive index changes. Following the research into the areas of SWW's in photopolymers, and the process of self-focusing and self-trapping, it has been seen that certain areas require further research. These include investigating the self-cleanup and self-bending effects in the photopolymer further, and this is done by way of simulation. The effect a SWW has on the transmission of light through the photopolymer is also further tested, as not much had been shown in the literature regarding this [1-8].

Tow laser Gaussian beams are incident on the photopolymer material with an angle along z-direction. The incident laser beam on the medium and the changes induced by localized photo-polymerization reactions during the self-focusing and self-trapping processes in a bulk PVP photo-sensitive material, are recorded. In this case, Rhodamine 6G (R6G) ($C_{28}H_{31}N_2O_3Cl$) is used. Which is photosensitive to green light [19, 20]. The creating of self-written waveguides are explored using the green light beam ($\lambda = 532$ *nm*) as shown in the setup, Fig. 1. The two beams are focused onto the front face of the masks (contains holes in a straight line), which touches with the front face of the photopolymer bulk (for both sides). An additional the two mirrors are used on the both other sides of the photopolymer bulk to guide the beam lights inside material.

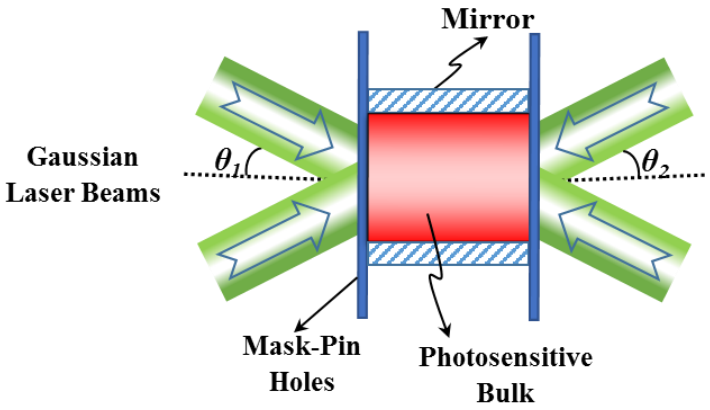

Figure 1. Schematic diagram of the proposed setup used to product the self-written waveguides.

The techniques of fabrication the trajectory structures in various materials are provided that during self-writing process. Commonly, when these sensitive materials are exposed by the light that the refractive index will be changed dramatically. A standard numerical model is used to predict both the evolution of the light intensity distribution and the channel formation inside the material during the exposure. The output intensity as a fraction of the input light intensities is indicated to the transmission (normalized) which can be defined as I_{out}/I_{in} [1-8]. Fig. 2 shows the normalized of transmission values which are rising dramatically during formation of the SWWs at t_{exp}= 1000s. These includes of the overcome for inhibition and absorption losses stabilize, that during the formation of waveguiding refractive index.

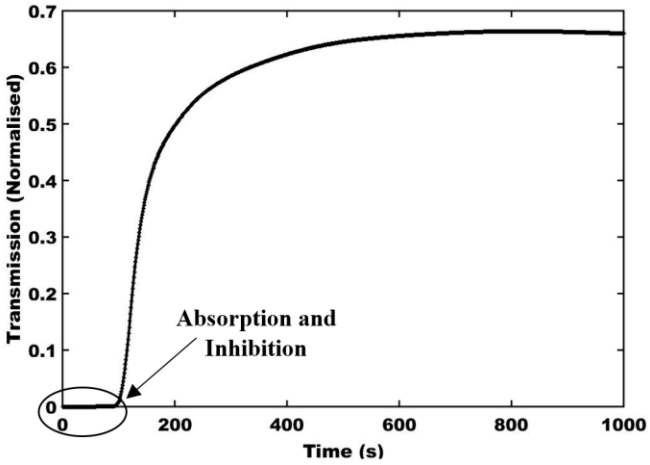

Figure 2 Numerical prediction of Transmission (normalised), plotted against exposure time.

