Laser ablation and waveguide fabrication using CR39 polymer

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We report on the ablation and fabrication of optical waveguide using allyl-diglycol CR39 polymer. Pulse nanosecond (ns) laser (248 nm KrF) and continuous wave (CW) (244 nm argon-ion) irradiation are performed to observe surface modification on the polymer and potentially utilize it for channel waveguide. The pulsed UV laser creates craters with different depth as fluence increases to quantify threshold fluence for this material. For continuous wave UV irradiation, refractive index value on the CR39 channels varied as fluence changed, and shows the potential use of this polymer in planar waveguide applications. An upper fluence limit where laser ablation commences is also determined.

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1. Introduction

Laser and polymeric materials that induce surface modification and ablation are an interesting topic since decades ago [1]. Polymeric materials have been used in various applications including in high-performance photonics devices such as micro/nano fluidics, channel fabrication, micromachining/microdrilling [2,3], splitters, waveguide gratings and filters, and also in optical waveguide fabrication [3–5]. Few significant studies in the research field of photonics are refractive index modification of germanium doped silica glass using 244 nm UV laser irradiation as well as studies on nonlinear refractive index change of glass by femtosecond laser irradiation, [6] an all-optical switch with simple configuration realized with rare earth doped fiber with pump laser [7] and a proposal of low power switching for rare earth doped fiber [8]. Over the years, interaction of polymer materials with laser at different fluence changes are investigated under microscope and the depth of each crater is determined. Relation between changes of energy fluence and etch depth is established and the fluence threshold is also obtained. For continuous wave laser, the refractive index is calculated after laser induced is based from the numerical aperture measurement of the written waveguides. Positive refractive index change is observed and relation between irradiation fluence and refractive index change is also determined. An upper fluence limit is also obtained where laser ablation commenced above this limit.

2. Experimental setup

2.1. Pulsed UV laser at 248 nm

Laser ablation experiment used in this study was a KrF excimer laser (Opto Systems Ltd Excimer Laser series CLS100) operating at 248 nm wavelength. Maximum repetition rate range is up to 100 Hz with a maximum average output power of 5 W and a pulse duration range from 9–11 ns. A 50 mm focusing lens onto the CR39 focuses the light. The CR39 sample is in sheet form with a thickness of 1 mm (product from Solarlens). The sample was mounted onto a 3-axis x-y-z translational stage. Position of the sample varied through the micrometer driven sample holder, in order to place the polymer at the focus point. The minimum spot size created on the
CR39 surface at the focus of the laser beam is observed to be 465 × 255 nm². Fluence of laser ablated on the CR39 can be calculated from the ratio of pulse energy (mJ) per laser spot area:

\[ \text{Fluence} = \frac{\text{Energy (mJ)}}{\text{Area (cm}^2\text{)}} \quad (1) \]

For the whole experiment, fluence measurements are within an uncertainty of ± 5%.

2.2. Continuous UV laser

For waveguide channel fabrication on CR39, a frequency-doubled argon-ion laser emitting at 244 nm was used as a light source. A 25 mm focusing lens onto the CR39 focuses the laser beam. It was placed onto a 3-axis stepper motor. By translating the stepper motor along the laser-focusing plane, straight waveguides were produced. Fluence of laser irradiation on the CR39 can be calculated by the following equation [11],

\[ \text{Fluence} = \frac{P_{\text{out}}d}{\nu A} \quad (2) \]

where \( F \) is the fluence, \( P_{\text{out}} \) is the fiber output power, \( d \) is the beam diameter, \( \nu \) is the relative traveling speed and \( A \) the beam area.

The refractive index change, \( \Delta \text{RI} \) of the UV irradiated area can be calculated from the measured numerical aperture (NA) of the written waveguide by the following equation

\[ \text{NA} = \sqrt{n_c^2 - n_{cl}^2} \quad (3) \]

where \( n_c \) and \( n_{cl} \) are the refractive index of UV written area and unwritten area, respectively. \( \Delta \text{RI} \) can be calculated from the difference between \( n_c \) and \( n_{cl} \). In order to measure NA, a 1550 nm laser source was coupled into the CR39 waveguides using a fiber pigtail, while an objective lens was used to project the output of CR39 waveguides onto an image capture device. The NA of a waveguide can be obtained by measuring the divergence angle, \( \theta \) of the waveguides according to the equation:

\[ \text{NA} = n_c \sin \theta \quad (4) \]

A straight waveguide with 3 cm length was fabricated using different fluence (between 1 and 5 kJ cm⁻²). Throughout this work, the laser power was fixed at constant value and the laser beam was aligned so that the focal plane is positioned on the CR39 sample surface. Fig. 1 shows the schematic diagram of waveguide channel written on the polymer.

This laser direct-write system in this study is operating at a wavelength of 244 nm laser, where the beam is transmitted through an attenuator to control the power, a shutter and beam expander for the beam to expand about 15 mm before passing through the 25 mm focusing lens to focus the beam. The waveguides were fabricated on the CR39 polymer, which is placed on the translational stage controlled by computer.

