Direct laser writing of self-developed waveguides in benzyldimethylketal-doped sol-gel hybrid glass

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Exposure of benzyldimethylketal (BDK)-doped sol-gel hybrid glass films to ultraviolet light produces a refractive index increase up to 43×10^{-3} and an increase in thickness due to photolocking of the BDK into the sol-gel hybrid glass matrix. Thus, single mode ridge waveguides at $\lambda = 1550$ nm can be fabricated by direct laser exposure without using photomask and development processes. The slower laser writing speed gives greater refractive index change producing more circular guided mode profiles.

Planar waveguides in optically transparent materials such as silica and polymers have long been of interest in integrated optical circuit device applications.[1–3] Channel waveguide fabrication has generally relied on techniques involving multistep processes for defining waveguide patterns in the films. Channel waveguide fabrication by photolithography or laser beam writing in photosensitive films, where the refractive index is increased by light exposure, is attractive due to its simplicity. Specifically, photopolymers offer important advantages for making waveguides since their refractive index can be readily controlled by many mechanisms. Among the many channel waveguide fabrication techniques, the most common method is to apply wet chemical etching to wash off the unexposed area to leave waveguide ridges.[4] This technique has also been applied to photosensitive sol-gel hybrid glass (SGHG) waveguides in which photopolymerizable organic monomers are covalently bonded to the silicate network.[5] Material in the UV exposed region of the SGHG film is polymerized (cross-linked) and becomes resistant to wet etching, resulting in a ridge waveguide. The fabrication of ridge waveguides can be further simplified by using photolocking of a volatile dopant in the polymer films; in this case waveguides are self-developed by the light exposure.[6–8] Typically, dopants that act as photoinitiators are photodecomposed and then locked or fixed into the host materials during the light exposure. On the other hand, the photoinitiator in unexposed regions is thermally diffused out during a baking process, lowering the refractive index as well as the thickness. Thus, a ridge waveguide can be fabricated in the exposed region without any wet development process. The photoinitiator most commonly used in the photolocking process in polymers is benzyldimethylketal (BDK). Schematic representation of the ridge waveguide fabrication using photolocking of dopants in SGHG films is shown in Fig. 1. Recently, the photolocking process was employed in fabrication of SGHG waveguide without using a photolithographic step.[9] For the fabrication of waveguides, the direct laser writing technique has the advantage of being maskless, allowing rapid and simple processing compared to conventional mask-based photolithographic techniques.[10] Direct laser writing allows independent control of focus, beam power, and scanning speed, permitting the fabrication of novel waveguide devices with refractive index varying along the propagation direction.

In this paper, we report on the simple fabrication of ridge waveguides in methacrylate-modified silica SGHG films doped with BDK by direct laser writing and self-development. BDK is sensitive to a wide range of ultraviolet (UV) light around 360 nm, photodecomposing to radicals that initiate polymerization.[7,11] As polymerization proceeds, the mobility and volatility of the radicals are reduced, and ultimately the BDK is locked into the material, increasing the refractive index. On the other

hand, the BDK remaining in the unexposed region is removed by annealing, lowering the refractive index and the thickness.

The SGHG was synthesized by hydrolysis and polycondensation of methacryloxypropyltrimethoxysilane (MPTMS) and zirconium *n*-propoxide (TPZ) chelated with methacrylic acid (MAA) as described in other studies.[5,11] The molar ratio of MPTMS:TPZ:MAA was 4:1:1 in this work. BDK, acting as a photoinitiator as well as a refractive index increasing modifier, was added to the solution before coating; the BDK content was varied from 0 to 50 mol% with respect to methacrylate species. Films were deposited by spin-coating (2000 rpm, 30 s) onto silicon and thermally oxidized silicon (12-μm oxide layer thickness). The film thickness was 4–6 μm depending on the BDK content and UV exposure. To examine the photosensitivity, the films were exposed to a Hg lamp (12 mW/cm^2) in a Mask Aligner system for 10 min (total exposure approximately 8 J/cm^2). Waveguides were fabricated in films on thermally oxidized silicon substrates using a direct writing system with an intensity stabilized HeCd laser focused to a 5-μm diameter spot, as described in a previous report.[10] The BDK is decomposed to initiate polymerization of the methacrylate component of the SGHG films. After this exposure, the films were annealed at 70 °C for 20 h to diffuse out the remaining BDK, and then they were consolidated by baking at 150 °C for 5 h.

The refractive indices and the thicknesses of the films were measured at 633 nm using a prism coupler. Figure 2 shows the refractive index and the relative thickness change caused by an 8 J/cm^2 exposure, as a function of BDK content. As the BDK content increases, the refractive index change increases almost linearly up to 43×10^{-3} and the film thickness grows up to more than 1.5 times of the initial film thickness. Because the more BDK are decomposed and locked into the hybrid glass network increasing the refractive index as well as the thickness of the films. It has been revealed that polymerization of the methacrylate groups contributes to the refractive index change in both polymers and SGHGs, allowing the direct writing of buried-type channel waveguides.[5] However, it is known that the refractive index of SGHG films can also be adjusted by doping with a large quantity of BDK,[11] so that the refractive index is lowered when unreacted BDK in the unexposed film diffuses out during annealing, thereby enhancing the refractive index difference.

