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# SELF-BENDING OF OPTICAL WAVEGUIDES IN A DRY PHOTOSENSITIVE MEDIUM

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## ABSTRACT

Optical waveguide trajectories formed in an AA/PVA a photopolymer material photosensitive at 532 nm are examined. The transmission of light by this materials is discussed. The bending and arching of the waveguides which occur are investigated. The prediction of our model are shown to agree with the observed of trajectories. The largest index changes taking place at any time during the exposure, i.e. during SWW formation are found at the positions where the largest light intensity is present. Typically, such as maxima exist close to the input face at the location of the *Primary Eye* or at the location of the *Secondary Eyes* deeper with in the material. All photosensitive materials have a maximum saturation value of refractive index change that it is possible to induce, which is also discussed.

**Keywords:** Photopolymer materials; Optical waveguides; Self-trapping; Acrylamide/polyvinyl alcohol.

## 1. INTRODUCTION

As noted different types of self-process photopolymer materials have been studied for use in fabricating self-writing waveguides (SWWs) [1-3]. Such materials have several advantages: Large stable index changes can be obtained during exposure. They typically exhibit reproducible photosensitivity that occurs rapidly (seconds). These characteristics facilitate the investigation of self-writing by producing consistent experimental results and make them suitable for device applications [4-6]. Other advantages include optical quality (relatively low scatter), low cost, good spatial frequency response and in the case of volume gratings high diffraction efficiency [7, 8]. Studies have been performed to examine the use of SWWs in photopolymers to couple, (including repairing by self-healing) between optical fibers, to form micro-tips at the end of optical fibers, to create biologically inspired microstructures and to implement strain sensors [2, 7, 9-11]. All of these applications require high-contrast refractive-index changes and high recording sensitivity, both of which can be provided by photopolymers [7]. It should also to be noted however that many recent studies into self-guided (self-trapped) optical beams have involved beams propagating in slab waveguides or nonlinear bulk media [12].

It has been observed that during exposure the exposing intensity distribution varies spatially and temporally inside the material. The innate tendency of optical beams is to diffract (spread) as they propagate in a homogeneous medium. However, this diffraction can be compensated for in a photopolymer material as the refractive index increases in the locally exposed regions during beam propagation [12]. SWW processes have previously been studied because of their possible use to produce steerable self-induced waveguides. For example, one beam is used to steer other beams in the same (attract) or different (repel) directions. In most cases it is desirable to record permanent SWWs. Ideally a highly photosensitive material which generates stable long-lasting refractive-index changes in response to illumination at a specific wavelength, are needed [13, 14]. In this paper, the optical properties required for a material host SWWs, are discussed.

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## 2. SELF-WRITTEN WAVEGUIDE EVOLUTION

The self-writing process is indirectly monitored by observing the transmitted light distribution emerging from the output of the sample during the exposure. It is also examined by capturing images of the light scattered from the sample side, (along the waveguide path). In our experiments the output beam is initially observed to narrow and become more intense during exposure as the index within the material increases with the formation of the SWW [14, 15].

A 3D model (combining material and electromagnetic effects), is necessary to describe SWW creation as the exposing light beam distribution in $x$ and $y$ propagates through a photopolymer material. As the light propagates in the $z$ direction, the rate (partial differential) equation, that governs the spatial and temporal ground state photosensitizer concentration, can be given by [14, 15]:

$$\frac{\partial[A(x,y,z,t)]}{\partial t}=\frac{\partial}{\partial x}\left\{D_A(x,y,z,t)\frac{\partial[A(x,y,z,t)]}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{D_A(x,y,z,t)\frac{\partial[A(x,y,z,t)]}{\partial y}\right\} \tag{1}$$
$$+\frac{\partial}{\partial z}\left\{D_A(x,y,z,t)\frac{\partial[A(x,y,z,t)]}{\partial z}\right\}+k_r\left[Dye^*(x,y,z,t)\right]-k_a(x,y,z,t)[A(x,y,z,t)].$$

$[A(x,y,z,t)]$ and $[Dye^*(x,y,z,t)]$ (mol cm$^{-3}$) denote the ground and excited states of the photosensitizer respectively. $D_A(x, y, z, t)$ (cm$^3$ mol$^{-1}$ s$^{-1}$) is the diffusion rate of the ground state photosensitizer. The rate of production of the excited state photosensitizer is given by $k_a(x, y, z, t)$ (s$^{-1}$). The effects of dye diffusion $D_A(x, y, z, t)$ are assumed negligible, due to the relatively slow diffusion of the large dye molecules, compared to the other process taking place [16, 17]. It is also assumed that during the exposure the dye recovery is negligible, i.e., $k_r \approx 0$, being much faster than the recovery rate [18, 19].

