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Fabrication of buried waveguides in planar silica films using a direct CW laser writing technique

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ABSTRACT

A CW CO_2 laser ablation technique is used to form buried waveguides in planar silica films. It is shown that the refractive index of a silica thin film is reduced sufficiently adjacent to the laser processed region to allow the fabrication of low loss waveguides. The refractive index distribution of these structures is measured using the reflectance of a focussed spot from the surface of the films. The change in refractive index is measured to be of the order of the core cladding refractive index difference of typical single mode waveguides. The spatial resolution of the reflectance technique is 1.3 μm with a refractive index resolution of $\pm 5 \times 10^{-4}$. Devices such as 1×2 and 1×4 multi-mode interference (MMI) splitters have also been demonstrated and shown to exhibit low transmission losses.

1. Introduction

Direct laser writing has been proposed to realize planar optical waveguides without the need for complex photolithographic processes over the past few years. Of these techniques, UV irradiation [1,2] or femto-second lasers [3–5] have been used to induce an increase in the refractive index of the exposed region in silica and in doped silica planar films. Experimental parameters such as exposure time, optical power and focused beam size have a profound influence on the change in the refractive index. Using a femto-second laser ridge waveguides may be formed by localizing a narrow stripe of raised refractive index, e.g. doped silica and air on two sides and implemented by ablating two trenches separated by a few microns, sandwiching a light confining region in between. This has been proposed and applied to fabricate ridge optical waveguides on different materials [6–8]. Femto-second lasers have also been used for the ablation [9] to fabricate ridge waveguides in thin films of silica on silicon. What distinguishes this technique from others is the fact that the light confining region, i.e. the waveguide core remains unaffected, while the cladding area is modified. However, this process remains rather slow with writing speeds of less than 100 μm/s and further post-processing is required to achieve smooth walls to reduce propagation loss induced by the roughness of the waveguide wall.

Recently, we proposed a similar scheme in which a simple CW CO_2 laser was used to ablate two adjacent trenches, creating single mode waveguides. This technique enabled us to produce low loss single mode waveguides (0.1 dB/cm) at high writing speeds (50 mm/s) [10,11]. As with other techniques, CO_2 laser ablation cannot be used for the production of all types of photonic circuits. Its main limitation is the focussed laser spot size which is of the order of 20 μm and thus limits the size of trenches: therefore couplers cannot be created easily with low loss as the spacing between adjacent waveguides is too large. A modification may occur in the core area as it is known that CO_2 lasers melts silica. A decrease in refractive index is possible in densified silica glass or silicon oxy-

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nitride thin films by CO_2 laser irradiation [12,13]. This observation implies not only that the core region can be modified but more interestingly that it may be possible to form a cladding of lower refractive index around the core effectively burying the waveguide and leading to lower propagation loss.

One of the main parameters affecting waveguiding is the refractive index profile (RIP) of its cross-section. This data can provide valuable information on the waveguide fabrication process and the transmission properties of the waveguide. Thus, for the design of optical circuits, knowledge of the two-dimensional distribution of the refractive index of the waveguide is important, as it may be used to simulate and predict the transmission properties. Several techniques have been proposed to measure the refractive index profile of optical fibers and waveguides, such as refracted near-field (RNF) method [14], interferometry, and reflectance measurement (RM) [15]. In this paper, we present the measurement of the two-dimensional refractive index profile of CO_2 laser written buried channel waveguides in germanium doped planar silica films using a reflectance measurement technique, with a respective spatial and index resolution of 1.3 μm and $\pm 5 \times 10^{-4}$. There is a reduction in the refractive index in the region adjacent to the ablated channel. We conclude that the mechanism for the reduction of the refractive index is annealing of the glass rather than loss of germanium from the doped film.

2. Experimental – results

2.1. Processing silica thin films on silicon

Fig. 1 shows silica samples ablated by a focussed CO_2 laser beam. Visually, it is easy to see the change in the morphology of the glass adjacent to the ablated region. This has led us to believe that the refractive index has been altered locally, as also reported by others [12,13]. However, we have not been able to measure accurately the changes in the refractive index of the sample; this has been discussed in Ref. [13], in which they show a small lowering in refractive index of the affected region, possibly through stress relaxation. However, if the changes can be made larger, it could be an effective method of making useful waveguides with smooth walls. We have recently demonstrated these in commercially available phosphorous and germania doped silica planar films. The effect of ablating these wafers is shown in Fig. 1(d), in which the different layers may be identified. The bright layer is the doped guiding region which traps light when illuminated from the rear. The layer immediately below the core region is the thermally deposited oxide followed below by the silicon substrate. Above the core layer is the deposited silica cover layer. One can see the dark 'bat-eared' region immediately adjacent to the ablated region. This is the heat affected zone, the subject of the following discussion below.

