Journal of the Optical Society of Korea, Vol. 7, No. 3, September 2003, pp. 156-159

Photoinduced Singlemode Waveguide in Optical Fluoride Glasses Using Plasma Filaments

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(Received June 25, 2003)

Permanent structure of photoinduced singlemode waveguide in optical fluoride glasses was demonstrated using the self-channeled plasma filament excited by a femtosecond (110 fs) Ti:sapphire laser (λ_p = 800 nm). The photoinduced refractive index modification in ZBLAN glasses reached a length of approximately 10 - 15 mm from the input surface of the optical glass with the diameters ranging from 5 to 8 μm at input intensities more than 1.0×10^{12} W/cm^2. The graded refractive index profiles were fabricated to be a symmetric form from the center of an optical fluoride glass and a maximum value of refractive index change (Δn) was measured to be 1.3×10^{-2}. The beam profile of the output beam transmitted through the modified region showed that the photoinduced refractive index modification produced a permanent structure of singlemode waveguide.

OCIS code : 140.3390.

I. INTRODUCTION

Several types of structures of optical fluoride glasses have been developed in the fields of optical communication, medicine, and optical sensors because of their high transmission from UV to near IR [1]. Among them, much attention has been paid to the structure of optical waveguide as a powerful tool for upconversion waveguide lasers, erbium doped fiber amplifiers [EDFA] with high optical pumping efficiency, and sensitive mode interferometer in optical waveguide sensors [2,3]. Although the methods used are the casting method, the rotation method, and rotational casting method to fabricate the waveguide structure of optical fluoride glasses, there has been a technical issue in making the structure of singlemode waveguide onto the limited region of optical fluoride glasses in the sense of high costs and complicated fabrication technologies [1,4,5].

In the meantime, the interaction between ultrashort, high-intensity laser light and transparent materials has become of major concern since the advent of high-intensity femtosecond lasers. The plasma induced structural bulk modification in bulk dielectrics by tight focusing of femtosecond laser pulses was recently demonstrated [6]. Although the physical mechanisms responsible for infrared photosensitivity are still under investigation, this technique has been applied to three-dimensional optical storage, couplers, and photonic crystals [7–12]. However, related experiments for optical plasma formation and bulk modification using high-power femtosecond laser pulses have been reported mostly in silica based glasses.

In this paper, we report on the experimental results of permanent singlemode waveguide structure composed of photoinduced refractive index modification in an optical fluoride glass using the self-channeled plasma filaments excited by a high-intensity femtosencond laser. Although the change of refractive index by tightly focused femtosecond laser pulses in fluoride glasses has been reported [13], to our knowledge, no experimental results have been published of photoinduced refractive index modification by self-channeled plasma filaments in optical fluoride glasses by high-intensity femtosecond IR laser. This process would be a machine tool for the design of the limited refractive index modification in optical fluoride glasses induced by the self-channeled plasma filaments using compact, high-intensity femtosecond lasers.

II. THEORY

Intense ultrashort laser excitation of optically transparent materials causes a change in the refractive index of materials which is dependent on the intensities, which is written as $n = n_0 + n_2E^2$, and can thus induce self-focusing and plasma formation. Where n_0 is a linear refractive index of material and n_2 is a Kerr coefficient. The self-focusing occurs when the focusing effect exceeds the diffraction of the propagating beam. It is evident that self-focusing in fluoride glasses occurs at input intensity of 8×10^{11} W/cm^2 where n_2 is 2.8×10^{-16} cm^2/W in ZBLAN glass [14]. The complex refractive index variation in the created plasma is quantitatively described by means of the laser-induced plasma index modulation, Δn_{pl}, defined as [15]

$$\Delta n_{pl} = \frac{2}{n_0}\frac{e^2\tau}{m\omega}\left(\frac{(1-\omega^3\tau^3)+i(\omega^2\tau^2+\omega\tau)}{\omega^4\tau^4+1}\right)N_0\exp\left\{\int_0^t \eta(E)dt\right\} \qquad (1)$$

where τ is the electron collision time, ω is the light angular frequency, N_0 is the initial plasma density, m is the mass of electron, e is the electronic charge, and $\eta(E)$ is the possibility per unit time for an electron to undergo an ionizing collision. The plasma formation causes a decrease in the real part of the medium refractive index explained by Eq. (1) and acts as a concave lens. The refractive index variation of the plasma can compensate for the self-focusing due to the optical Kerr effect in order to characterize the diameter of the pulsed laser beam where the permanent structural transformation can be induced.

