

SELF-TRAPPING OF OPTICAL BEAMS IN A SELF-WRITTEN CHANNEL IN A SOLID BULK PHOTOPOLYMER MATERIAL

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ABSTRACT

We demonstrate theoretically and experimentally that the light can be self-focused and self-trapped in a self-written optical waveguide in a bulk acrylamide/polyvinyl alcohol (AA/PVA) solid photopolymer material volume. The manufacture method, i.e., how to prepare the AA/PVA photopolymer material is detailed. In our experimental observation the refractive index changes induced are permanent. The resulting optical waveguide channel has good physical stability and can be integrated with optoelectronic devices as part of integrated optical systems. The theoretical model developed predicts the formation/evolution of the observed self-written waveguides inside the bulk material. The model involves appropriately discretizing and then numerically solving the paraxial wave equation in Fourier space and the material equation in time space.

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

1. INTRODUCTION

When a beam of light alters the refractive index distribution of the medium it travels through, the diffraction effects are exactly balanced by the focusing effects. This nonlinear optical phenomenon has been well studied defined as self-trapping¹⁻⁴. In the last few years, different types of photopolymer materials have been used extensively as self-trapping media⁵⁻⁹. Photopolymer materials have many significant advantages for self-trapping as: (1) large refractive index change, such as Kewitsch et. al., reported that the refractive index changes are larger than ~ 0.04 in a liquid photopolymer⁵; (2) rapid response time (seconds), for photosensitive glass it generally needs several hours⁴; (3) low average intensities, for the photo-polymerization process it is a function of absorbed energy rather than of intensity as Kerr index change. Polymers based on acrylamide/polyvinyl alcohol (AA/PVA) have received considerable attention as effective holographic storage materials¹⁰ and they were also proved suitable for the self-trapping applications⁸. Jisha et. al., were the first to demonstrate that self-written waveguide can form in a liquid AA/PVA material⁸. In any attempt to optimize the potential of AA/PVA material for self-trapping, a more physical stable and solid material state is necessary.

In this paper, we demonstrate experimentally that optical beams are self-trapped in a channel in a bulk AA/PVA material which is prepared as solid state. During this process, the channel is permanent and acts as a waveguide for any wavelength light. A theoretical model is also used to describe the self-trapping process and the numerical simulations allow us to predict the light intensity variation and the material refractive index evolution.

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2. THEORY

Considering a Gaussian beam propagating in free space, the physical properties are as follows, wavelength is λ , the beam width is a , and the maximum light intensity is I_0 . The waist of this beam is assumed to illuminate the bulk photopolymer material from the left at $z = 0$. Then the self-written evolution is theoretically predicted by combining the physical paraxial wave model and photo-polymerization material model.

The paraxial wave equation for the optical electric field is used for describing the light propagation¹¹ in the material,

$$ik_0 n_0 \frac{\partial E}{\partial z} + \frac{1}{2} \nabla^2 E + k_0^2 n_0 \Delta n E + \frac{i}{2} k_0 n_0 \alpha E = 0 \quad (1)$$

where k_0 is the free space wave number, n_0 is the initial refractive index, Δn is the change in the refractive index, α is the attenuation coefficient, and E is the electric field envelope amplitude. For our bulk material the Laplace operator is $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$.

The refractive index evolution during the self-writing process can be approximated using the phenomenological model^{5,12,13}:

$$\frac{\partial E}{\partial t} = AI^p \left(1 - \frac{\Delta n}{\Delta n_s}\right) \quad (2)$$

where t is the time, Δn_s is the fixed saturation value of the refractive index change, I is the local light intensity, and the coefficient A depends on the material properties. For photopolymer materials, $p = 1$, and there has a short delayed time τ due to the photo-polymerization process for calculating the electric field^{5,12}. It is worth emphasizing that Eq. (2) is used as the material model because it is simple and so can be combined with the paraxial wave equation easily and the give useful analytical results. Typically the light propagation occurs in nanoseconds whereas the polymerization takes milliseconds or seconds. Therefore we can use the Split-step Fourier Method¹⁴ to solve Eq. (1) and then combine this with regular updates of the refractive index distribution using Eq. (2).