Next, four Gaussian beams are passed throughout four holes, fig. 1, two beams for each side with angles θ_1= θ_2=35° and separated by 2.5mm. These beams are propagated through a photopolymer material in the *z*-direction, i.e. 0 < z < 8 mm. Self-cleanup and self-bending effects to create SWWs inside bulk can be predicted in fig. 3(a). As can be seen the interaction of four beams during SWW process. The photo-polymerization effects lead to increase the refractive index, and thus create trajectories for light transmission, see fig. 3(b).

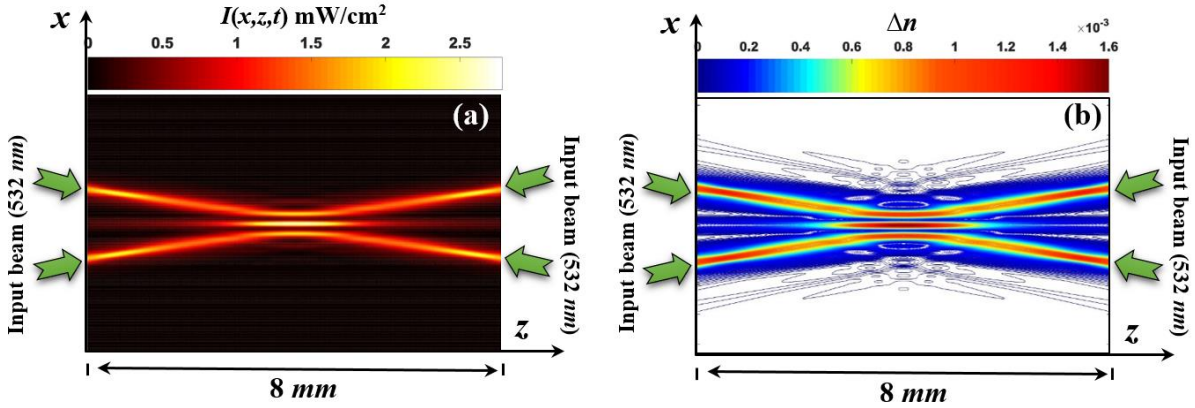

Figure 3 Numerical prediction of (a) light intensity distribution, and (b) change in refractive index. For two holes (with opposite two holes) separated by 2.5mm with exposure incident light angles as θ_1= θ_2=35°.

Having simulated two beams propagating from each side of the material, it was then desired to test more beams using several holes from either side. This was done in order to test the scalability of the self-cleanup effect with a higher number of light beams entering the material. Due to the high number of propagation beams being simulated, a net-shape waveguides has been created during photo-polymerization process, see fig. 4. Eight beams from each side of the material, which are getting from four holes in each side separated by 1.5mm, have been simulated. Each beam is making an angle 75° with z-axis.

Some interesting interactions are seen to take place during this simulation, with the structure formed after 10 seconds, the trajectories have begun appearing in front face of each side, see fig. 4(a). These beams are seen to join headily after a reflected from both mirrors that distanced by 8mm. It was seen that the beams collided in the middle of the material before the self-cleanup process was completed between the eight beams on either side of the material. When the counter-propagating beams meet in the middle, it is seen that the light intensity increases rapidly, as all of the light is focused at the point at which they meet (at t_{exp}=1000s), see fig. 4(b). Consequently the numerical prediction results of the SWWs in the dry photopolymer material are shown in fig. 4. We obtained that the Gaussian beams have a self-written the optical waveguide trajectories along the full length of the sample, z = 8mm.