Thus, the higher refractive index and thickness in exposed region than in unexposed region enable the ridge waveguides to be written and self-developed without using wet etching. Figure 3(a) shows a top-view optical micrograph of several waveguides written into a 30% BDK-doped SGHG film by direct laser exposure with a range of writing speeds from 0.2 to 1.0 mm/sec. Figure 3(b) shows an atomic force microscope (AFM) image of a ridge waveguide written by direct laser exposure at 1.0 mm/s. Broad asymmetrical ridges about 1.0 μm in height were fabricated regardless of the writing speed, with the asymmetry possibly due to stress formation in the film or laser back-reflection from the silicon wafer.

Single mode waveguides at $\lambda = 1550$ nm films were fabricated by direct laser exposure in 30% BDK-doped SGHG. Since the total UV exposure causing the refractive index increase can be controlled through both the laser power and the scan velocity, the mode profile can be carefully controlled and even varied along a waveguide. A slower writing speed causes a greater refractive index increase, which confines modes more tightly. The mode confinement is usually reflected by the ellipticity of the guided mode profiles in the waveguide. Figures 4(a) and 4(b) show photographs of guided mode profiles at $\lambda = 1550$ nm in waveguides written with a laser intensity of 60 μW/cm^2 and writing speeds of 1.0 and 0.2 mm/s, respectively. The slower writing speed gives a more circular mode profile because of the greater refractive index increase. Figure 5 presents the dependence of the mode ellipticity on laser writing speed for 60 μW/cm^2 laser intensity. The mode ellipticity decreases almost linearly from 2.234 to 1.337 as the writing velocity changes from 1.0 to 0.2 mm/s. An almost circular mode profile can therefore be obtained without an upper cladding layer and despite the ridge asymmetry.

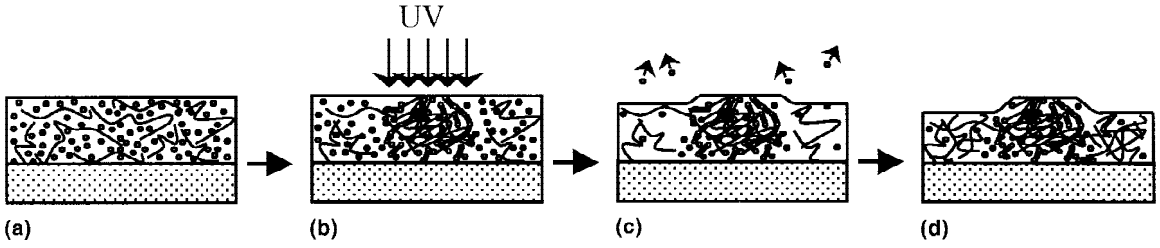

FIG. 1. Schematic representation of photolocking of photoinitiator dopants in films: (a) film coating; (b) photoinduced polymerization and photolocking of photoinitiator dopants by UV exposure; (c) evaporation of photoinitiator dopants by annealing; (d) condensation and densification of the films by baking.

In summary, the ridge waveguides have been defined in the BDK-doped SGHG films by direct laser writing, without photomask and wet development processing. Single mode waveguides with a near-circular mode profile at 1550 nm have been fabricated, without depositing an upper cladding layer. This simple writing technique depends on the photolocking of BDK radicals into the matrix and direct laser writing conditions.

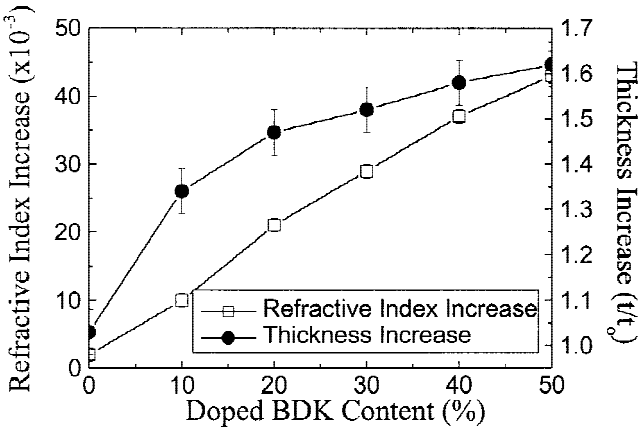

FIG. 2. Photoinduced refractive index and thickness increase in sol-gel hybrid glass films, as a function of BDK content for a Hg lamp fluence of approximately 8 J/cm^2.