From Eqs. (1) and (2), we note that the typical time and length scales involved depend on the intensity and the spatial extent of the input Gaussian profile. In order to simplify the calculation, we used dimensionless transverse coordinates, and normalize the time and propagation distance. In total five of the physical quantities, i.e., x , y , z , t , and E (intensity) are normalized. The new quantities are defined as follows¹³, $X = x/a$, $Y = y/a$, $Z = z/(k_0 n_0 a^2)$, $T = k_0^2 a^2 n_0 A I_0^p t$, and the normalized light intensity is $I_N = I/I_0$, where $I_0 = 1 \text{ mW cm}^{-2}$. The initial parameter values used in the simulations are: $\lambda = 532 \text{ nm}$, $\alpha = 0.2$, $n_0 = 1.493$, $\Delta n_s = 2 \times 10^{-3}$, and $a = 20 \text{ }\mu\text{m}$. The measured material thickness is $d = 8.5 \text{ mm}$, and we set $A = 1.2 \times 10^{-3}$. The numerical simulations in this letter have been carried out using the MATLAB 7.0.1. The total number of points used in the Split-step Fourier Method (for X and Y) is $N = N_X = N_Y = 1000$. The normalized step lengths in X and Y are $\Delta X = \Delta Y = W/N$ where normalized window size (in X and Y) is $W = W_X = W_Y = 16$. The number of steps in material normalized depth (Z -axis) is $N_Z = 100$ and the step length is $\Delta Z = d/(N_Z k_0 n_0 a^2)$. The number of time steps used was $N_T = 200$ for a chosen normalized step duration of $\Delta T = 0.05$.

Fig. 1(a) illustrates the theoretical simulations of the normalized light intensity distributing in photopolymer material transverse surface. Before self-focusing the light diffracts freely though the uniform photopolymer material assuming no index changes have yet been induced. Note that in our numerical simulations the lengths in x - z axis and the time Δt step are dimensionless and the light intensity is normalized. The highest light intensity is found at the input face reducing the most rapid index changes in this region. After self-focusing the light diffraction is exactly compensated by the refractive index change and a self-written waveguide is formatted in material. It is worth noting that the light peak intensity starts to move along the propagation axis and the region of relatively higher intensity is referred to as “*primary eye*”^[13]. In Fig. 1(b) the optical beam profiles at the output edge ($Z = 100$) and the initial input Gaussian beam at $z = 0$ are showed as the normalized distribution at $T = 0$ and $175\Delta T$, where the ΔT is a parameter chosen as the time step. It is clear that the output beam (solid line) becomes dramatically narrower and more intense as the self-writing processes and a channel forms. When $T = 175\Delta T$, the dashed line denoting input beam distribution almost fit the solid line denoting output beam distribution. Due to the evolving index change counteracts the diffraction of the input beam, beam intensities distributing at $Z = 0$ and 100 are the same profile, meaning that self-trapping occurs.

