Design of Organic-inorganic Hybrid Waveguide

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Channel waveguides are produced from organic-inorganic hybrid materials derived by the sol-gel process. The organic-inorganic hybrid film containing photosensitive C=C bonds changes by the UV irradiation. The solubility difference between irradiated and unirradiated parts can easily give a core with about 8 μm square. The refractive indexes of the core and cladding layers are measured and the single mode waveguide is designed for the materials.

Keywords: organic-inorganic hybrid material, C=C bond, waveguide, sol-gel process

1. Introduction

Integrated optical components using the sol-gel process have attracted a lot of attention due to their low cost, this is compared to the traditional technologies like ion exchange in glass [1], sputtering [2], or flame hydrolysis deposition.[3] The sol-gel process is based on the mixture of liquid precursors (generally alkoxide) which gel at room temperature under the reaction of water. The sol solution can be deposited into a film by inexpensive equipment as that for spin-coating or dip-coating. However, since the thickness of the film produced in a single deposition step is 0.1-0.3 μm [4, 5], a multideposition process was necessary to prepare thicker coatings for waveguides.[6]-[8]

Recently, a precursor sol containing an organically modified alkoxide with metal alkoxide has been used to prepared thick organic-inorganic hybrid films. The film is superior to the inorganic film in flexibility, and superior to the polymer film in strength and heat-resistance. Especially, the films, which contain polymerizable group such as unsaturated hydrocarbon [9]-[13] or epoxide substitutes [14], can photopolymerize by laser or UV light. Some waveguides have been prepared by

utilizing the photopolymerization.

The core of these waveguides consisted of organic-inorganic material. However, for some of these waveguides, the cladding layer was a SiO_2 layer formed by thermally-oxidizing Si of the substrate surface. So, the thickness of the silica layer is not thick enough to be useful to the cladding. Another problem is that the difference of refractive indexes between the core and the silica layer is significant. This difference in the refractive index is important to design the waveguide. If the difference is too dramatic, then the core, which is able to guide the light by the single mode, is minuscule and the coupling loss becomes problematic because the refractive index of SiO_2 is far low. Other waveguide structures were prepared by the difference of the refractive index between the irradiation and the unirradiation sections.[11] For both waveguides, core layers are prepared from photopolymerizable materials. If the C=C bonds remain in the layer, the C=C bonds would change by light or heat. So, the remaining C=C bonds in the layers makes the waveguide unstable.

In this paper, we produce a waveguide which is stable for light or heat and the difference of

Fig. 1. Flow chart of fabrication process; (a) preparation of Sol A for cladding layer and Sol B for core layer, (b) preparation of waveguide.

refractive index between core and cladding layer is small enough to be able to guide the single mode light in the core with large size.

2. Experimental

Two sols A and B for a waveguide are prepared from methacryloxypropyl trimethoxysilane (MAPTMS; Shinetsu Co.), and aluminum butoxide (Al(OBu)₃; Aldrich). The fabrication process is shown in Fig. 1. The Sol A is a solution for a cladding layer and the Sol B for a core layer. MAPTMS and Al(OBu)₃ are cohydrolyzed by 0.001M HCl. The molar ratio of MAPTMS : Al(OBu)₃ : HCl is 0.9 : 0.1 : 3 for the Sol A, and is 0.8 : 0.2 : 3 for the Sol B. Darocur (Chiba Chemicals Co.), which is a photoinitiator to polymerize the methacrylic groups by light, is dropped into the mixture with the concentrations of 2.0 weight% to the sum of the solution weight. The sol solution is stirred at 30 °C and is aged for several hours. The viscosity of the sol is measured by B style rotating viscometer (Tokimec Inc.). The Sol A is filtrated through a 0.45 μm filter and the Sol B through a 0.2 μm filter.

The Sol A is dip-coated on a glass substrate to prepare the first cladding layer. The film is pre-baked at 130 °C for 1 hour. Then, the second cladding layer is deposited on the first layer to produce the cladding layers. The film is exposed to UV light for a few hours to photopolymerize C=C bond in methacrylic group. The sol B is dip-coated on the cladding layers. The film is pre-baked at 120 °C for 30 min and is exposed to UV light through a mask. The mask pattern has a form of straight channels with 5-20 μm opening widths. After exposing for several minutes, the film is etched in n-propanol for 5 min to remove the unirradiated parts. The film is exposed again by UV light to photopolymerize C=C bonds in the film. The ridge waveguide is post-baked at 130°C for 1 hour.

The thickness of the coated film is measured by a surfcom (Tokyoseimitsu). The IR spectra of C=C double bond in the film is investigated by FTIR spectrometer. The refractive indexes of the cladding and core layers are determined by a prism coupling method. The waveguide is observed by a scanning electron microscope (SEM, Hitachi).

