Ultrafast laser fabricates high-index-contrast structures in glass

Kiyotaka Miura

Adding metallic aluminum to silicate glass allows a femtosecond-laser irradiation to create silicon precipitates within the glass, suggesting new fabrication methods for high-index-contrast integrated optical devices.

Compact integrated optical devices require tight confinement of the optical field, which in turn demands a high refractive-index difference between the material of the waveguide and the surrounding matrix (see Figure 1). Currently, most planar-waveguide devices in optical networks use a low refractive-index difference between the core and the cladding layers, whose indices are approximately 1.50 and 1.45, respectively.

Femtosecond-laser irradiation is a well-known method of producing three-dimensional patterns of structural and refractive-index change in various types of glass. Promising applications, including three-dimensional optical waveguides and photonic crystals, have been demonstrated. However, because the increased index results from local densification of the glass, the maximum laser-induced refractive-index difference is limited to \( \approx 10^{-2} \).

Achieving a high refractive-index difference is possible if silicon can be deposited within the glass, because the respective refractive indices of Si and conventional oxide glass are approximately 3.4 and 1.5, respectively. As a photonic medium, Si offers unique advantages for photonic integrated circuits. It is transparent in the range of optical telecommunications wavelengths (1.3 and 1.55 \( \mu \)m) and its high refractive index enables sub-micrometer structures for photonic devices.

Our previous research suggested the possibility that Si clusters or particles could be extracted from silicate glasses with the femtosecond laser. The focused laser causes a complex sequence of phenomena, including formation of oxygen-deficiency centers in silica or silicate glasses, reduction or oxidation of specific ions, reduction of metallic or semiconductor ions by capture of electrons from non-bridging oxygen atoms, aggregation of metallic atoms into nanoparticles after heat treatment, and diffusion of ions over distances of micrometers.

However, very little has been published on creating Si inside a bulk glass. Presumably this is because general oxide glass cannot trap O ions, which are generated by breaking Si-O bonds and growth of Si in an enclosed space inside the glass. To circumvent this problem, we have attempted Si precipitation in silicate glass by adding metallic aluminum to the starting material and using femtosecond-laser irradiation. The Al ions should act as O-trapping centers, because metallic Al acts as a reducing agent via the thermite reaction. Therefore, we assumed that silicon precipitation results when the laser energy dissociates silicon and oxygen and the dissociated oxygen ions react with the aluminum during heat treatment, as illustrated in Figure 2.

This strategy successfully created Si precipitates (see Figure 3). The inset is a scanning electron microscope (SEM) image of a Si particle, and the graph plots the results of elemental analysis by energy-dispersive x-ray spectroscopy (EDS) on the polished glass surface at the depth of the focal point.

Why does Si precipitation occur when the glass is irradiated with a femtosecond pulse, but not with longer pulses? To address this question, we estimated the density, pressure, and temperature caused by laser irradiation. The temperature at the center of the beam is higher than 3000K, corresponding to a pressure increase of 1 GPa. In addition, the pressure wave propagates outward with a constant velocity of 6.2 \( \mu \)m/ns, which agrees with the longitudinal sound velocity in conventional silicate glass at room temperature. High local temperatures and pressures and the generation of shock waves appear to be very important for forming the Si-rich structures that are needed for the growth of Si particles.

Focused irradiation with femtosecond lasers is very useful for forming Si structures inside glass. Although much still remains

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Figure 1. To shrink integrated optical devices, they must be built from materials having very different refractive indices. In the past, refractive indices of core and cladding layers were approximately 1.50 and 1.45, respectively. Our present design uses silicon and conventional oxide glass, with indices of about 3.5 and 1.5, respectively. In the future, we want 3D integration of different components in the glass.

Figure 2. A femtosecond laser can form Si precipitates if Al is present to react with the oxygen that the laser liberates.

Figure 3. Femtosecond-laser irradiation of silicate glass formed a micron-sized particle (shown in the scanning electron micrograph in the inset). This particle is rich in Si, as shown in the energy-dispersive x-ray spectrum on the left and the elemental maps on the right.

to be done to clarify the precipitation mechanisms and to control the shape and size of Si structures that are formed, our findings open up new fabrication options for Si integrated devices and Si photonics.

Author Information

Kiyotaka Miura
Material Chemistry
Kyoto University
Kyoto, Kyoto, Japan
http://www1.kuic.kyoto-u.ac.jp/

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