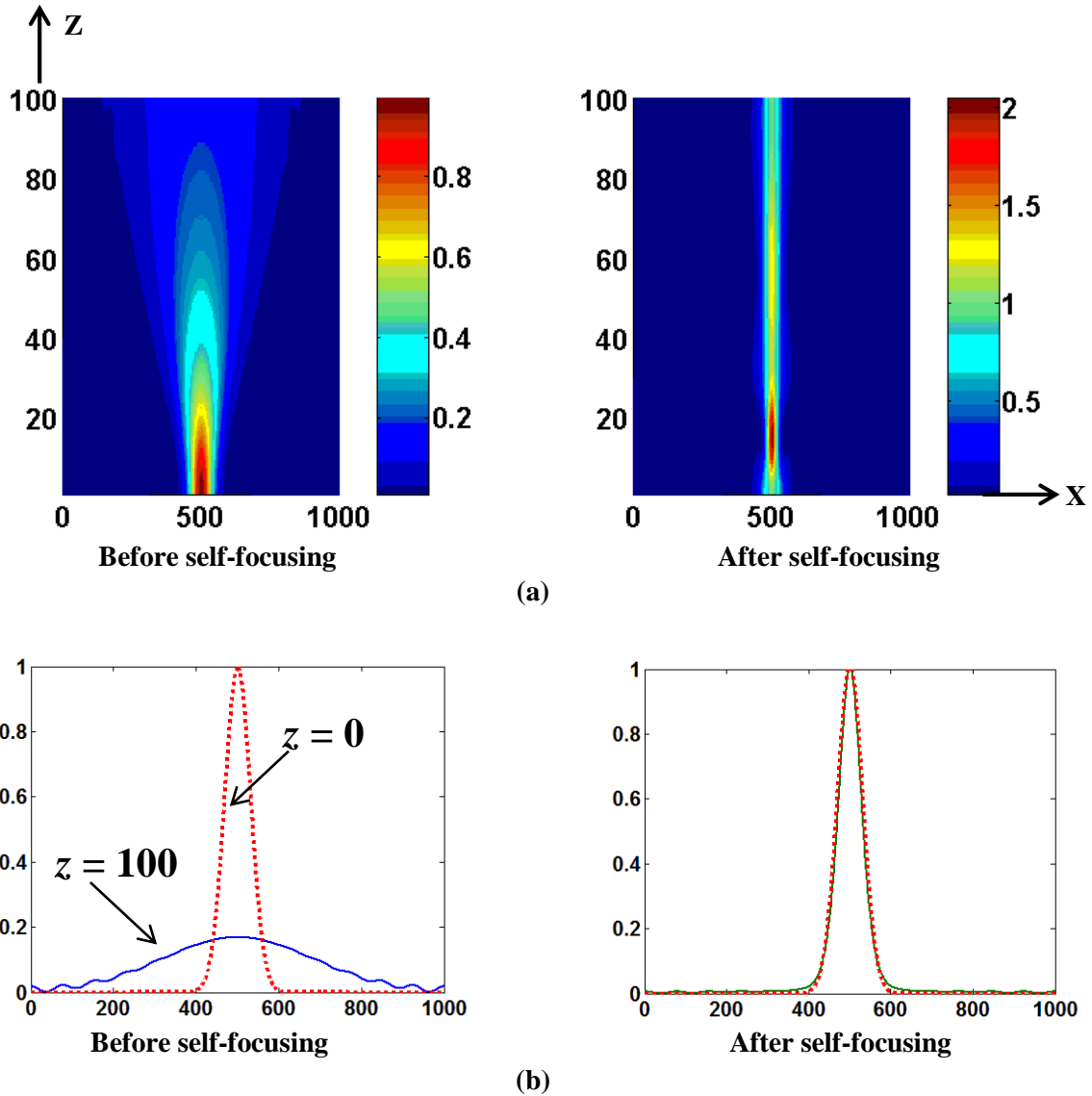


Fig. 1. Numerical simulations of self-trapping in photopolymer before and after photo-polymerization, for (a) normalized light intensity distribution in X-Z axis; and (b) comparisons of normalized light intensity at $Z = 0$ (dashed line) and $Z = 100$ (solid line) along x -axis.

The corresponding predicted refractive index change Δn in the material is shown in Fig. 2. At each time step the predicted index is used to update the resulting light intensity distribution using Eq. (2). Fig. 2(a)–2(d) clearly indicates that an optical waveguide is being formed in the material with time. As noted this index change becomes sufficient to overcome the diffraction effects. However the index changes induced by the initial diffraction pattern are still present in the material in Fig. 2(d).

