Optica Applicata, Vol. XLI, No. 2, 2011

Optical channel structures based on sol–gel derived waveguide films

Paweł KARASIŃSKI*, Cuma TYSZKIEWICZ, Roman ROGOZIŃSKI

Department of Optoelectronics, Faculty of Electrical Engineering, Silesian University of Technology,
ul. Bolesława Krzywoustego 2, 44-100 Gliwice, Poland

*Corresponding author: pawel.karasinski@polsl.pl

Rib waveguides were fabricated with the use of selective, wet chemical etching of two-component waveguide films SiO_2:TiO_2 which were obtained using the sol–gel method. Photoresist was applied as a mask in the process. The etching of the layers SiO_2:TiO_2 was carried out in water solutions of ammonia fluoride. The paper presents the results of theoretical analysis as well as the power distributions in the obtained strip waveguides and directional couplers.

Keywords: rib waveguide, sol–gel, directional coupler.

1. Introduction

Planar optical waveguide devices are of interest for use in integrated optical circuits for optical networks and sensors applications. Planar waveguides can be produced with the application of: ion exchange in glass [1, 2], chemical vapor deposition (CVD) [3] or sol–gel technology [4–11]. The sol–gel technology has a big advantage as compared to others since it does not require expensive technological equipment and it can provide various dielectric materials of controlled structure for optoelectronics. Through an appropriate selection of components we can obtain dielectric films of different refractive indexes [4]. From the viewpoint of fabrication potential of films having high refractive index contrast, a two-component system SiO_2:TiO_2 is very attractive. Refractive indexes of such films can be formed within the range from $n = 1.2$ (porous silica) to $n = 2.3$ (dense titania). Films of high refractive indexes are particularly attractive for the technology of planar evanescent wave sensors [5 ,6, 9, 10]. In some sensor systems, slab waveguides can be used [5, 6, 10, 11]. However, in many other applications such as planar evanescent wave sensors in the system of Mach–Zehnder interferometer or in the system of Young interferometer, strip waveguides are required.

The present paper demonstrates the application of the method of chemical selective etching of sol–gel derived silica–titania films for the fabrication of channel rib waveguides. The work demonstrates the results of theoretical analysis as well as power distribution in the fabricated rib waveguides and directional couplers.

2. Theoretical analysis

The diagram of a rib waveguide is presented in Fig. 1. The optical and geometrical parameters describing the rib waveguide are: refractive index of waveguide film n_1, substrate n_b, cover n_c and thickness h in a rib area, rib height t and width w.

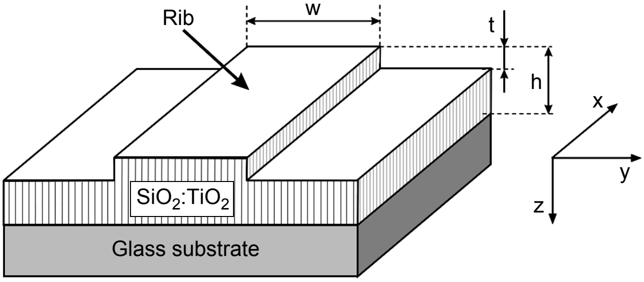

Fig. 1. Diagram of rib waveguide.

In theoretical analysis of rib waveguides we can use numerical methods, spectral method [12] or effective index method [13]. In our studies, a theoretical analysis of rib waveguides was carried out using an effective index method [14, 15]. Figure 2 shows the calculated modal characteristics of a slab waveguide for TE polarization and a wavelength of $\lambda = 635$ nm. The values of waveguide refractive indexes taken for calculations are: waveguide layer $n_1 = 1.793$, substrate $n_b = 1.515$ and cover $n_c = 1.000$. These values correspond to refractive indexes of fabricated structures. The modal characteristics of a rib waveguide for selected values of height t are shown

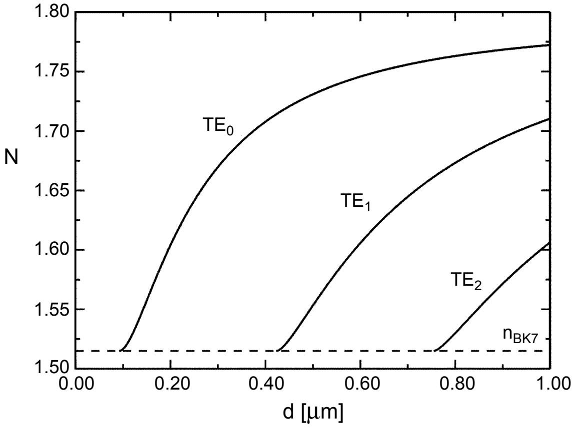

Fig. 2. Modal characteristics of slab waveguide for TE polarization.