Initially, the refractive index and absorptivity, inside photosensitive material, are considered to be homogeneous. Assuming linearly polarized monochromatic incident light, the electric field can be described by, $\boldsymbol{E}(x,y,z,t) = E(x,y,z,t)\,\hat{x}\,exp\{i(n_o k_o z-\omega t)\}$, where $E(x, y, z, t)$ is time varying amplitude of the electric field. $n_o$ is the initial average refractive index of the homogenous medium, $\omega = 2\pi c/\lambda$ the light angular frequency and the wave number in free space is $k_o = 2\pi/\lambda$ [20-22], where $\lambda$ is the free space wavelength. In this case, propagation in the material is governed by the paraxial wave equation [23, 24]:

$$\frac{\partial^2 E}{\partial z^2}+2ik_0 n_0\frac{\partial E}{\partial z}+\nabla_\perp{}^2 E+2k_0{}^2 n_0\Delta n E+2k_0{}^2\Delta n^2 E+ik_0 n_0\alpha E=0, \tag{2}$$

where $\nabla_\perp{}^2=\partial^2/\partial x^2+\partial^2/\partial y^2$ denotes the 2-D Laplace operator, and $\Delta n(x,y,z,t)$ is the refractive index change. The index in the material is $n = n_0 + \Delta n$. The absorption parameter is defined by $\alpha = \mu c\sigma/n_0$, where μ and σ are the permeability and conductivity of the medium respectively, and $c$ is the speed of light [2, 11, 25, 26]. A simple approximate phenomenological model has been typically used to describe the refractive index change induced during the self-writing process [2, 25, 26]:

$$\frac{\partial\Delta n(x,y,z,t)}{\partial t}=A_s I^p(x,y,z,t)\left(1-\frac{\Delta n(x,y,z,t)}{\Delta n_s}\right), \tag{3}$$

The constant $\Delta n_s$ denotes the maximum (i.e. saturation) value of the refractive index change in the particular medium being studied. The local light intensity is described by $I(x, y, z, t) = |E(x, y, z, t)|^2$. The number of photons that are involved in the process of photo-polymerization is typically assumed to be $p = 1$ [25]. $A_s$ is a real coefficient that depends on the material used, i.e. the value of $p$, and the wavelength of the exposing light [2, 25, 26].

The experimental system used is illustrated in figure 1, with an actual setup inset. In the experiments, the two fibers are attached to a microscopic slide glass with theirs ends aligned and pointing toward each other, (each fiber produces a Gaussian beam with $P_0 = 0.1$ mW). The photopolymer material is drop cast between the ends of the optical fibers so that it fills the space between them. The process of SWW formation was monitored using a microscopc. Initially the desire was to observe whether the medium exhibited the ability to interconnect the fibers and therefore possibly other integrated optical devices. Silica based photopolymer materials have been used to combine integrated optical devices [27]. The photopolymer material, as used in this work [19], consists of several components: A binder (Polyvinyl Alcohol-PVA), a monomer (Acrylamide-AA), a cross-linker

(Bisacrylamide-BA) and an electron donor (Triethanolamine-TEA). The dye used here is Eosin-Yellowish (EY), which is photo-sensitive to green light at wavelength λ = 532 nm, and acts to initiate the polymerization process [17, 28].