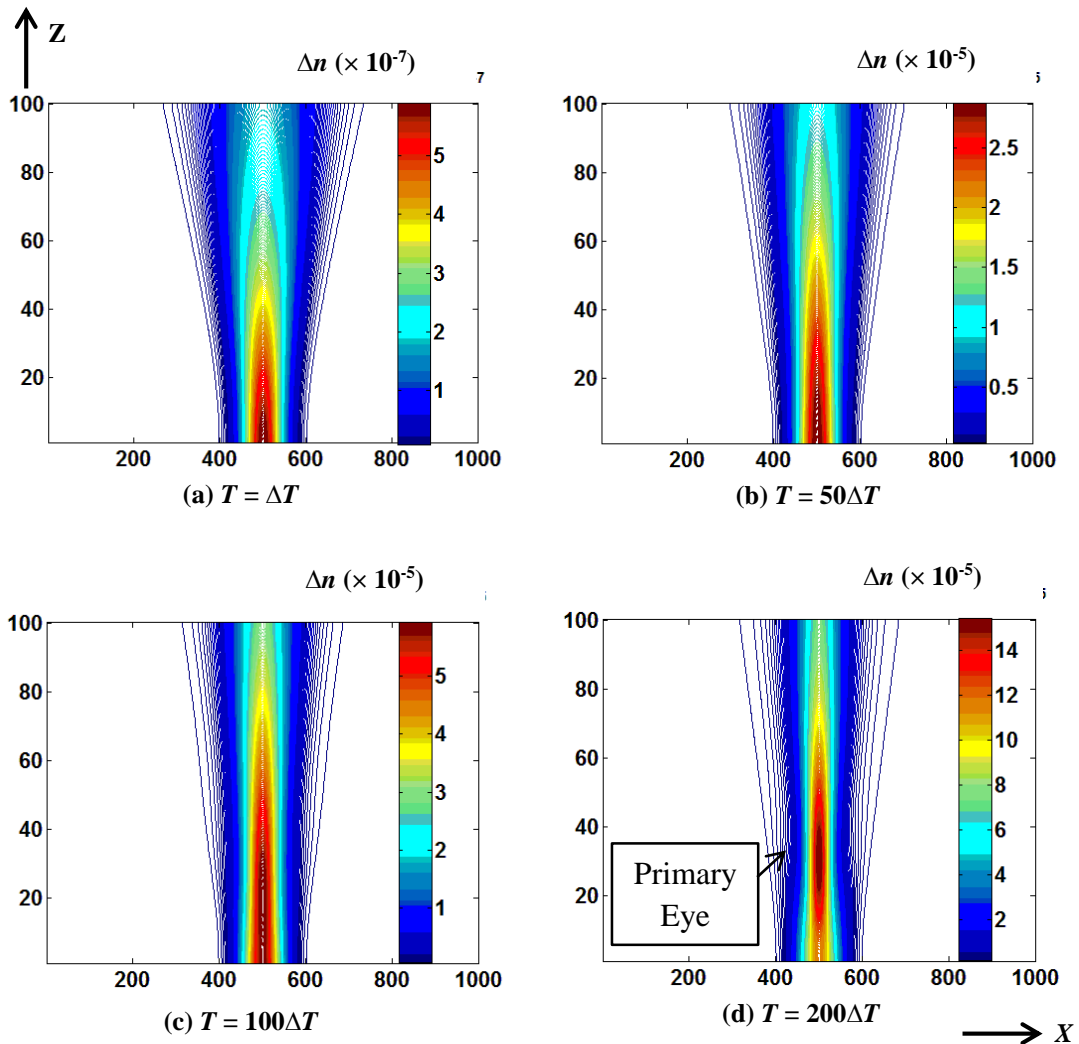


Fig. 2. (color online) Contour plot of refractive index change Δn distribution in X - Z axis within the material at four time steps: (a) $T = \Delta T$; (b) $T = 50\Delta T$; (c) $T = 100\Delta T$; and (d) $T = 200\Delta T$.

