Optical Splitters Based on Self-Imaging Effect in Multi-Mode Waveguide Made by Ion Exchange in Glass

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Abstract. *Design and modeling of single mode optical multi-mode interference structures with graded refractive index is reported. Several samples of planar optical channel waveguides were obtained by* $Ag^+ \leftrightarrow Na^+$ *and* $K^+ \leftrightarrow Na^+$ *one step thermal ion exchange process in molten salt on GIL49 glass substrate and new special optical glass for ion exchange technology.*

Waveguide properties were measured by optical mode spectroscopy. Obtained data were used for further design and modeling of single mode channel waveguide and subsequently for the design of 1 to 3 multimode interference power splitter in order to improve simulation accuracy. Designs were developed by utilizing finite difference beam propagation method.

Keywords

Ion exchange, glass substrate, single mode channel waveguide, power splitter, multi-mode interference.

1. Introduction

Multimode interference (MMI) effect has been observed on planar lightwave circuits (PLC) structures based on step index waveguides since early 1990s [1]. The first possibility of existence self-imaging effects in gradient-index waveguides made by ion-exchange (IE) in glass was shown in [2]. As a result of self-imaging phenomena, the input field, which most frequently comes from single mode waveguide, is reproduced as a simple, reflected and multiple images. On this basis, many different MMI structures can be proposed.

Gradient waveguides made by IE in glass substrate are very attractive for these structures. Due to multistep diffusion process modal properties of the waveguides can be changed in depending on the inter-mode interference. Thus, the MMI structures in combination with IE technology have low loss in the near-infrared region, small size, relatively simple and economic fabrication and relatively low cost. These advantages make them unique for realization of splitters, couplers, multiplexers, passive phase shifters and modulators [3].

2. Ion Exchange

Ion exchange is a diffusive process, in which alkali ions in glass (usually sodium) are replaced by ions of larger size but with same chemical characteristics, such as silver or potassium. Consequently, the refractive index of the glass is locally changed and the waveguide layer is created. Optical glasses used for IE must possess several properties, such as sizeable concentration of mobile network modifiers, chemical and physical resistance to alkali salt melts and the ability to withstand the polishing process.

Determination of the refractive index profile has paramount importance in the device design. The equation governing the evolution of the concentration of new ions in the glass has the following form [4]

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[\frac{D_1}{1-\alpha c}\frac{\partial c}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{D_1}{1-\alpha c}\frac{\partial c}{\partial y}\right] \tag{1}$$

where

$$c = c_1 / c_0$$

and

$$\alpha = 1 - D_1 / D_0$$

where c_1 and D_1 are the concentration and self-diffusion coefficient of the incoming ions, D_0 is the self-diffusion coefficient of the outgoing ions, and c_0 is the concentration of outgoing ions present in the glass prior to the exchange.

Thereby, the channel waveguide with graded refractive index is created on the surface substrate glass (Fig. 1), where n_c represents refractive index of the cover layer and n_s stands for refractive index of the substrate.

Refractive index change (Δn) and diffusion depth (h) are dependent on duration time of ion exchange and temperature of molten salt. The resulting surface channel waveguide can then be buried by application of the electric field-assisted method several micrometers into glass substrate [4], [5].

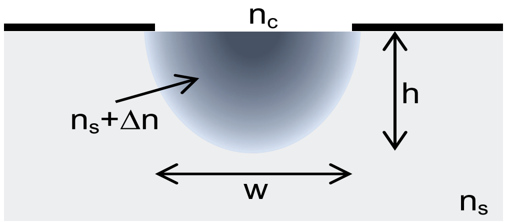

Fig. 1. Schematic representation of channel waveguide made by one step thermal ion exchange.

3. Experiment

At first, four samples of optical planar waveguides were developed to obtain more accurate data for designing precise optical channel waveguide. Two types of highly pure optical glass substrates were evaluated in our experiments. A special soda-lime silica glass GIL49 and a special glass produced by Dr. Mika at the Institute of Chemical Technology in Prague. Refractive indices of chosen glass samples were measured by optical mode spectroscopy (OMS) with the METRICON 2010 system [6].