III. EXPERIMENTAL

The schematic diagram of the experimental setup for refractive index modification induced by self-channeled plasma filament is shown in Fig. 1. The laser used in the experiment is a Ti:sapphire oscillator-amplifier laser system (λ_p = 800 nm) based on the chirped pulse amplification technique with a 110 fs pulse duration, 1 W average output power, and 1 kHz repetition rate, as an irradiation laser source. The linearly polarized laser beam with a Gaussian profile is focused through a quartz lens with the focal-length of 60 mm and is incident onto the input end face of the optical fluoride glass located away from the breakdown point to avoid optical damage at the input end surface. The energy of the incident beam irradiating the planar silica plate is controlled using neutral density (ND) filters that are inserted between the laser and focusing lens. The used fluoride glass is commercially available ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) provided by the *Tokyo Furuuchi Chem. Co.*.

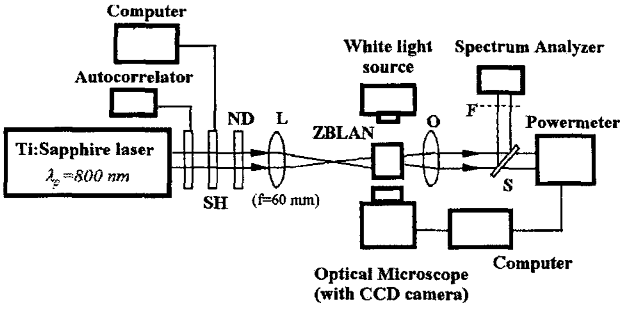

FIG. 1. Schematic of the experimental setup for self-channeled plasma filament and bulk modification in the fluoride glass (ZBLAN) excited by a femtosecond laser; SH: Shutter, ND: Neutral density filter, L: Lens, O: Objective lens, S: Silica plate, F: Filter.

The size of ZBLAN is 15 mm × 25 mm × 20 mm. The four sides of ZBLAN glass were optically polished for *in situ* observation. The sample (ZBLAN glass) is set on the X-Y-Z stage with space resolution of 50 nm set to be scanned. The diameter of the laser beam on the input end face of optical ZBLAN glass is 100 μm to be coupled. Optical images of the temporal behavior of plasma filaments and photoinduced bulk refractive index modification were observed from the direction perpendicular to the optical axis by use of a trans-illuminated optical microscope (Leica M420) with CCD camera (Pixera PVC 100C) connected to the computer.

IV. RESULT AND DISCUSSION

The first plasma spot was observed at 40 μm distant from the input end face of the optical glass by self-focusing effect at input intensity of 4×10^{11} W/cm^2 on the input end face of optical glass. When input intensity exceeds 1.0×10^{12} W/cm^2, the uniform self-channeled plasma filament with a diameter of 15 - 20 μm was observed and reached the length of 10 mm from the first self-focusing point in a fluoride glass (Fig. 2). Self-channeled plasma filament was attributed to the balance of refractive index profile between self-focusing caused by the optical Kerr effect and self-defocusing due to the plasma ions within single-shot laser irradiation [16].

Some visible modifications were observed in the center of the optical glass after the self-channeled plasma filament occurred and it proceeded to the deeper distance than the first self-focusing point as the number

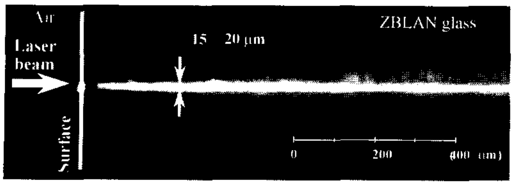

FIG. 2. Microscopic side view during self-channeled plasma filament in an optical fluoride glass (ZBLAN).

of laser pulses was increased. Bulk modification was formed onto the distance of 10 mm with a diameter of approximately 5 μm after laser shot number of 1×10^4 (Figs. 3(a) and (b)).

When input intensity was 1.5×10^{12} W/cm^2, the refractive index modification with the diameter of 6 μm and a length of 13 mm was obtained. The bulk modification with a diameter of 8 μm and the length of 15 mm was also formed at input intensity of 2.0×10^{12} W/cm^2. In all cases, optical damages at the input end face of the optical glasses was not observed. The variation of induced bulk modification profile as a function of distance was within 6 % in the diameter of refractive index modification. The photoinduced waveguide has some threshold for modification. However, when input intensity exceeded 3.5×10^{12} W/cm^2, the induced modification which has some cracks, so-called optical damages, was seen. The beam intensity of the plasma formation in an optical fluoride glass reached 1.5×10^{14} W/cm^2, which is the damage threshold for fused silica and several crystals, which is reported in recent damage studies with femtosecond laser pulses [17,18].