3. MATERIAL PREPARATION

Based on above analysis, a self-writing optical channel can be formed theoretically upon photo polymerization. In order to make the AA/PVA photopolymer material easier to integrate with existing devices such as optical fibres, it is necessary to prepare the material as solid using the heating and drying processing techniques.

Firstly the standard AA/PVA photopolymer material solution was prepared as in previous papers^{8,10}. Then heat the standard solution (hold the temperature less than 100 C°) to allow the water to evaporate using a conventional magnetic stirrer, under red light and in safe laboratory conditions. When most percentage of the water content has evaporated (the required heating period is around 6 hours per 100 mL), the resulting hot and colloidal material was removed to the cuvettes (12.5 × 12.5 × 4.5 mm). Following that put these cuvettes in vacuum atmosphere immediately. The purposes of doing so are as follows (i) eliminating the contained air bubbles produced by the magnetic stirrer and (ii) cooling the hot material using the low temperature produced by low air pressure. The material cuvettes were left in the dark for a long period (normally several days) to allow shaping as solid state. Finally the solid bulk AA/PVA photopolymer material applying for self-writing experiments was ready for exposure.

4. EXPERIMENTAL RESULTS

The initial concentrations of the components in the resulting samples are: Phloxine B, which is sensitive at a $\lambda = 532$ nm, $[A_0] = 1.22 \times 10^{-7}$ mol cm $^{-3}$; monomer (Acrylamide), $[U_0] = 2.83 \times 10^{-3}$ mol cm $^{-3}$; electron donor (Triethanolamine), $[ED_0] = 3.18 \times 10^{-3}$ mol cm $^{-3}$. All the experiments were performed using the experimental setup shown in Fig. 3.

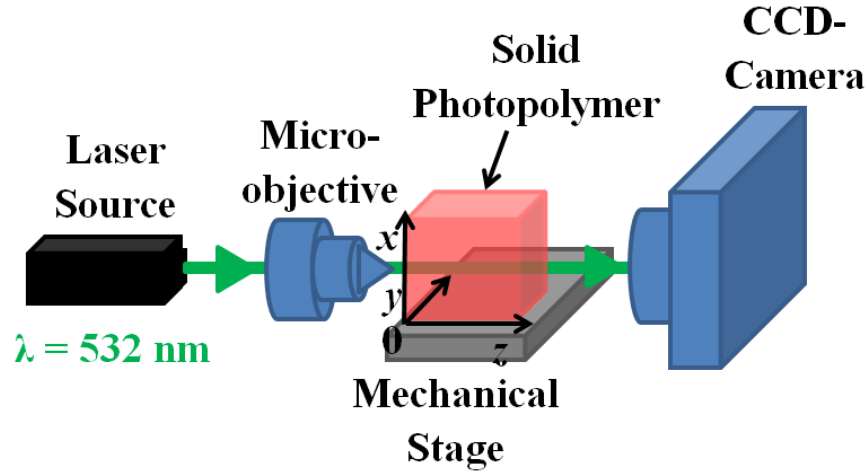


Fig. 3. (color online) Schematic diagram of the setup used to monitor self-focusing and self-trapping of optical beams.

In Fig. 4, the experimental images show that the output beam narrows with time. During the early stage of the exposure, the light is scatter as it passes through the material and the resulting output light intensity pattern is shown in Fig. 4(a) when $t = 8$ s. The light propagating through the material changes the refractive index, due to the photo-polymerization along the light path, and the optical waveguide is self-formed. As can be observed from Fig. 4(b) and 4(c), i.e., when $t = 15$ s and 20 s, the self-focusing effect gradually overcomes the light diffraction effect and the output beam continues to narrow (focus). Finally the diffraction of the light is balanced by the self-focusing effect and self-trapping occurs. In Fig. 4(d) we note that a light pattern having almost no divergence is obtained. Following removal of the writing beam the optical waveguide formed remains stably present, which is different to what is observed in the liquid photopolymer cases^{5,8,12}.

