Planar Fresnel lens photoimprinted in a germanium-doped silica optical waveguide

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A gradient-thickness Fresnel lens was photoimprinted in the germanium-doped core layer of a single-mode planar waveguide on silica by exposure to ultraviolet light through a mask, which increases the refractive index in the lens region by $\approx 5 \times 10^{-3}$. The lens is used to collimate the output of a standard single-mode optical fiber butt coupled to the waveguide at a wavelength of 1.3 μm. The method is applicable to the mass production of complex diffractive elements in a planar waveguide geometry.

Planar waveguide lenses have been proposed and fabricated from the early days of integrated optics,[1,2] and they are still the object of research[3–5] because of applications such as integrated-optical spectrum analyzers (see Ref. 6 for several examples of applications). We present here results of a new fabrication technique for planar lenses based on photoinduced refractive-index changes (Δn between 10^{-3} and 10^{-2}) in doped silica planar waveguides.[7–9] Although most of the effort dealing with photosensitivity has been concerned with optical fiber and channel waveguide devices[10,11] (including planar waveguide lasers[12]), the possibility of such large refractive-index increases opens up new fields of application, such as using silica glass as a holographic medium.[13]

We propose here that two-dimensional optical elements such as lenses, prisms, and complex diffractive elements[14] can be fabricated by the photosensitive process and then proceed to demonstrate a planar Fresnel lens. The technique described here involves the illumination of a photosensitive planar waveguide with intense UV light through a suitably designed opening in an otherwise opaque mask. The process replicates the pattern in the planar waveguide as a region of higher refractive index across the core layer. This photoimprinting can be carried out on a fully cladded waveguide because the top cladding of the core guiding layer is typically transparent to UV light.[7] Other approaches for the fabrication of waveguide lenses include patterning the substrate before depositing the waveguide (geodesic lenses) or patterning a top cladding layer adjacent to the core layer.[6] Such approaches induce scattering losses at the lens boundaries because of the abrupt index changes at interfaces located asymmetrically relative to the core, a problem that is minimized in our method in which the refractive-index changes extend across the waveguide core. More importantly, our method requires no additional layers or etching and works well with fully cladded (commercially available) low-loss waveguides (losses typically below 0.1 dB/cm).[15] Because the exposure time required to photoinduce the index change is short (a few minutes), mass production is possible with a single shadow mask. The mask can be designed and fabricated with high accuracy and tolerances because its cost will be distributed over many devices.

In practice, the mask used to photoimprint the lens patterns must have a UV-transparent substrate and a masking layer to block high-intensity UV laser pulses without damage. First we fabricated a precision chrome-on-quartz master mask by electron beam lithography. Then we made a copy of the master by transferring the pattern to a 200-nm-thick aluminum film deposited upon a 0.5-mm-thick synthetic fused-silica substrate by using conventional photolithography. It is the copy that is used in the photoimprinting process. For this demonstration, the opening in the mask was shaped as a planar gradient-thickness Fresnel lens[6] with a design goal of collimating the light from a standard single-mode telecommunication fiber butt coupled to the planar guide. A photograph of the lens pattern in the mask replica is shown in Fig. 1. The relevant parameters of the lens are the focal length in the guide $f = 1.890$ mm, diameter $D = 260$ μm (giving an f-number of 7), and thickness $H = 260$ μm (the guided wavelength is 1.3 $\mu\text{m}/N_{\text{eff}}$, where N_{eff} is the effective index of the waveguide described below). The designed lens is optically very thick ($H \gg$ wavelength), which is due to the low value of the effective refractive-index difference between the lens and the waveguide.

The analysis of the lens was performed with the thin-grating decomposition method (closely related to the beam-propagation method) that takes into account volume effects present in such a thick lens structure.[16] The lens is divided into thin slabs of equal thickness, which are assumed homogeneous with an effective index N_{eff}. The propagation through each slab is described by the angular spectrum representation of the field, and the index modulation is taken into account by a multiplicative phase factor in each slab. The paraxial approximation may be used inside the modulated region, but propagation must be treated nonparaxially outside the lens.

