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Observation of light-induced refractive index reduction in bulk glass and application to the formation of complex waveguides

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Abstract: We show that illuminating bulk Nd-doped Bk7 glass at 488 nm induces a decrease in refractive index of order 10^{-4}. Using this index change we experimentally demonstrate that it is possible to use self-writing to enhance the divergence of a Gaussian beam. Here simulations with a Laguerre-Gaussian 'donut' writing beam show that a depressed-index 'pipe' structure can be created. We demonstrate that these complex waveguide structures can subsequently be used to guide light of different wavelengths.

OCIS codes: (190.5940) self-action effects, (230.7370) waveguides

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1 Introduction

When a beam is focused onto the edge of a photosensitive material, the beam diffracts and this light distribution begins to change the refractive index, with the greatest changes occurring where the intensity is highest. For the simplest case of a Gaussian writing beam the largest changes occur at the input face and along the propagation axis.

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If the index of the material increases in response to illumination, this area of higher index reduces the diffraction of the incoming beam and over time a *self-written* channel waveguide can evolve [1, 2, 3]. These waveguides offer a number of advantages in comparison with other methods of fabricating waveguides such as epitaxial growth, diffusion methods and direct writing. It is a one-step process that requires no translation when creating buried or surface waveguides. Also, these waveguides evolve dynamically, and they experience minimal radiation losses due to the absence of sharp bends.

Previously, increases in index have been used to self-write channel waveguides in bulk photopolymers [4, 5] and in glass in the planar geometry [2]. Recently we showed the first self-writing effects in bulk chalcogenide glass [3]. Self-writing has also been investigated in thin film photopolymers [6] where a decrease in index is induced. Numerical simulations of self-writing have mainly concentrated on the planar geometry, although it has been shown that channel waveguides can form in a bulk material using a Gaussian writing beam [3, 7]. The bulk geometry offers more flexibility to form complex three-dimensional waveguides, however no investigations into writing more complicated structures have been conducted to date.

2 Experiment

The material used for self-writing must be capable of a significant change in refractive index in response to light in order to create a waveguide. The material used in the experiments presented here is bulk Bk7 borosilicate glass uniformly doped with neodymium (1.5-wt% Nd_2O_3, n_0=1.5 and absorption band edge=400 nm [8]). A tunable argon-ion laser is used, giving a single mode cw Gaussian output beam, and experiments are carried out using three different wavelengths, 457, 488 and 514 nm. The beam is focused down to a waist on the input edge of the sample and the output light is imaged onto a beam profiler, and in this way the beam shape at the output face of the sample is monitored over time. Fig. 1 shows that the beam emerging from the 12 mm long sample evolves during a typical experiment at 488 nm when a writing beam with a FWHM of 9μm and a power of 92 mW is used. The blue and black lines in the figure show the beam in two orthogonal directions.

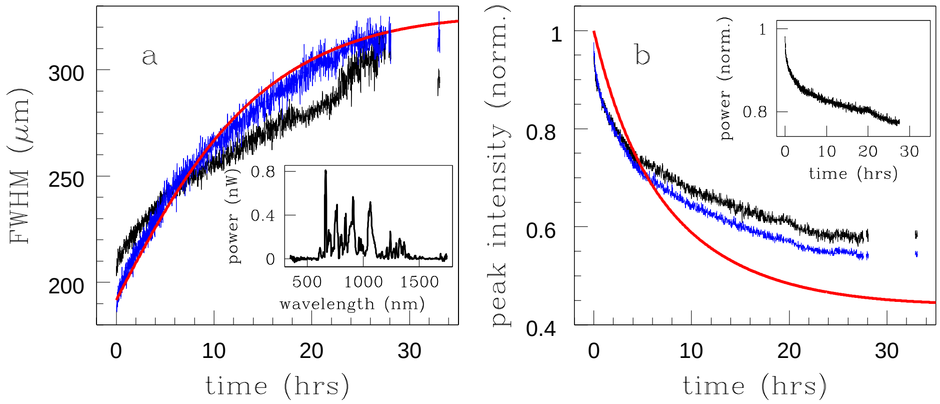

Fig. 1. Observed evolution in FWHM and peak intensity at the output face, λ=488 nm and writing beam FWHM=9μm. The power through the sample and the observed luminescence are shown in the right and left insets respectively. The red line shows corresponding simulation results.