In order to measure refractive-index change of bulk modification induced by self-channeled plasma filament, the measurement method of perpendicular Fresnel reflection was employed. The measured refractive index profiles were shown in Fig. 4 obtained by the use of parabolic fit.

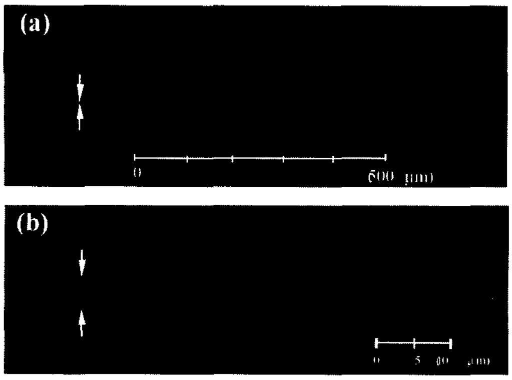

FIG. 3. Microscopic side view of refractive index modification induced by self-channeled plasma filament. (a) × 100, (b) × 1000 magnified views in ZBLAN.

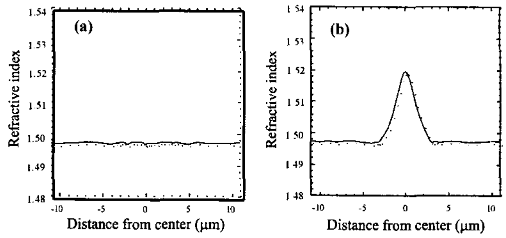

FIG. 4. The profiles of laser-induced refractive index in an optical fluoride glass. Before irradiation (a) and after irradiation of the pulses of 1×10^4 shots at input intensity of 1.0×10^{12} W/cm^2 (b).

The refractive index profiles of bulk refractive index modification irradiated higher than input intensities of 1.0×10^{12} W/cm^2 show clearly that the bulk modification provides the waveguide structure with graded refractive index profiles in optical glass (Fig. 4(b)), in relation to the refractive index profile of an unmodified optical glass (Fig. 4(a)). It had a symmetric graded index profile around the center of an optical fluoride glass and a maximum value of refractive index change(Δn) was 1.3×10^{-2}.

Fig. 5 shows the intensity profile of output beam transmitted through an optical fluoride glass with the refractive index modification. The propagating loss through the refractive index modification is low (< 0.23 dB/cm). From the trigonometrical measurement, the estimated NA from the refractive index modification was 0.17. It means that induced refractive index modification provides a singlemode waveguide structure in an optical fluoride glass.

Although the permanent structural changes on the lateral side of optical materials by the irradiation of the high-energy sources like e-beam, x-ray, UV laser can be induced, however, the permanent structural

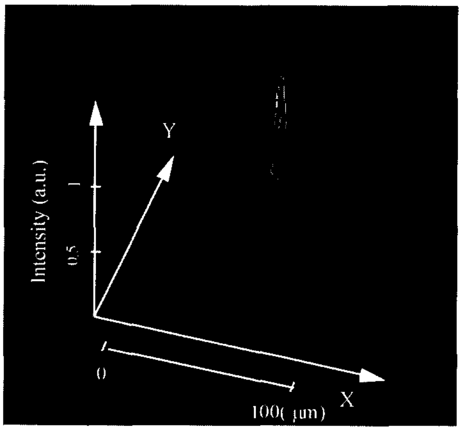

FIG. 5. The output profile of transmitted laser beam of 633 nm.

transformation along the z-axis in optical fluoride glasses that can provide the singlemode waveguide structure is not obtainable by these methods. The self-channeled plasma filament over the distance longer than the Rayleigh range provides a useful method to induce the structural transformation along the z-axis in an optical fluoride glass due to characterization of the diameter of the pulsed laser beam. Although the physical mechanisms responsible for infrared photosensitivity in fluoride glasses are still under investigation, this technique can be applied to the new fabrication method of permanent structure of singlemode waveguide in optical fluoride glasses. In general, the structure of singlemode waveguide have a core diameter ranging from 4 to 10 μm, based on the laser wavelength regime. By considering the diameter of plasma filament-induced refractive index modification from 5 μm to 8 μm, it could be used as a singlemode waveguide structure in the optical fluoride glass that has a singlemode waveguide in the range of the laser wavelengths from visible to near infrared of 1.3 - 1.5 μm for optical communication.

V. CONCLUSION

We have demonstrated refractive index bulk modification with the length of 10 - 15 mm, the diameter of 5 - 8 μm in an optical fluoride glass by the use of self-channeled plasma filaments excited by a high-intensity femtosecond laser, as a new fabrication method of singlemode waveguide structure in optical fluoride glasses.

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