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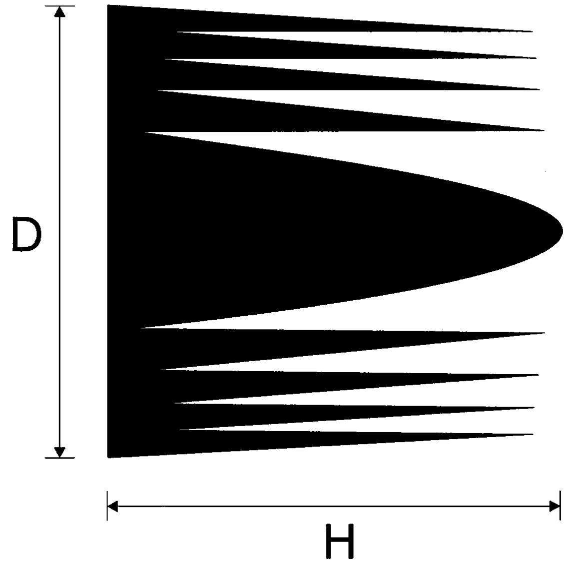

Fig. 1. Photograph of the lens pattern in the aluminum-coated silica mask. The aperture diameter D and thickness H are both equal to 260 μm.

The planar waveguide structure is made up of a 5-μm-thick germanium-doped core ($\Delta n = +0.7\%$) on top of a 20-μm-thick cladding of silica deposited by the flame hydrolysis technique onto a synthetic fused silica substrate.[15] No top cladding was used in this device, but we expect no significant difference because cladded waveguides have been used extensively without difficulties in past experiments.[7,12] The effective index of the single-mode waveguides at a wavelength of 1.3 μm is $N_{\text{eff}} = 1.46$, with a modal birefringence below 5×10^{-4}. The index increase achieved with UV photoimprinting in the conditions used for these experiments is of the order of 5×10^{-3}, obtained in waveguides sensitized by hydrogen loading or flame brushing.[7,17] For the work presented here, the waveguides were left in hydrogen at room temperature for 30 days at a pressure of 150 atm, resulting in a concentration of dissolved molecular hydrogen in the core layer of 2 mol. %. The exposure to UV light was carried out with 193-nm light from an ArF excimer laser operating at 50 pulses/s with 40 mJ/cm^2 per pulse.[18] Under these conditions, exposures of 15–20 min with the mask clamped to the waveguide are sufficient to increase the index by 5×10^{-3}.

The measurement of the collimating performance of the Fresnel lens was made with unpolarized monochromatic light from a laser diode operating at 1.3 μm. The light was butt coupled from a standard single-mode telecommunication fiber with a mode field diameter (MFD) of 9.5 μm (measured at the $1/e^2$ width of the Gaussian intensity distribution) into an 18-mm-long, 5-mm-wide planar waveguide. The distance between the waveguide input edge and the entrance face of the lens was 1.75 ± 0.1 mm (the theoretical value for the best collimation is 1.85 mm).

The near field of the guided light at the output of the waveguide was imaged on a vidicon camera and digitized by a frame grabber. Without the lens the beam diverges freely to a MFD of 2.2 mm [Fig. 2(a)], in very good agreement with the calculated value for this length of waveguide. However, when the input beam is aligned to go through the lens, the MFD at the output of the guide is reduced to 250 μm in the main peak of the pattern [Fig. 2(b)]. The theoretical curve with a MFD of 180 μm in Fig. 2(b) is not a fit to the data but an *a priori* calculation based on the device parameters given above. The difference in the MFD is probably due to two factors: (1) the uncertainty in estimating the distance between the waveguide input edge and the entrance face of the lens; a distance shorter by 0.1 mm is sufficient to explain the observed difference in the MFD; and (2) an error in the estimation of the photoinduced refractive index increase. In terms of our design goal of collimating the beam, because the MFD at the entrance of the lens is 205 μm, our result shows that the guided beam diverges by only 45 μm over the remaining 16 mm