3.1 Planar Optical Waveguide Fabrication

Three samples of optical planar waveguides were manufactured by silver IE and one by potassium thermal IE in molten salt. Process conditions are depicted in Tab. 1.

Sample	Substrate	Ion exchange	Temperature [°C]	Time [min.]
1587	I1T1	$Ag^+ \leftrightarrow Na^+$	280	20
1588	B1T1	$Ag^+ \leftrightarrow Na^+$	280	20
1923	GIL49	$Ag^+ \leftrightarrow Na^+$	280	20
1924	GIL49	$K^+ \leftrightarrow Na^+$	400	180

Tab. 1. Ion exchange process conditions.

Before the ion exchange process, the glass substrate must be cleaned from any impurities and dust after glass grinding and polishing. Cleaned substrate was inserted into molten salt for a defined period of time and temperature.

3.2 Planar Optical Waveguide Measurement

All samples were measured by OMS with METRICON 2010 system at wavelengths of 632.8 nm, 1311 nm and 1552 nm while considering TE polarization.

Waveguides made by silver IE showed from three to four guided TE modes at the wavelength of 632.8 nm. Depth of the waveguide layer was approximately 4 µm and refractive index difference in the order of hundredths. The fabricated waveguides provided single mode regime for wavelengths of 1311 nm and 1550 nm.

Waveguide layer of the sample made by potassium ion exchange had 2 µm depth and refractive index difference in the order of thousandths. Complete properties of fabricated planar waveguides are presented in Tab. 2.

Sample	n_s	Δn	h [µm]	Modes
1587	1.5146	0.06	4.3	4
1588	1.5013	0.03	4.0	3
1923	1.5204	0.06	2.4	3
1924	1.5091	0.002	7.8	3

Tab. 2. Properties of the fabricated planar waveguides measured by METRICON 2010.

Refractive index of the substrate was determined as a refractive index of the last guided mode. Refractive index difference was determined as a difference between refractive index on surface of the planar waveguide and last guided mode. However, we can determinate the depth profile only if the number of guided modes is greater than one. This condition satisfied only for the wavelength of 632.8 nm.

For a modeling of graded waveguide it is very important to know the shape of refractive index profile. Fig. 2, 3, show the depth refractive index profile of the samples, where the points indicate the modes and their effective refractive index. As we can see, the refractive index profile of the samples made by $Ag^+ \leftrightarrow Na^+$ is closer to step index profile and is thus more suitable for design and modeling described in the following section.

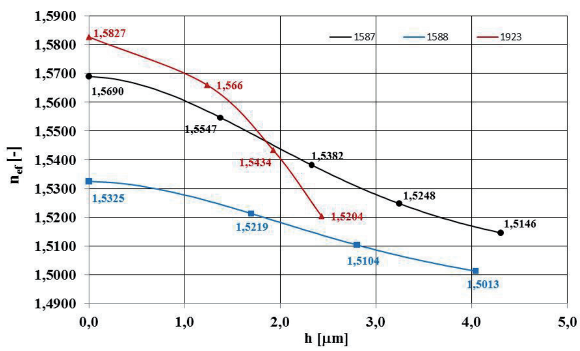

Fig. 2. Depth refractive index profile of fabricated planar waveguides made by $Ag^+ \leftrightarrow Na^+$ (λ = 632.8 nm).