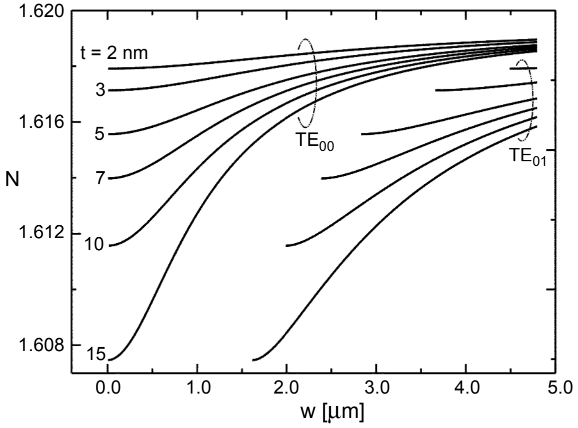

Fig. 3. Modal characteristics of rib waveguide; $h = 219$ nm.

in Fig. 3. It can be seen that along with an increase in the rib height t, the cut-off width w_{cut} of TE$_{01}$ mode is decreasing. For a rib height of $t = 5$ nm, the TE$_{01}$ cut-off width is $w_{\mathrm{cut}} = 2.83$ µm.

3. Technology

3.1. Slab waveguides

The silica–titania waveguide films were produced using the precursors: tetraethyl ortosilicate (TEOS) for silica and tetraethyl ortotitanate (TET) for titania [7]. The gel formation procedure was carried out in two stages. In the first stage, the hydrolysis of TEOS and TET was carried out separately. Then, partially hydrolyzed TET solution was added to partially hydrolyzed TEOS solution and the sol formation process was carried on. The solutions were mixed in proportions ensuring that the molar ratio Si:Ti is 1:1. Ethyl alcohol was used as homogenizing agent and hydrochloric acid was applied as catalyst. Waveguide films were deposited on BK7 glass substrates (76×26×1 mm^3) using the dip-coating method. The fabricated structures were annealed for 1 hour at 500 °C. The obtained waveguide films SiO_2:TiO_2 were characterized by low attenuation (below 0.5 dB/cm) [15, 16]. The refractive index of waveguide films which were applied for the fabrication of rib waveguides was $n_1 = 1.793$.

3.2. Rib waveguides

The rib waveguides were fabricated as follows. The waveguide films formed in the sol–gel process were coated with photoresist (Shipley-Microposit S1813SP15). Then, the structures were subjected to UV radiation through a photomask designed for this purpose. The development of photoresist, was followed by the selective uncovering of SiO_2:TiO_2 film whose thickness was being reduced in the etching process. The described method was used to obtain strip waveguides of the rib width w

and height *t*. The width *w* of the ribs of the produced strip waveguides was from 1 to 10 μm, and the height *t* was 5 nm.

Strip waveguides were produced through selective chemical etching of films SiO_2:TiO_2 as described in details in Refs. [15, 17].

4. Measurement set-up

For the produced strip waveguides the power distribution in the near field was recorded. The measurement set-up is presented in Fig. 4. The laser diode (LD) was applied in the research as a light source of the wavelength $\lambda = 635$ nm. Strip waveguides were being excited with single mode fibre (SMF) of the cut-off wavelength $\lambda_{\text{cut}} = 590$ nm. The controlled coupling of waveguide fibre with strip waveguides was made possible using a precise positioner *xyz*. The distribution of power in the near field was recorded with a CCD camera coupled with a computer.

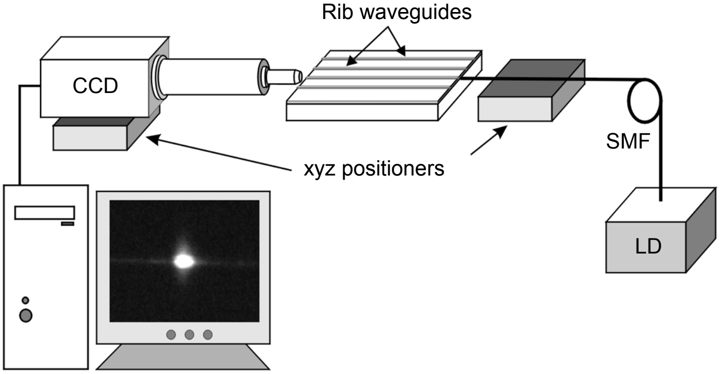

Fig. 4. Measurement set-up. LD – laser diode, CCD – camera CCD, SMF – single mode optical fibre.