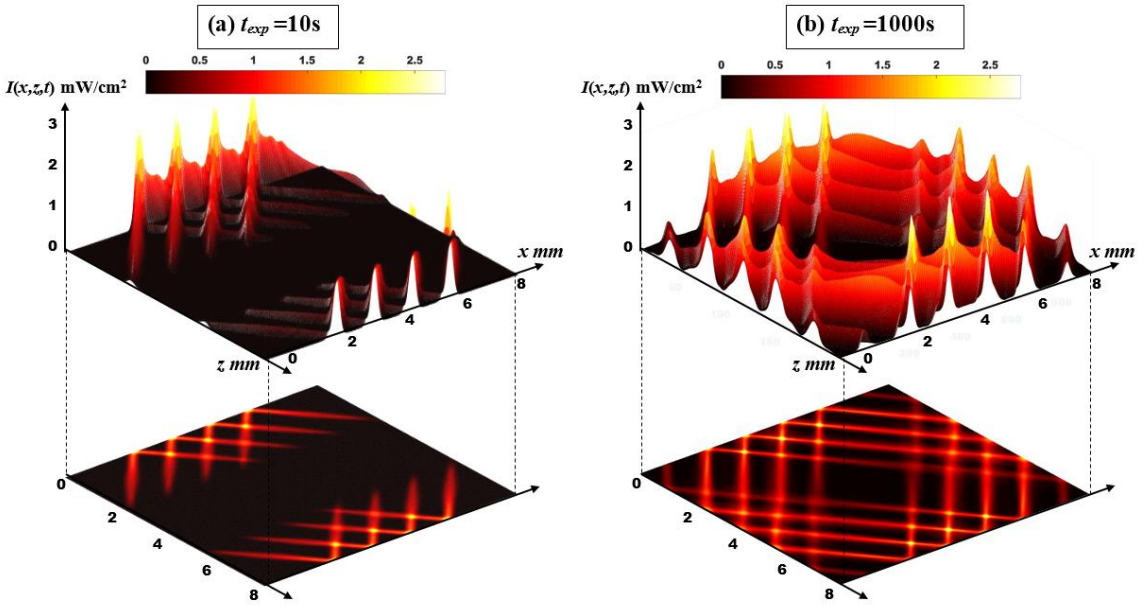

Figure 4 Numerical prediction of the light intensity distribution for interactions of light propagating, using four holes in each side: (a) short time t_{exp}=10s, and (b) long time t_{exp}=1000s.

The complex Trajectories have been created during propagation Gaussian beams inside photopolymer bulk. The self-writing fabrication method of waveguides shows great potential for future practical applications and integration with existing devices. The self-writing approach offers great potential for the fabrication of couplers and splitters for application in integrated optical devices and components.

4. CONCLUSION

Polymer materials that undergo structural changes when exposed to light are known as photopolymers. These structural changes can lead to change the refractive index of the photopolymer. The mechanism by which this takes place is polymerization of the material when it is exposed to light, and this is known as photo-polymerization. Photopolymers have been shown to be very quick to react when exposed to light, which leads to increase the refractive index change during the illumination process.

Due to the predictions of beam self-focusing, self-trapping and self-written process theoretically, simulations are preformed to describe the growth and interaction of the beam shape distribution in photopolymer media. Thus the complex dynamical interactions take place during the exposure process. These interactions are governed by the input light intensity and pattern, exposure time and the photochemistry. All of these affect the SWW paths, changing the refractive index profiles and trajectories. Results showed that the SWW's allowed for efficient transmission of light and promising results were found from the self-cleanup and self-trapping simulations. From these results, the photopolymer was deemed a viable solution to several optical applications.

ACKNOWLEDGMENTS

Authors would like to acknowledge the supports of Iraqi Ministry of Higher Education and Scientific Research.

REFERENCE

[1] Malallah R., Li H., Kelly D. P., and Sheridan J. T. "A review of hologram storage and self-written waveguides formation in photopolymer media," Polymers 9, 337 (2017).

[2] Malallah R., Cassidy D., Muniraj I., Ryle J. P., Healy J. J., and Sheridan J. T. "Self-written waveguides in photopolymer" Applied Optics, 57 (22), E80-E88, (2018).

[3] Monro T., Moss D., Bazylenko M., Martijn de Sterke C., and Poladian L. "Observation of Self-Trapping of Light in a Self-Written Channel in a Photosensitive Glass," Physical Review Letters, 80(18), 4072-4075, (1998).