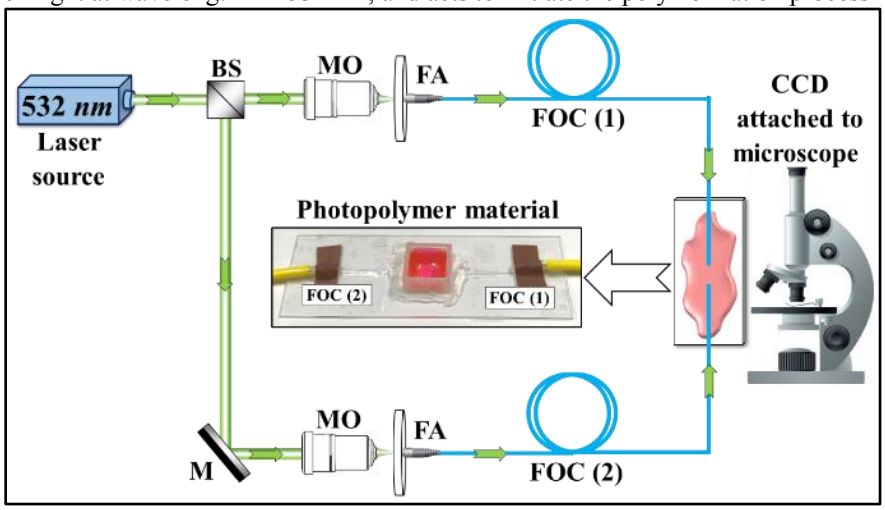


Figure 1. Optical setup for observing self-written waveguide formating through photopolymer material in order to observe dual single-mode fiber optic beams exposure.

A Gaussian beam at this wavelength emerges from the SM fiber inside the photosensitive material, see figure 1. The light propagates into the photosensitive material. The resulting refractive index changes generated due to polymerization make the SWW index higher than that of the surrounding material. Self-focusing will take place [29, 30]. Stable SWWs are formed if the exposing wavelength induces long lasting refractive index changes.

## 3. EXPERIMENTAL RESULTS

In order to predict waveguide formation and therefore be able to optimize fabrication, the evolution of the refractive index distribution needs to be experimentally monitored. However, during the self-writing experiments, there is no simple method to directly measure the refractive index distribution induced in *x*, *y* and *z* with time without destroying the sample. Therefore, we indirectly observe waveguide formation by measuring the transmitted and scattered light.

In all cases the FOCs are positioned with microscopic accuracy. The self-writing process is indirectly monitored by observing the light emerging from the sides of the material sample during exposure. As the SWW forms, this imaged light narrows and become more intense as the index within the material increases in response to the waveguide formation. Numerical simulations of the self-writing process are performed and compared to the observed results.

The two FOCs (counter-FOCs) are placed onto a glass plate, held in place by tapes and a solution of photopolymer drop cast on to them under dark room conditions. The photopolymer solution covering the fibers was then left to dry, for 24 hours. The two optical fibers are positioned separated by gaps of 21.28 µm, in figure 2(a), and by 63.47 µm, in figure 2(b). All the measurement values listed here (i.e. distances and angles) are calculated from image data using the ImageJ software package [31]. Two beams then expose the AA/PVA simultaneously from the optical fibers. The beam counter-propagating (in opposite directions) directly towards the opposite fiber. The resulting passive connection should operate equally well for beams travelling in either direction (reciprocity). The exposure process was continued for 1600 s (each fiber has $P_0$ = 0.1 mW) allowing the SWW process to complete (to saturation). i.e. after this time no further evolution of the channel was observed.

The corresponding simulation results, are presented in figure 2(a2) and figure 2(b2). Good qualitative agreement with the experimental results is observed. This technique of connecting two optical fibers is potentially very advantageous as light from the actual fibers "automatically" generates the optical waveguide channel. In the simulation, the movement of the symmetrically located eyes (due to both the left and right illuminations) can be seen along the propagation axis. As noted experiments were performed with fibers placed, (a) 21.28 µm apart, and (b) 63.47 µm apart. This enabled us to examine the effects of the separation distance on the process by comparing the results, see figure 2(a2) and figure 2(b2). In both cases simultaneous coherent exposures clearly produced waveguides. We also note that our model produces qualitatively consistent predictions. The model predicts the increase in optical power along the waveguide as the two exposing beams meet and then cross. This can be seen in figure 2(b2) where the optical power level is identified by the color. Yellow indicates the highest intensity value which occurs in the middle of the gap. In figure 2(a2) an increase in optical power can also be seen as the two beams cross.