5. Experimental results

The recorded image of the light emanating from the edge of the waveguide of the rib width $w = 3$ μm and height $t = 5$ nm for the wavelength $\lambda = 635$ nm is presented in Fig. 5**a**. Figure 5**b** presents the power distribution from the horizontal scan of the image from Fig. 5**a**. The crosses were used to mark measurements points, which were approximated with Gauss curve. The presented results show that the waveguide of the rib width $w = 3$ μm is a single mode.

The carried out analysis of recorded optical power distributions for a rib of width greater than 3 μm showed that these waveguides are multimode for wavelength $\lambda =$ $= 635$ nm. The determined attenuation of fabricated rib waveguides is approximately 1.5 dB/cm. The attenuation was measured using the streak method [15]. At the current stage of the investigations, sidewall roughness is the main source of attenuation.

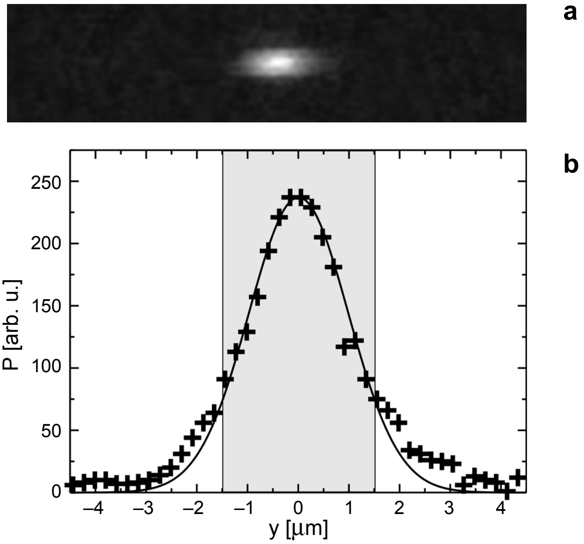

Fig. 5. Light emanating from the edge of a rib waveguide (**a**), horizontal power profile (**b**); $w = 3$ µm, $\lambda = 635$ nm.

In Figure 6 the recorded near-field pictures of 1×2 directional coupler's outgoing rib waveguides are shown. In this figure are also shown the optical power distributions determined on the basis of these distributions. The particular figures correspond to various coupling length L and separation s in a directional coupler. It can be seen

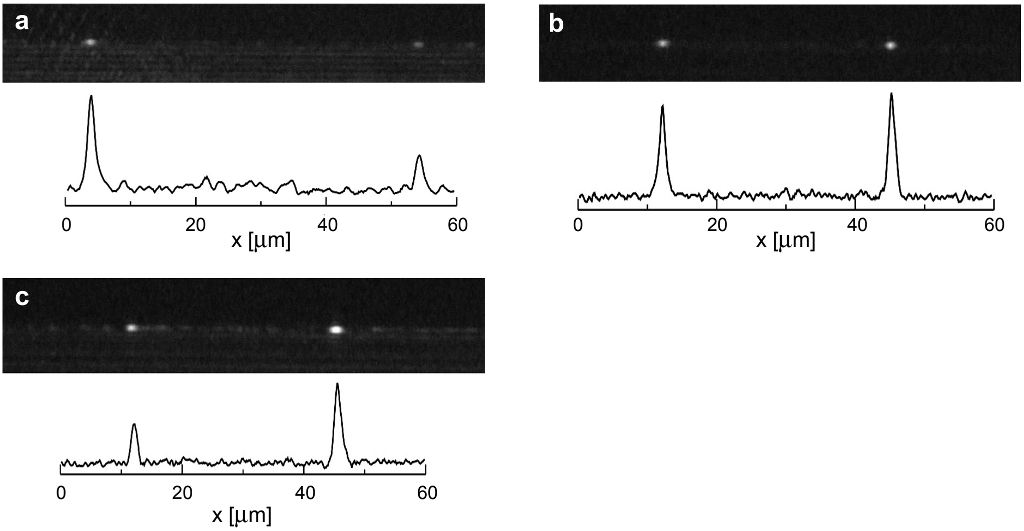

Fig. 6. Images and power distributions in near field on the outputs of the directional couplers. $w = 3$ µm, $t = 5$ nm, $\lambda = 635$nm and $s = 1.5$ µm, $L = 1.5$ mm (**a**), $s = 2.0$ µm, $L = 4.5$ mm (**b**), $s = 2.5$ µm, $L = 4.5$ mm (**c**).

that power division in outgoing rib waveguides depends on coupling length L and separation s.