[4] Monro T., Poladian L., and de Sterke C. "Analysis of self-written waveguides in photopolymers and photosensitive materials," Physical Review E, 57(1), 1104-1113, (1998).

[5] Li H., Qi Y., Malallah R., and Sheridan J. "Modeling the nonlinear photoabsorptive behavior during self-written waveguide formation in a photopolymer," Journal of the Optical Society of America B, 32(5), 912-922, (2015).

[6] Li H., Dong Y., Xu P., Qi Y., Guo C., and Sheridan J. "Beam self-cleanup by use of self-written waveguide generated by photopolymerization," Optics Letters, 40(13), 2981-2984, (2015).

[7] Li H., Qi Y., Ryle J., and Sheridan J. "Self-written waveguides in a dry acrylamide/polyvinyl alcohol photopolymer material," Applied Optics, 53, 8086-8094, (2014).

[8] Mikami O., Enomoto T., Soeda Y. and Fujikawa C. "Self-Written Waveguide Technology with Light-Curable Resin for Easy Optical Interconnection," Transactions of The Japan Institute of Electronics Packaging, 7(1), 46-51, (2014).

[9] Gleeson M., and Sheridan J. "Nonlocal photopolymerization kinetics including multiple termination mechanisms and dark reactions Part I Modeling," Journal of the Optical Society of America B, 26(9), 1736-1745, (2009).

[10] Shi Y., Tangdiongga E., Koonen A. M. J., Bluschke A., Rietzsch P., Montalvo J., M. De laat M., N. Van den Hoven G., and Huiszoon B. "Plastic-Optical-Fiber-Based-In-Home Optical Networks," IEEE Communications Magazine, June 2014, 186-193, (2014).

[11] Mikami O., Enomoto T., Soeda Y., and Fujikawa C. "Self-Written Waveguide Technology with Light-Curable Resin for Easy Optical Interconnection," Transactions of The Japan Institute of Electronics Packaging, 7(1), 46-51, (2014).
[12] Jradi S., Soppera O., and Lougnot D. "Fabrication of polymer waveguides between two optical fibers using spatially controlled light-induced polymerization," Applied Optics, 47(22), 3987-3993, (2008).
[13] Shoji S., Kawata S., Sukhorukov A., and Kivshar Y. "Self-written waveguides in photopolymerizable resins," Optics Letters, 27(3), 185-187, (2002).
[14] Shoji S., and Kawata S., "Optically-induced growth of fiber patterns into a photopolymerizable resin," Applied Physics Letters 75, 737-739, (1999).
[15] Shoji S. , Kawata S. , Sukhorukov A. A., and Kivshar Y., "Self-written waveguides in photopolymerizable regins," Optics Letters 27, 185-187, (2002).
[16] Monro T. M., Poladian L., and Sterke C. M. de, "Analysis of self-written waveguides in photopolymers and photosensitive materials," Phys. Rev. E 57(1), 1104-1113(1998).
[17] Kewitsch A. S., and Yariv A. "Nonlinear optical properties of photoresists for projection lithography," Appl. Phys. Let. 68(4), 455-457(1996).
[18] Monro T. M., Moss D., Bazylenko M., Martijn C. Sterke de, and Poladian L., "Observation of self-trapping of light in a self-written channel in a photosensitive glass," Phys. Rev. Let. **80**(18), 4072-4075(1998).
[19] Parvathy Rao A., and Venkateswara Rao A., "Luminiscent dye Rhodamine 6G doped monolithic and transparent TEOS silica xerogels and spectral properties,"Science and Technology of Advanced Materials 4, 121-129, (2003).
[20] Sugiarto I. T., Isnaeni, and Putri K. Y., "Analysis of dual peak emission from Rhodamine 6G organic dyes using photoluminescence," Journal of Physics Conference Series 817(1), 012047, (2017).