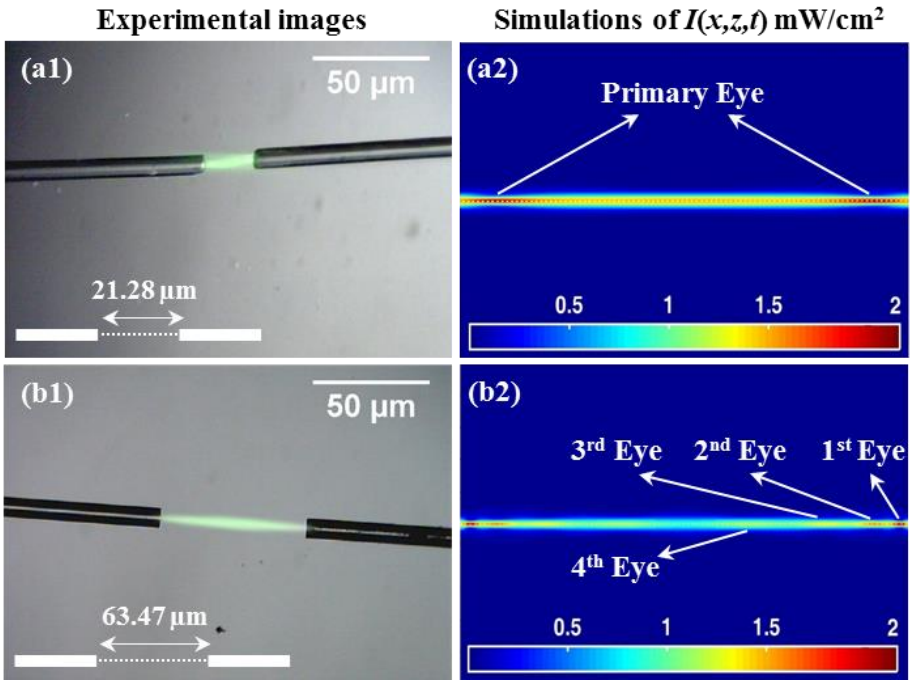


Figure 2. SWW for coupling using counter-propagation beams from single mode optical fibers. $t_{exp}$ = 1600 s of $\lambda$= 532 nm and $P_0$= 0.1 mW (i.e. each fiber has $P_0$ = 0.1 mW). FOCs are aligned and separated by: (a) 21.28 µm, and (b) 63.47 µm.

In figure 2(a2) the two symmetrically located *Primary Eyes*, are shown appearing in the region in front of both optical fibers. In figure 2(b2) the *Primary Eye* (1st) and a series of higher order eyes (2nd, 3rd and 4th) can be identified positioned symmetrically along the SWW [32]. This indicates that the two counter-propagating beams are present and are being confined. The *Secondary Eyes* can be seen in figure 2(a2), but due to the short distance between the two fibers the intensity is more uniform across the gap. However as the gap between the two fibers increases, see figure 2(b2) the *Secondary Eyes* can be more clearly distinguish from one another as they are more widely separated. Using the model it is possible to predict the maximum percentage normalised transmission, (the value for propagation to the mid-point). If $I_{in(1)}$ is the input intensity from the right and $I_{in(2)}$ is the corresponding intensity from the left. Then dividing the predicted central intensity, $I_{mid}$, by the sum of the two input beams ($I_{in(1)} = I_{in(2)}$) gives the fraction of light from each propagating that distance, i.e. $\{I_{mid}/(I_{in(1)} + I_{in(2)})\} \times 100\%$= 41.42% at $z$=10.64 µm, see figure 2(a2), and 33.73% at $z$=31.73 µm, see figure 2(b2).

In figure 3 we examine cases in which the input optical fibers were not aligned. In this way the ability of the photopolymer material to act so as to help direct the waveguide formation trajectories to produce a waveguide capable of connecting mis-oriented optical fiber cables is demonstrated.

In figure 3(a) two optical fibers are examined separated by ~36.75 μm with a lateral displacement (or shafting) of ~5.34 μm. In the second case the optical fiber cables are separated by a distance ~36.32 μm, figure 3(b), however in this case they were not displaced but angled with respect to one another, having an angular difference of ~7.76°. Once again two identical light beams are simultaneously transmitted along the optical fibers and then propagate inside the drop cast photopolymer material layer. The fibers are oriented so that the beams do not exactly cross propagate. However theoretically they are predicted to produce a self-written waveguide, see figure 3. Clearly the two beams do interacted with each other during the process of SWW formation. The result is single waveguide rather than two separate waveguides. In effect the two waveguides converge, i.e. the trajectories bend toward one another. Therefore, a method to connect two separated and misaligned optical fibers has been demonstrated.