In a typical experiment, if the refractive index of the glass increases in response to light, we would expect the beam at the output edge of the sample to narrow and become more intense as the light begins to be guided by the index change it induces. However, it can be seen that the FWHM increases and the peak intensity decreases, and so we infer that the refractive index decreases in response to light in this material. After the initial exposure the induced index change is monitored, and Fig. 1 shows that the change is long lasting, and indeed we find that the structure does not decay significantly over a few days. Experiments have also been carried out using a wider writing beam and we observe the same magnitude of change although, as expected, this took a longer time. Note that significant changes have been obtained at both 488 and 457 nm and that the greatest expansion was induced at 488 nm.

A strong red luminescence was observed during experiments at both 457 and 488 nm (inset Fig. 1a). This luminescence is faint when the sample is illuminated at 514 nm and increases in intensity with decreasing exposure wavelength. Similar fluorescence has been observed previously in neodymium-doped silica fibres [10], where fluorescence was excited using 780 nm resulting in emission bands centred at 940, 1088, and 1370 nm. This corresponds well with the peaks at longer wavelengths observed in our experiments, and in addition we observe strong peaks at 660 and 760 nm.

During the evolution shown in Fig. 1 the beam expanded in width by a factor of 1.7. This diffraction is larger than the equivalent beam diffracting in free space, and to obtain such a large diffraction in a uniform material would require an index of 0.85, which is clearly impossible. This implies that a structure, such as the one written here, is needed to achieve this enhanced divergence. Note that the structure acts like a diverging gradient-index (GRIN) lens [9], which are traditionally fabricated using ion-exchange techniques. These enhanced divergence self-written structures could be useful in devices where a large low loss expansion of light over a short distance is required.

When 1047 nm light is launched into the self-written structure, the diffraction of the beam increases by a factor of 1.2 relative to free diffraction. Although the inset in Fig. 1b shows the power typically falls during the self-written exposure at the writing wavelength, at this longer wavelength the light propagation losses are minimal.

3 The model

In order to get a deeper understanding for the self-writing process, numerical simulations are carried out. Here two differential equations [1] are used where the paraxial wave equation describes the propagation of light (in the direction z) and the photosensitivity equation describes the change in refractive index (Δn) in response to light (Table 1). Previously a simple model has been shown to agree well with experiments in germanosilicate [2] and chalcogenide glass [3], and in photopolymers [4]. Here we modify this model to describe a decrease in index in response to light. The simplest choice of writing beam is a Gaussian, as shown in the table.

Table 1. Equations and appropriate parameters used when modelling self-writing.

Paraxial wave equation $ik_0 n_0 \frac{\partial E}{\partial z} + \frac{1}{2}\nabla^2 E + {k_0}^2 n_0 \Delta n E = 0$	$E = E(x, y, z, t)$, field envelope amplitude $k_0 = 2\pi/\lambda$, n_0, initial refractive index
Photosensitivity equation $\frac{\partial \Delta n}{\partial T} = -I^p \left(1 + \frac{\Delta n}{\lvert \Delta n_s \rvert}\right)$	$I = EE^*$, intensity, T, normalized time $p = p$ -photon process (1 or 2) Δn_s, saturation index change
Gaussian input beam $E(x, y, 0, t) = E_0\, exp\left(-\frac{x^2+y^2}{a^2}\right)$	FWHM $= a\sqrt{2 \ln 2}$

The photosensitivity equation is a phenomenological model that incorporates a saturation index change, Δn_s, and $T = A_p I^p t$ where A_p is a material coefficient that depends on p and λ, and t is the time in seconds. In solving these equations, the light propagation, which occurs in nanoseconds, is separated from the refractive index evolution, which takes minutes. A split step beam propagation model is used, and since this approach for the bulk geometry involves 2D Fast Fourier Transforms, these calculations are computationally intensive and a typical calculation requires 1-2 Gbytes computer memory and takes between days and weeks to run on a 1GHz processor.

In fitting numerical simulations to experimental results in section 2, the saturation value for the refractive index, Δn_s, can be chosen and the time, T, can be scaled. In Fig. 1 the results from the simulation (scaled) are shown together with the experimental results. The best agreement for the FWHM evolution is obtained with a one-photon process (p=1) and the right magnitude of change occurs using Δn_s=7×10^{-5}. In order to also obtain good agreement for the peak intensity, a more complete model for the index change is needed. For example, the effects of absorption need to be included to account for the observed luminescence and induced losses, and in previous work a variable exposure-dependent absorption [3, 7] has been shown to improve the agreement.