3. Results and discussion

3.1. Pulsed UV laser at 248 nm

Fig. 2(a) shows the image of the ablated CR39 craters’ spot size under optical microscope. The dark spot on CR39 surface indicate the removal of material and formation of crater due to ablation process. At the edge of craters, a partial transparent curve was observed surrounding the craters. This might be due to the heat-affected zone (HAZ) that happens during laser ablation process. Materials that melt due to heat transfer from crater and cooled rapidly will result in heat affected zone (HAZ). However, heat transfer from ablated crater is reduced due to short pulse width of excimer laser. Besides, we suspect that it is due to photothermal effect where the absorption of laser energy by the material is transformed into heat energy that causes localized modification of its structure.

Fig. 2(b) shows the image of the crater under Field Emission Scanning Electron Microscopy (FESEM) and Fig. 2(c) shows the crater at higher magnification, which indicates micro structuring on the surface of this polymer.

The average etch depth per pulse as a function of fluence (\( F \)) for CR39 ablated at 248 nm based on 150, 180 and 210 pulses is shown in Fig. 3. A linear fit of the form

\[ d = k^{-1} \ln F/F_t \]

gives an ablation threshold of 6–7 J cm⁻². This value is much higher than reported using 157 nm laser which gives \( F_t \) as 11 mJ cm⁻² [12].

3.2. Continuous UV laser at 244 nm

Fig. 4 shows the mode field diameter (MDF) and refractive index contrast of CR39 waveguide against the laser fluence. Propagation loss measurement has been performed using the insertion loss technique for various waveguide lengths (cut-back method). Waveguides have been measured by coupling-in light from laser diode (1310 nm, 2 mW). The propagation loss of written waveguide is about 2 dB/cm, with the insertion loss slightly higher due to the mode mismatch between the launching and output coupling [7]. Hence, the total insertion loss is about 15 dB. It is observed that the refractive index change is more significant as the fluence increases. Similar to the response of other optical materials such as silica glass to laser ablation, higher laser fluence will induce a higher change of refractive index. Extrapolation of the results in Fig. 4 also predicts that irradiation of CR39 with higher fluence can increase the refractive index. However, we observed that this increase is not indefinite as there exists an upper fluence limit.
limit (5 KJ/cm²). If the laser fluence is higher than this limit, ablation will occur and UV irradiation of the CR39 will result in the removal of materials from its surface, which is the same situation which happens in Section 2.1.

Fig. 5 shows the microscope image of the modification and ablation of CR39. As seen from the figure, a partial transparent line as a result of refractive index modification can be observed in Fig. 5(a) while a darker line indicating removal of material and formation of craters due to ablation is observed in Fig. 5(b). Cross sectional view of the ablated sample is shown as inset in Fig. 5(b). Ablation effect is easier to identify from cross sectional images where a portion of CR39 is removed. The depth of the removed area can be up to several microns depending on the laser fluence being applied.

3.3. Changes of refractive index and its potential application as planar waveguide

Fig. 6 shows the near field image of one of the fabricated CR39 waveguides. It is observed that the fabricated waveguides are faintly guided waveguides. This is because the light is not very well confined in the core whose centre is marked by the cross hair. Fig. 5 shown above proves the guiding characteristic of waveguide where the largest refractive index change measured is less than 0.07% for the studied fluence range. It shows that the changes of refractive index due to laser fluence are leading to reduction of mode field diameter (MFD) as a result of better light confinement by the waveguide core.

The higher the refractive index change, the stronger the waveguides’ confinement where a larger portion of light is being confined in the core and causes the MFD of the waveguides to reduce.

The successful writing of straight waveguides is evidence that there exists a positive refractive index response of CR39 upon irradiation by 244 nm UV laser since refractive index for core must be higher than its surrounding for light guiding by the principle total internal reflection. The mechanism behind the modification of refractive index of CR39 is not yet established. However, we suspect that it is due to the photo thermal effect where the absorption of laser energy by the material is transformed into heat energy that causes localized modification of its structure and subsequently, its refractive index. Fig. 7 shows UV–vis absorption spectrum of CR39, 244 nm was located at the longer wavelength end tail of its UV absorption peak at 220 nm. Hence, we suspect that the 244 nm laser energy is partially absorbed by CR39 during irradiation and triggers the photo thermal phenomenon. Nevertheless, further investigation on the origins of refractive index modification in CR39 is still being carried out.

The fabricated channel has a high potential as planar waveguide due to its refractive index changes when exposed to UV laser. It serves as a good prototyping method for low index contrast waveguide such as splitter. As the channel demonstrates a low confinement of light at the core, it serves as a promising refractive index sensor as high leaky mode gives a high sensitivity to surrounding refractive index changed.
4. Conclusion

CR39 ablation with 248 nm UV lasers is studied in this work. Etch depth changes in craters is measured and the fluence is calculated from the laser energy and spot size. Etch depth increases when the laser fluence is varied from 6.3 J cm$^{-2}$ to 19.0 J cm$^{-2}$ respectively. Fluence threshold for CR39 determined from the graph is 6 J cm$^{-2}$. Refractive index change from $1 \times 10^{-5}$ to about $1 \times 10^{-3}$ (0.0009%–0.065%) is achieved on CR39 by varying the laser fluence from 1.2 kJ/cm$^2$ to 4.8 kJ/cm$^2$, respectively. We suspect that the mechanism responsible for the refractive index change in CR39 by 244 nm laser irradiation is the photo thermal effect where localized heat generated by absorption of 244 nm laser modifies the structure/densified of CR39.

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