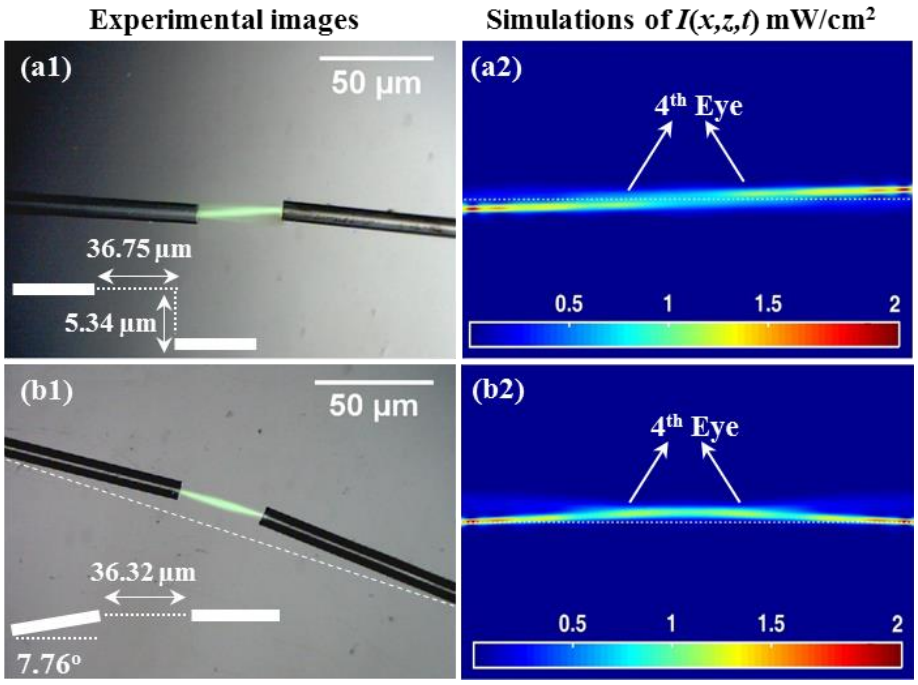


Figure 3. SWW for coupling single mode optical fibers, at $t_{exp}$ = 1600 s of $\lambda$= 532 nm and $P_0$= 0.1 mW (i.e. each fiber has $P_0$ = 0.1 mW). Experiments and simulayions: (a) Separated by 36.75 μm with shafting 5.34 μm, and (b) separated by 36.32 μm with angle 7.76°.

The experimental results are represented, in figures 3(a1) and (b1), and the corresponding predictions of our model, are shown in figures 3(a2) and (b2). There is good qualitative agreement. The model predicts the emergence of the *Primary Eye* and the *Secondary Eyes*. The symmetric appearance of eyes in both cases indicates that the two beams are involved in creating the connecting waveguides. The slight bending of SWW trajectories, which can be seen in both figures 3(a) and (b), indicates the path followed by the light within the waveguides formed. Clearly a connection is formed between the two optical fiber cables. Difficult opto-mechanical alignment which is currently needed for conventional fusion splicing or mechanical-splicing techniques, becomes less critical. Numerically it is predicted that the value of maximum percentage normalised transmission (in the mid distance between two beams), i.e. $\{I_{mid}/(I_{in(1)} + I_{in(2)})\} \times 100\%$, is calculated to be 22.63% at $z$=18.37 μm, see figure 3(a2), and 28.42% at $z$=18.16 μm, see figure 3(b2).

## 4. CONCLUSION

The possibilities created by the ability to fabricate self-written waveguides in photopolymer material has been further investigated. The photopolymer material used in this paper (sensitized at 532nm) is manufactured in our laboratory to strict guidelines. In this paper the formation of SWW in thin drop cast AA/PVA layers, is demonstrated. It is shown that the bending of the light trajectories during self-written waveguide formation can be used to form a wide range of potential useful photonic circuits. Experiments and simulations have been performed so as to understand self-bending phenomenon for different input beam (exposure) arrangements.

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