It can be seen that for $s = 2.0$ μm, $L = 4.5$ mm (Fig. 6**b**, $\lambda = 635$ nm), the values of optical power in both outgoing rib waveguides are very close one to another. Presented rib waveguides and directional couplers may form the basis for development of planar interferometers for sensor applications.

6. Summary

The presented method of chemical etching of the sol–gel derived silica–titania waveguide films allows in a relatively simple way fabrication of strip waveguides. Such waveguides, having high refractive index, applied in the planar sensor system with phase detection will allow to obtain high measurement sensitivity. Elaborated rib waveguides and directional couplers will be applied in the technology of chemical and biochemical evanescent wave sensors working in the system of Mach–Zehnder interferometer or Young interferometer.

Acknowledgements – This work is partially financed from the research grant N R01 0034 06/2009.

References

[1] Opilski A., Rogoziński R., Błahut M., Karasiński P., Gut K., Opilski Z., *Technology of ion exchange in glass and its application in waveguide planar sensors*, Optical Engineering **36**(6), 1997, pp. 1625–1638.

[2] Najafi S.I., *Introduction to Glass Integrated Optics*, Artech Hous, Boston–London, 1992.

[3] Selvaraja S.K., Sleeckx E., Schaekers M., Bogaerts W., Van Thourhout D., Dumon P., Baets R., *Low-loss amorphous silica-on-insulator technology for photonic integrated circuitry*, Optics Communications **282**(9), 2009, pp. 1767–1770.

[4] Brinker C.J., Scherer G.W., *Sol–Gel Science*, Academic Press, San Diego, 1990.

[5] Lukosz W., *Integrated optical chemical and direct biochemical sensors*, Sensors and Actuators B: Chemical **29**(1–3), 1995 pp. 37–50.

[6] Vörös J., Ramsden J.J., Csúcs G., Szendrö I., De Paul S.M., Textor M., Spencer N.D., *Optical grating coupler biosensors*, Biomaterials **23**(17), 2002, pp. 3699–3710.

[7] Karasiński P., *Sol–gel derived optical waveguide films for planar sensors with phase modulation*, Optica Applicata **34**(4), 2004, pp. 467–475.

[8] Karasiński P., *Sol–gel derived sensitive films for ammonia evanescent wave sensors*, Optica Applicata **33**(2–3), 2003, pp. 477–487.

[9] Karasiński P., *Influence of waveguide parameters on the difference interference in optical planar structure*, Optica Applicata **32**(4), 2002, pp. 775–796.

[10] Stamm Ch., Lukosz W., *Integrated optical difference interferometer as immunosensor*, Sensors and Actuators B: Chemical **31**(3), 1996, pp. 203–207.

[11] Karasiński P., *Embossable grating couplers for planar evanescent wave sensors*, Opto-Electronics Review **19**(1), 2011, pp. 13–24.

[12] Alharbi F., Scot J.C., *Multi-domain spectral method for modal analysis of optical waveguide*, Optical and Quantum Electronics **41**(8), 2009, pp. 583–597.

[13] Kin Seng Chiang, *Effective-index analysis of optical waveguides*, Proceedings of SPIE **2399**, 1995, pp. 2–12.

[14] Karasiński P., Tyszkiewicz C., Rogoziński R., *Single-mode rib waveguides fabricated by means of sol–gel method*, Acta Physica Polonica A **118**(6), 2010, pp. 1168–1170.

[15] Karasiński P., Tyszkiewicz C., Rogoziński R., Jaglarz J., Mazur J., *Optical rib waveguides based on sol–gel derived silica–titania films*, Thin Solid Films **519**(16), 2011, pp. 5544–5551.

[16] Karasiński P., Jaglarz J., Mazur J., *Low loss silica–titania waveguide films*, Photonics Letters of Poland **2**(1), 2010, pp. 37–39.

[17] Karasiński P., Rogoziński R., *Rib waveguides fabricated by means of chemical etching of sol–gel* SiO_2:TiO_2 *films*, Optics Communications **245**(1–6), 2005, pp. 237–242.

Received September 25, 2010