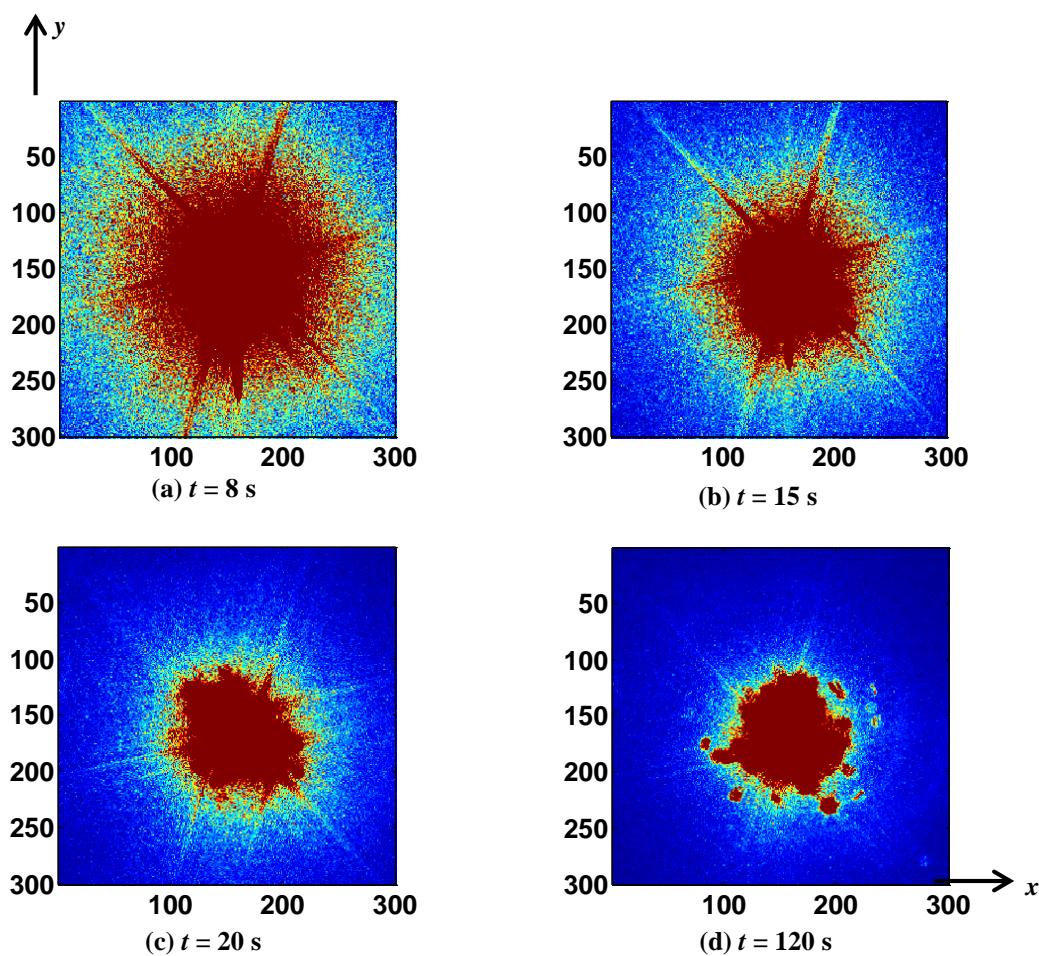


Fig. 4. (color online) Experimental patterns in output surface as the beam propagates through the bulk material after (a) 8 s, (b) 15 s, (c) 20 s, and (d) 120 s; with the CCD-camera pixels $\Delta x = \Delta y = 7.4 \mu\text{m}$.

5. CONCLUSION

In summary, we have predicted theoretically and demonstrated experimentally that optical beams can be self-focused and self-trapped in a bulk AA/PVA photopolymer material due to photo-polymerization. The results achieved, and the stability of the self-written optical waveguide produced, support potential applications in the areas of optical fibre and micro-fabrications³⁻⁶.

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