As mentioned, the technique for forming waveguides is simply by the ablation of two adjacent trenches in a planar waveguide substrate, as shown in Fig. 2. A tightly focused CO_2 laser beam with a CW power of approximately 2 W locally ablates the material and creating two air cladding regions trapping the high index region doped region in between [10,11]. This thermal ablation process leads to a reduced refractive index region in a few microns adjacent to the trenches in the core. A buried waveguide is thus formed between the guiding layer, the two adjacent lower refractive index heat affected zones, the top over-cladding and the bottom buffer layer (Fig. 2) These trenches permit light confinement horizontally while vertical confinement is insured by the higher refractive index core layer. This technique is similar to photolithography-based waveguide fabrication, but it has several advantages: the pattern mask is replaced by an XYZ translation stage that directly defines the desired pattern on the surface of the sample, adding flexibility to the process since only the trajectory of the stage needs to be controlled for new designs. The overall fabrication time of the waveguides is shorter because there is a single processing step, with no further chemical or mechanical processing. In addition, the present writing speed is 50 mm/s but can be much higher with better XY stages. Finally, the laser used for production of these waveguides is inexpensive and requires low maintenance, leading to potentially lower cost planar optical waveguide devices.

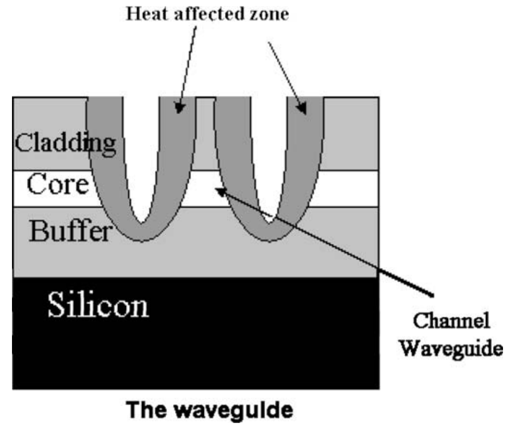

Fig. 2. Schematic of the waveguide with two trenches defining the core region in one of the guiding structure fabricated with the CW CO2 laser.

We chose silica thin films on silicon for our waveguides as it is one of the most widely used structures in planar light-wave circuits. The CO_2 laser radiation at 10.6 μm is strongly absorbed in silica making it an excellent choice for micromachining. Further, the absorption coefficient of silicon is very small at this wavelength which in turn insures that the substrate remains unaffected by the writing process. As shown in the schematic in Fig. 2, a buried waveguide with a trapezoidal shape is expected from this writing process, significantly different from the standard rectangular profile made by photolithographic techniques. By adjusting the spacing between the two trenches, single- or multi-mode waveguides may be fabricated. Knowledge of the refractive index profile of the fabricated structure provides useful

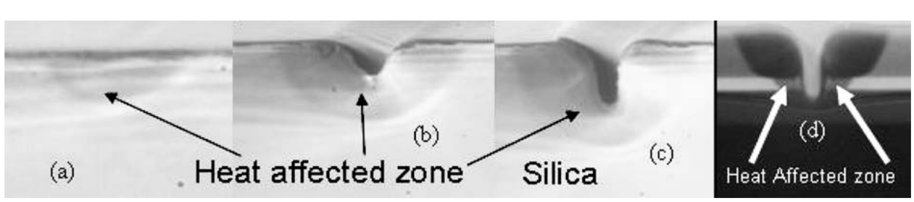

Fig. 1. Images of three facets of pure silica samples treated with CO_2 laser radiation with increasing powers from (a) to (c), respectively, showing regions affected by the heat treatment. With sufficient power, ablation occurs as seen in figures (b) and (c). (d) Shows the effect of ablation when a CVD deposited planar doped silica wafer sample is treated with CO_2 laser radiation. See text for details.