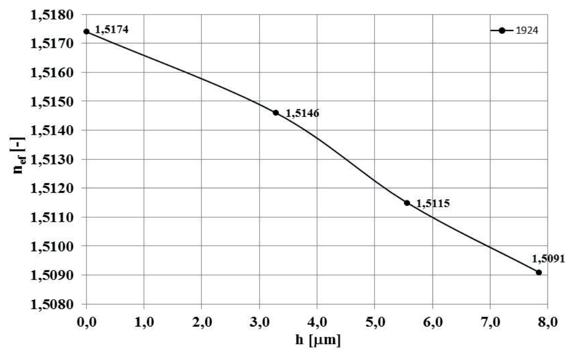

Fig. 3. Depth refractive index profile of fabricated planar waveguides made by $K^+ \leftrightarrow Na^+$ (λ = 632.8 nm).

4. Design of the Channel Waveguide

To obtain more accurate data for design of optical channel waveguides, we at first realized four samples of optical planar waveguides as described in [5].

For the diffused channel waveguide, no analytic solutions exist for (1), therefore numerical techniques must be employed. We use BeamPROP simulation engine of the Rsoft CAD photonic suite [7]. Software uses finite difference beam propagation method to solve the well-known parabolic or paraxial approximation of the Helmholtz equation [8].

By using the data measured on fabricated waveguides a single mode optical channel waveguide was designed. Its properties are presented in Tab. 3.

n_s [-]	1.4923
Δn [-]	0.03
n_c [-]	1
w [μm]	4
h [μm]	4

Tab. 3. Properties of designed channel waveguide for wavelength 1552 nm.

The design was developed for surface channel waveguide made by one step thermal IE. The diffusion profile is in BeamPROP software defined by [8]

$$n(x,y) = n_S + \left[\Delta n g(x) f(y)\right] \tag{2}$$

where function $g(x)$ is expressed as

$$g(x) = \frac{1}{2}\left\{ erf\left[\left(\frac{w}{2}+x\right)/h_x\right] + erf\left[\left(\frac{w}{2}+x\right)/h_x\right]\right\} \tag{3}$$

where n_s is refractive index of the substrate, Δn is maximum refractive index change produced by diffusion from an infinitely extended source, w is the width of the source in the horizontal direction, and h_x and h_y are diffusion lengths in horizontal and vertical direction respectively.

The vertical profile $f(y)$ is determined by the diffusion shape. Based on measurements of depth refractive index profile, Gaussian diffusion shape was employed and is expressed by

$$f(y) = \exp\left[\frac{-y^2}{h_y^2}\right]. \tag{4}$$

Substituting parameters from Tab. 3 into equations (2) to (4) we get the refractive index profile (Fig. 4).

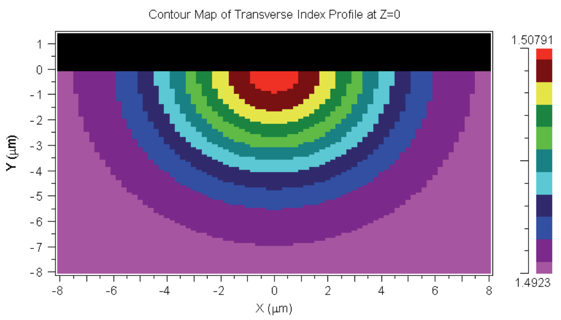

Fig. 4. Refractive index profile of designed channel waveguide.

Number of guided modes for wavelength of 1550 nm with TE polarization was verified. The transversal mode profile of the fundamental mode is shown in Fig. 5. The single mode regime of the designed channel waveguide was verified in a wavelengths band of 1260-1625 nm.

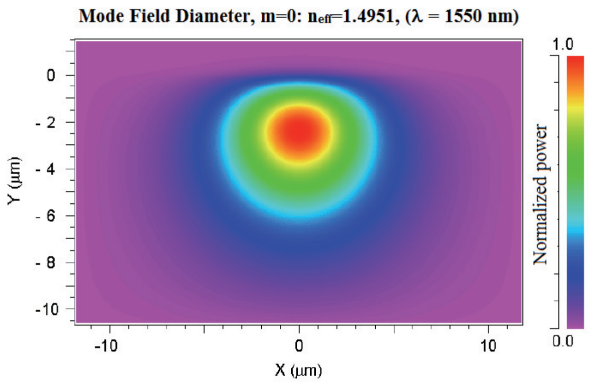

Fig. 5. Refractive index profile of designed channel waveguide.