4 Self-writing a light guide

So far we have shown that using a simple Gaussian input beam, the diffraction of light increases during the self-writing process in bulk Nd-doped Bk7 glass, and so no light-confining structure is created using this simple beam shape. Previous theoretical work shows that the shape of the resulting waveguide can be tailored via the choice of writing beam [7]. Therefore using a carefully chosen writing beam, it should be possible to self-write channels and more complicated structures that could guide light in our material. For example, consider a normalized m^{th} order Laguerre-Gaussian 'donut' beam [11] incident on the input face (z=0):

$$E(x,y,0,t) = \sqrt{\frac{1}{\pi \mathrm{m}!}}\left(\frac{\sqrt{2}}{a}\right)^{\mathrm{m}+1} \exp\left(i\mathrm{m}\tan^{-1}\frac{y}{x}\right)\left(x^2+y^2\right)^{\frac{\mathrm{m}}{2}} \exp\left(-\frac{x^2+y^2}{a^2}\right). \quad (1)$$

The free diffraction for the first order donut beam, i.e. m=1, is shown in Fig. 2a. Fig. 2b shows the cross sections (at z=0) for beams of different orders.

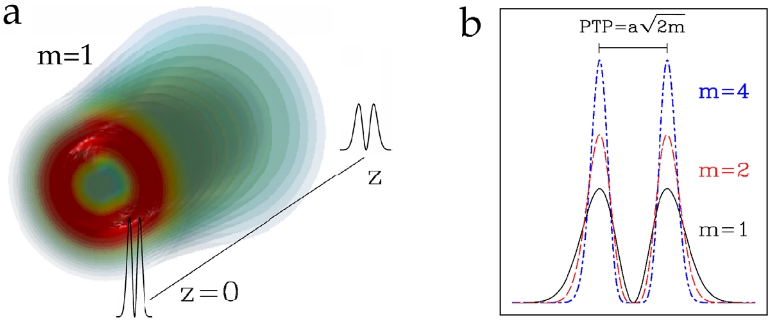

Fig. 2. (a) Diffraction of a m=1 donut beam over 1.5 Rayleigh ranges (transverse directions are expanded by a factor of 10). (b) Cross sections of donut beams of different orders.

If a material is illuminated with this donut shaped beam, the sample is exposed to a ring of high intensity with a zero in its centre. As this beam diffracts through the sample, and hence modifies the refractive index, it might be expected that a ring shaped 'pipe'

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structure of lower refractive index will be induced, surrounding an area of the initial (relatively higher) index. Such a structure could subsequently act to guide light.

In order to investigate this further, numerical simulations are carried out using the writing beam in Eq. 1 with m=1. The initial refractive index is taken to be 1.5 corresponding to Nd-doped Bk7 and the saturation value for the refractive index is 7×10^{-5}, the induced index change obtained in the experiments presented earlier. Note that in practice a donut shaped beam can be produced using several different techniques [12]. One way would be to use a computer generated hologram, which can convert part of a Gaussian laser beam into the desired beam shape.

Fig. 3 shows the evolution of the self-written structure within the material when a peak-to-peak value (PTP) of 30μm is used. The length of the sample (4.8 mm) corresponds to 1.5 Rayleigh ranges for this beam. Fig. 3a shows cross sections through the induced index distribution at the input (solid red lines) and output (dashed blue lines) faces of the material. Here T is the normalized time from section 3. Note that at time=135× 10^{-14} the maximum index change has penetrated to the output edge of the sample, resulting in uniform depth 'walls' around the unexposed region. In Fig. 3b, contour plots along the transverse direction are shown at two different times in the evolution. It can be seen that the outer regions of the structure spread as the diffraction of the beam increases but also, and more importantly, how the structure grows inwards towards the centre and thereby creates a uniform channel waveguide of unexposed material. Using PTP=20μm, a similar but narrower structure than the one in Fig. 3 is created.