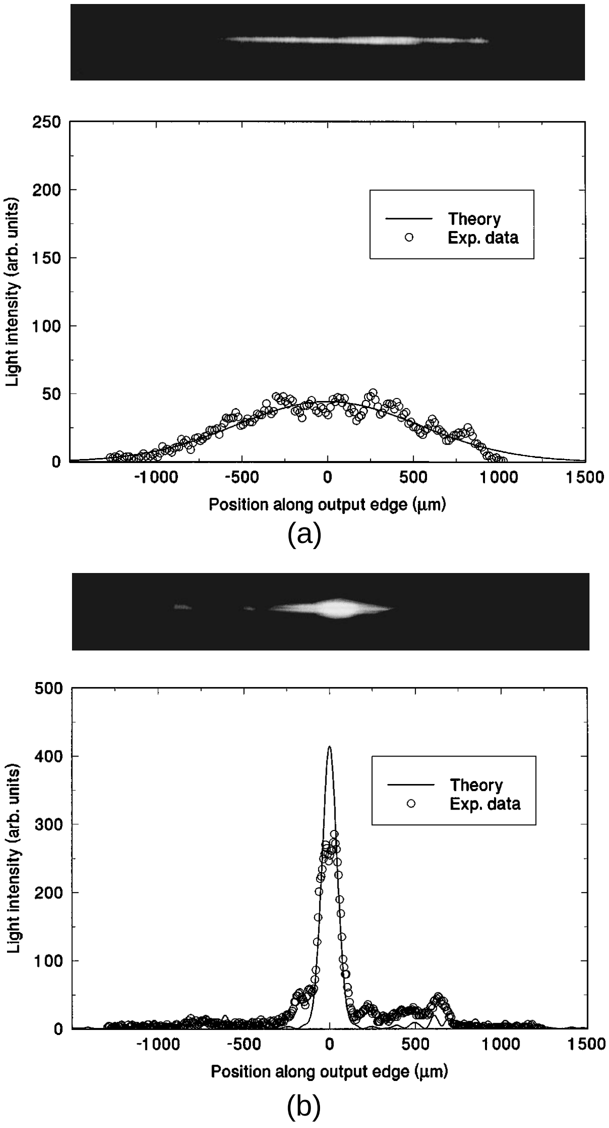

Fig. 2. Near-field light intensity distribution measured horizontally along the output edge of the planar waveguide. The experimental data and the calculated results are normalized to the same total output light intensity. The corresponding photograph of the output near field is shown above each case. (a) Freely diverging guided light (without the lens). (b) Guided light laterally collimated by the planar Fresnel lens (note the change in vertical scale).

of propagation after the lens, an angular divergence equal to $45/16{,}000 = 2.8$ mrad.

On the other hand, we observe in Fig. 2(b) that some stray light surrounds the main peak in the output near field and that the peak light level is lower than the theoretical result. If we define the collection efficiency of the lens as the ratio of the amount of light in the main Gaussian peak to the total output light, the efficiency of the lens used for the results shown in Fig. 2(b) is 62% (the theoretical value is 77%). Thick diffractive lenses are particularly sensitive to minor misalignments[19] and, therefore, the stray light is probably caused by an angular misalignment between the lens and the waveguide edge, in addition to the fabrication errors in the finer details (sharp points) of the lens pattern.

In summary, we have demonstrated the potential of the photosensitive process for the fabrication of waveguide lenses in high-quality doped silica planar waveguides. The fabricated lens collects 62% of the 1.3-μm light coupled into a planar waveguide by butt coupling a standard single-mode fiber and collimates the guided beam to a parallelism within 3 mrad over a propagation distance of 16 mm. With this technique more complex combinations of refractive or diffractive planar waveguide elements can be fabricated with single masks containing several elements (thereby self-aligned) or by multiple exposures through several masks (requiring alignment but allowing for different Δn's). In terms of mask design, the limitations imposed by the fabrication method are better understood and will be taken into account in further work to achieve optimum diffraction performance, such as compensating for the volume effects that reduce the efficiency of the lens.

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