5. Design of a Multimode Interference Power Splitter

Guided-wave devices based on MMI effect work on the self-imaging principle described in more detail in [1]. At first, it has been analyzed in waveguides with step index profile. The propagation constants of these waveguides show nearly quadratic dependence on the mode number m ($m = 0, 1, 2 \ldots m$-1). Similar dependence occurs also in waveguides made by $Ag^+ \leftrightarrow Na^+$ and $K^+ \leftrightarrow Na^+$ ion exchange in molten salt.

5.1 Basics of the Design of MMI Splitter

For determination of the MMI section length it is necessary to define L_π as a beat length between the two lowest order modes given by

$$L_\pi \cong \frac{4 n_{eff} W_{MMI}^2}{3\lambda} \tag{5}$$

where n_{eff} is effective refractive index of the fundamental mode in the MMI section, W_{MMI} is the width of the MMI section and λ is the free space wavelength.

If the MMI section is fed symmetrically, only the symmetric modes $m = 0, 2, 4, 6\ldots$ are excited and the self-image of input field is formed at a distance defined by

$$L_1 \cong \frac{3L\pi}{4}. \tag{6}$$

The N-fold image (Fig. 6) is then found at a distance given by

$$L_N \cong L_{MMI} \cong \frac{3L\pi}{4N}. \tag{7}$$

The length (L_{MMI}) and width (W_{MMI}) of the multimode waveguide is the most critical factor in determining the device performance [9].

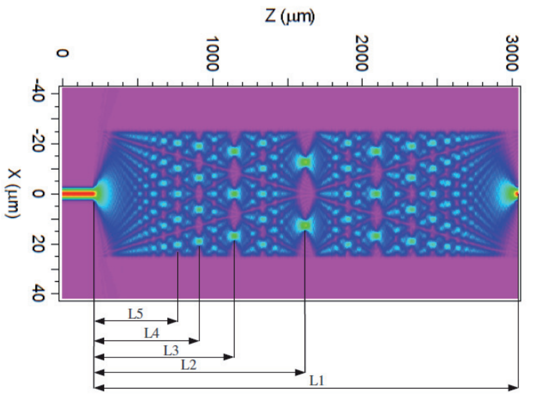

Fig. 6. Detail of MMI section. Input waveguide exciting the MMI section, where the self-image interference at the distance L1 and N-fold images at the distance L2-5 occur.

5.2 Design of 1 to 3 MMI Splitter

The design of MMI splitters (Fig. 7) was done by using the 3D beam propagation method implemented in RSoft BeamPROP tool for operation at the wavelength of 1550 nm.

The general structure of a MMI splitter 1 to N consists of three basic sections. The MMI section is excited from the single-mode channel waveguide designed in the previous chapter. This single mode waveguide is connected to the multimode waveguide, where the self-imaging effect is observed.

However, the W_{MMI} cannot be chosen arbitrarily small. The rule for low-loss and well balanced 1 to N splitting is, that the multimode waveguide section should guide at least $m = N + 1$ lateral modes. [9], [10].

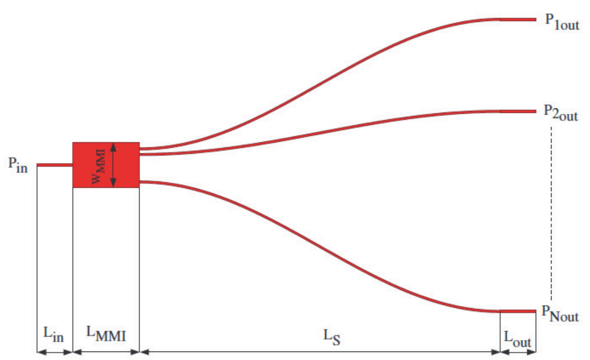

Fig. 7. Structure of the 1 to N MMI splitter.