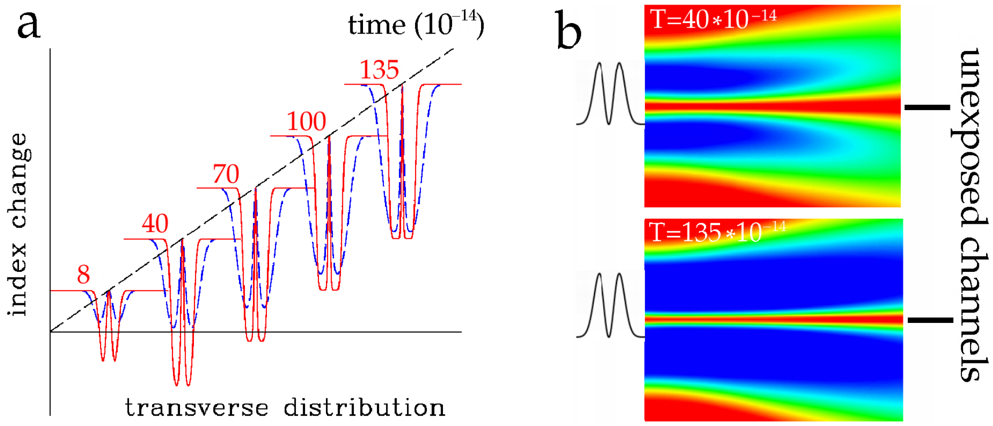

Fig. 3. Refractive index distribution during waveguide evolution. (a) Cross sections at sample input (red lines) and output (blue dashed lines). (b) Contour plots along one transverse direction (again the transverse direction is expanded).

4.1 *Guiding light through the depressed-index pipe structure*

Investigations into the propagation characteristics of the depressed-index pipe structures have been conducted by sending a Gaussian beam through the self-written structure. Structures written using different PTP and Gaussian beams with different wavelengths and beam widths are both considered. We observe that Nd-doped Bk7 is not sensitive to light around 1 and 1.5 μm, hence simulations were carried out at these wavelengths.

Fig. 4 shows light at 1047 nm (white contour lines) as it propagates through two different structures self-written using PTPs of 30 and 20μm. Note that the beam in the outer (blue) regions diffracts, but that the central portion of the beam becomes guided by the pipe. A range of beam sizes were launched into the structures and the best guidance was obtained using a FWHM of 10μm at the input face, and these are the results presented here. The beam diffracts over a distance equivalent to 15 Rayleigh ranges in free space. The insets show cross-sections of the beams emerging from the pipe (red beams) together with a beam that has travelled by free diffraction over the same distance (blue beams). It can be seen that better guidance is obtained for the central part of the beam using the 20μm structure, however the areas of lower index surrounding the channel are narrower. Using a Gaussian beam at 1550 nm results in similar guidance properties. Calculating the waveguide parameter [11] for the different structures (and assuming a step-index profile), it was found that both waveguides shown in Fig. 4 are single moded at 1047 and 1550 nm.

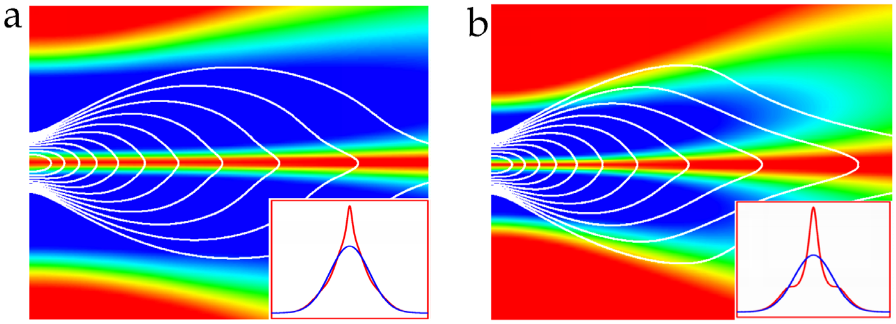

Fig. 4. A 10μm Gaussian beam travelling (white contour lines) within the pipe structures written using PTP=30μm (a) and PTP=20μm (b). Output cross sections of the guided (red) beam and the equivalent free diffracting (blue) beam are shown in the insets.

5 Discussion and Conclusions

We have found that Nd-doped Bk7 glass experiences a decrease in index of 7×10^{-5} when exposed to a Gaussian beam at 488 nm and that an enhanced divergence structure forms. Simulations of this process show good agreement with the change in width during the experiments, hence the self-written evolution can be described using a simple photosensitivity model, which previously only has been applied to refractive index increases. However, in order to get perfect agreement for the peak intensity as well as for the width, a more complete model is needed.

Numerical simulations show that when a Laguerre-Gaussian donut beam is used, a three dimensional pipe structure of lower refractive index is created. We show that a light guiding channel evolves along the centre of the diffracting donut beam making use of a refractive index decrease of 7×10^{-5} as induced during the experiments in Nd-doped Bk7. In this paper only the lowest order Laguerre-Gaussian donut beam is considered. This results in a small area of unexposed material along the central axis surrounded by relatively wide ‘walls’ of lower refractive index. Note that the guiding channel has the same index as the unexposed region outside the depressed index pipe, and so these waveguides will support only leaky modes. Ideally, if these walls are thick enough, it should be possible to reduce the leakage to practical values. The final waveguide shape created during this process can be modified by choosing the order and size of the writing beam, which should ultimately allow a wide range of structures to be produced.

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