Fig. 2. Viscosity versus aging time; ○: Sol A, ●: Sol B.

Fig. 3. Film thickness versus drawing speed; ●: the first cladding layer, ○: the first and the second cladding layers, ▲: core layer.

3. Results & Discussion

Figure 2 shows relations between the viscosity and the aging time for the Sol A and the Sol B. The viscosities increase gradually until 16 hours and go up drastically after 16 hours. The increase of the viscosity is caused by the growth of the network of the inorganic part such as -Si-O-Si- or -Si-O-Al-. As the film which is dip-coated from sol solution with higher viscosity has some cracks, the aging times of the sols are determined to be 16 hours from this figure.

The film thicknesses of one cladding layer, two cladding layers and core layer are plotted in relation to the drawing speed in Fig. 3. The films have no cracks and are adherent each other. This figure shows that the thickness of two cladding layers can be controlled for $\sim 20\mu\text{m}$ in proportion to the drawing speed. And it is clear that the cladding layer is thicker than the SiO_2 layer on silicon substrate, that is about $3\mu\text{m}$ thick.[15] The thickness of the second cladding layer which equals to the difference between the thickness of two layers and that of one layer is thicker than that of the first layer. The difference of thicknesses between the first and the second cladding layers may be caused by the difference between the wettings of the substrate and the film. The thickness of the core layer can be produced with $\sim 15\mu\text{m}$ by a single step.

There are polymerizable C=C bonds in the deposited films. As the C=C bonds change by light or heat during using as the waveguide, they should be removed from the materials for the optics. The C=C bonds in the film is investigated from FTIR spectra. Figure 4 shows FTIR absorption spectra of the cladding layer after exposure to UV light. The peak around 1635 cm^{-1} is assigned to C=C bond. The peak intensity decreases with the increase of

Fig. 4. FTIR spectra of the cladding layer after UV irradiation.

Fig. 5. SEM image of the waveguide.

Fig. 6. FTIR spectra of the core layer after UV irradiation.

UV irradiation time and does not change after 4 hours irradiation. However, the peak decreases more by the post-bake process. This means that the 4 hours UV irradiation and the post-bake process need for the preparation of stable cladding layer. Some of the C=C bonds likely remain still even in the post-baked film because of the disturbance by the inorganic network.

For the preparation of the channel waveguide, the core layer is exposed to UV light through a mask and the exposed layer is etched in propanol. After etching, the irradiated section is remaining but the unirradiated section is soluble in the propanol. The SEM image of the ridge waveguide prepared by 13 μm opening mask for 15 min exposure is shown in Fig. 5. This image represents that the core is 13 x 9.4 μm. When the irradiation time is shorter than 15 min, the width and height of the core are smaller than this image because the polymerization do not enough and the difference of

the solubility into propanol between UV irradiated parts and unirradiated parts is small. The FTIR spectra of the core layer are shown in Fig. 6. The C=C bonds in the core layer after 15 min irradiation decreases comparing to no UV irradiation, but some C=C bonds remain. In this figure, the spectra of the film which are irradiated for longer times are shown, too. The C=C bonds decrease also with the increase of the UV irradiation time and does not change after 4 hours irradiation. And then the peak decreases more by the post-bake process.

The cladding layer and the core layer are prepared by spin-coating at 3000 rpm for 30 sec, the 4 hours UV-irradiation and post-bake process. The refractive indexes of these films are measured at 632.8 nm and 1553 nm. The result is shown in Table 1. The relative refractive index differences

Table 1 Refractive indexes at each wavelength.

Wavelength (nm)	Cladding layer	Core layer	
	TE mode	TE mode	TM mode
632.8	1.499	1.497	1.494
1553	1.487	1.484	1.485

Fig. 7. SEM image of the waveguide which is satisfied with single mode condition.

(Δ), which are important factors for the design of waveguides, are calculated from the refractive indexes of cladding and core layers. They are 0.133 % for the wavelength at 632.8 nm and 0.202 % at 1553 nm for TE mode. From the Δ , the width of the core layer for the single mode is calculated for each cut-off wavelength. The maximum widths of the core layer at 632.8 and 1553 nm are estimated 4.1 and 8.2 μm , respectively. A waveguide which meets the condition for single mode at 1553 nm is prepared by the same process. The SEM image of the waveguide is shown in Fig. 7. The core size is 6.0 μm in width and 8.5 μm in height. This waveguide is satisfied with the single mode condition at 1553 nm.

4. Conclusion

A waveguide is produced from organic-inorganic hybrid film by sol-gel process. By the photopolymerization of the methacrylic group, the core is several μm square. From the measurement of the refractive indexes of the cladding and core layers, the single mode waveguide is designed.

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