Several widths were calculated for the four multiple images MMI section by the MOST optimizer tool of RSoft. The best results were obtained for 68.5 µm width and 4 µm depth of the MMI section. Thus, the multimode waveguide has 7 even modes in the lateral direction and is single mode in the transversal direction. The simulation result of energy coupling in the MMI section can be observed in Fig. 8.

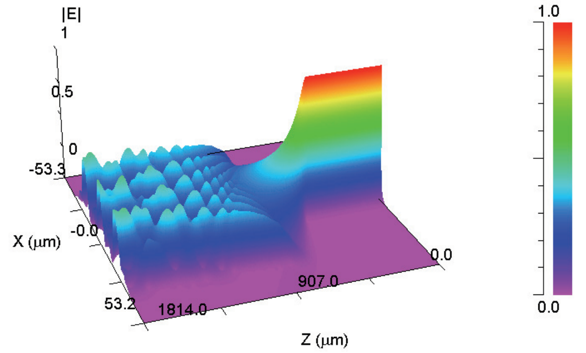

Fig. 8. 3D electromagnetic field evolution in MMI for W_{MMI} = 68.5 µm and L_{MMI} = 1514 µm.

The calculated length of MMI width W_{MMI} = 68.5 µm is, according to (7), equal to 1505 µm. However, the simulation results show that the length of the MMI is slightly longer for the designed diffused waveguide. The difference between the calculated length and the length obtained from the simulation is 10 µm.

Having set the dimensions of the MMI section, it is necessary to design S-bend waveguides that lead multiple images to the outputs. The spacing between output waveguides is set to 250 µm to provide fiber compatibility.

The S-bends were optimized to allow maximum bend loss of 0.1 dB in each bend and minimum bend radius larger than 20 mm, which is a requirement for waveguides made by ion-exchange. Under these conditions, the minimum length of the S-bends was calculated to be L_S = 9 324 µm.

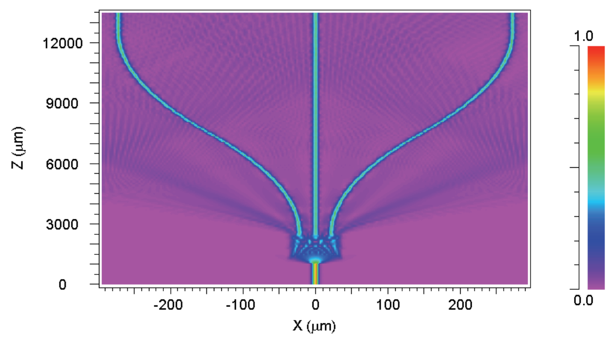

Fig. 9. Final simulation of the 1 to 3 MMI optical power splitter.

Fig. 9 shows the result of simulation of the complete structure of the 1 to 3 power splitter with coupling efficiency of 29.8% for each output waveguide. As can be seen from this figure, losses are caused by radiation from the end of the MMI section. This occurs due to diffracted energy in the multiple images, which is caused by bending of electromagnetic waves on the diffused waveguide layer and the substrate boundary.

6. Conclusion

The multimode interference power splitter design and modeling of thermal ion exchange in glass substrate is reported. At first, several samples of planar optical waveguides were fabricated by silver sodium and potassium sodium thermal ion-exchange technology process and measured by optical mode spectroscopy. Based on measurements, first, an optical single mode channel waveguide and then, a multimode interference 1 to 3 splitter with graded refractive index was designed.

When the length of the input and output waveguides $L_{IN} = L_{OUT}$ is chosen equal to 300 µm, the length of the MMI section 1515 µm and the S-bends waveguides 9 324 µm, the total length of the device will be approximately 12 000 µm.

Future research will be focused on fabrication of the designed splitter and the design of more complex structures of the optical multiplexers based on multimode interference effect in graded waveguides.

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