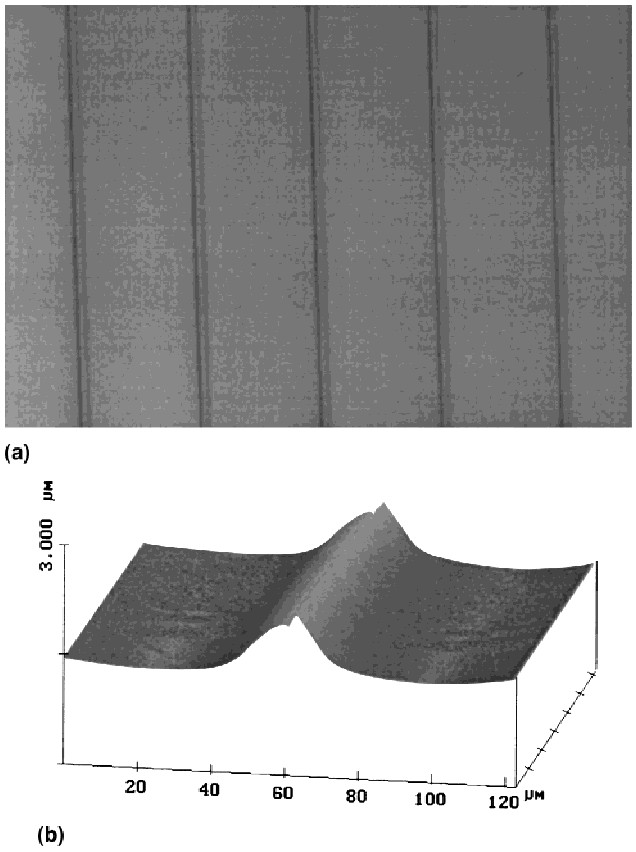

FIG. 3. (a) Optical micrograph of SGHG waveguides written by direct laser exposure (60 μW/cm^2) with various writing speeds. (b) AFM image of ridge waveguide written by direct laser exposure (60 μW/cm^2) with writing speed 1.0 mm/s.

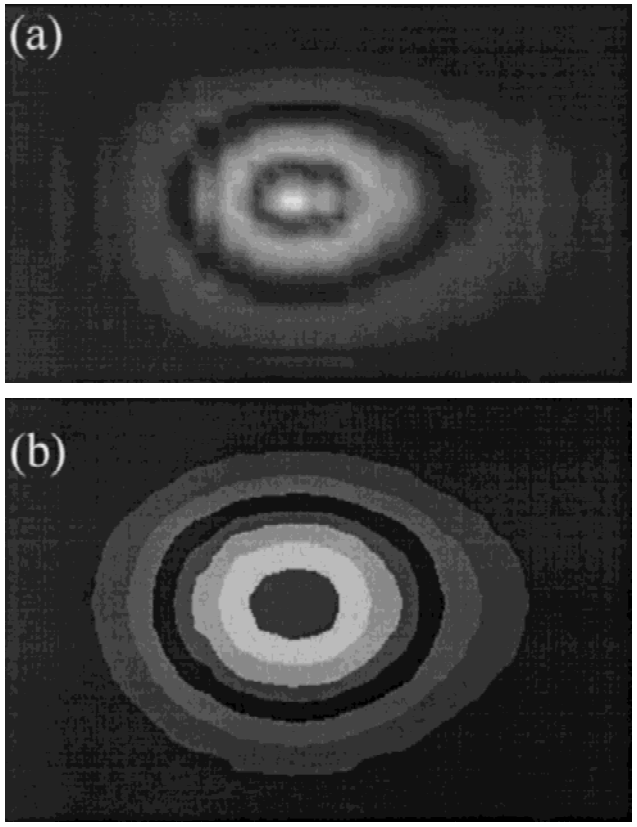

FIG. 4. Profiles of guided modes at λ = 1550 nm in waveguides written by direct laser exposure (60 μW/cm^2) with writing speeds (a) 1.0 mm/s and (b) 0.2 mm/s.

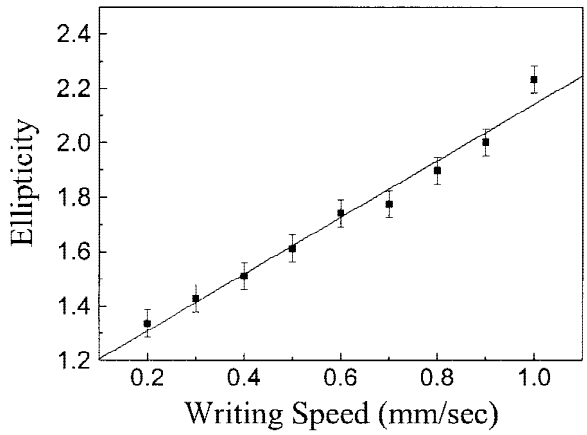

FIG. 5. Dependence of mode ellipticity at λ = 1550 nm on laser writing speed, in waveguides written by direct laser exposure (60 μW/cm^2).

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