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Ultra-compact three-port trench-based photonic couplers in ion-exchanged glass waveguides ☆

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ABSTRACT

An ultra-compact three-port photonic coupler is proposed on a glass substrate based upon a principle of frustrated total internal reflection. A single slash shape narrow trench at the "T" intersection of two ion-exchanged waveguides forms the coupler and is aligned 45° to the waveguides. The three-dimensional finite difference time domain (FDTD) theory is used to simulate the parameterization of the coupler, such as splitting ratios and efficiency versus trench widths, trench lengths, trench locations, and trench angles. The waveguide model used in FDTD is based on an experimental condition of the K^+–Na^+ ion-exchange process. A single-mode 6 μm wide glass waveguide at 1550 nm wavelength is fabricated through the analysis of the effective index method. The numerical results show that the arbitrary splitting ratios may be controlled by trench widths and trench angles. Comparing to Si, InP and GaAs materials, trench-based coupler on glasses may readily achieve the manufacturability since the low index of glass waveguides results in a wider trench opening. Taking advantage of low loss ion-exchanged waveguides, the high efficiency and short interaction length photonic couplers have a great potential to be integrated for large scale glass-based photonic circuits.

1. Introduction

Comparing to semiconductor materials, glass-based integrated photonics represent an alternative technological innovation that provides many advantages such as low cost, excellent transparency, high threshold to optical damage, and good mechanical rigidness [1]. A photonic coupler is a basic building block for optical integrated circuits since it requires the splitting of light propagation down one single waveguide into multiple waveguides and vice versa. Typical optical couplers, such as adiabatically tapered Y-branch, directional type or multimode interference structure [2–6], are either limited by a long interaction length or large amounts of real estate. On the other hand, the development of photonic integrated circuits needs more devices capable of being integrated into the circuits for a high dense purpose.

Trench-based photonic couplers operating on frustrated total internal reflection (FTIR) were first demonstrated in 1987 [7]. The miniature photonic coupler consists of a groove at the intersection of two perpendicular AlGaAs/GaAs ridge waveguides. Recently trench-based couplers gradually emerge from the demand of large scale photonic integrated circuitry due to small physical footprint. FTIR has been studied in depth in the literature and is a well understood phenomenon [8]. The behavior of FTIR was also verified in an alumina dielectric waveguide in millimeter wave regime [9]. Up to date these trench-based couplers have been realized in different substrates, including silicon-on insulator [10], GaAs–AlGaAs waveguides [11], and InP-based quantum well substrates [12,13]. The phenomenon is similar to the effect of optical tunneling. The field of the evanescent wave penetrates into a trench and reaches the opposite interface, forms the transmitted light. The reflected light exhibits a small lateral Goos–Hänchen shift and behaves as a total internal reflection wave.

In this work, an ultra-compact three-port trenched-based photonic coupler is proposed on a glass substrate based upon a principle of frustrated total internal reflection. A single-mode ion-exchanged channel waveguide at 1550 nm wavelength is fabricated and characterized through the analysis of the effective index method. The three-dimensional (3D) finite difference time domain (FDTD) theory is used to simulate the design parameters of the coupler, such as splitting ratios and efficiency versus trench widths, trench locations, and trench angles, etc. The waveguide model used in FDTD is built from the experimental condition of the K^+–Na^+ ion-exchange process. The numerical results for the parameterization of the couplers are also given.

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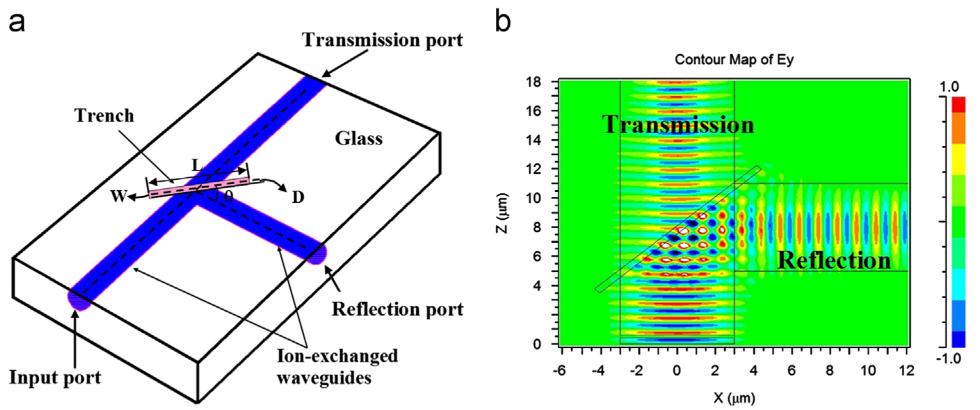

Fig. 1 (a) Schematic of a three-port trench-based FTIR coupler on a glass substrate, W: trench width, L: trench length, θ: trench angle, and D: trench location, (b) FDTD analysis of an air-filled trench 3dB FTIR coupler in single mode 6.0 μm wide K^+–Na^+ ion-exchanged waveguides.

2. Coupler description

Consider the case that includes two waveguides meeting a "T" intersection. A deep trench is cut into the intersection and aligned 45° to both waveguides. The lower index of the trench than that of the waveguide is assumed, and further it is low enough such that a 45° angle of incidence is totally internally reflecting through a lateral Goos–Hänchen shift, the trench may act as a mirror. If the trench is narrow enough that the exponentially decaying field on the far side of the interface has non-negligible strength when it is incident upon the far side of the trench, the mirror will be partially reflective and partially transmissive. Fig. 1(a) shows a schematic of the three-port trench-based couplers on a glass substrate. A single slash "/" shape trench located at the intersection of two ion-exchanged waveguides forms the coupler. The trench parameters are also labeled in the figure. For an air-filled trench, the critical angle is approximate 41.5° with a substrate index of 1.50834. Fig. 1(b) shows an equal power splitting through a FDTD analysis of the three-port FTIR coupler with a 0.55 μm wide air-filled trench for transverse electric (TE) polarized light.

3. Analysis of ion-exchanged waveguides used in the coupler modeling

The trench-based couplers proposed here are realized in ion-exchanged glass waveguides. Prior knowledge of the waveguides is required for the coupler modeling. The method to fabricate glass-based optical channel waveguides involves a conventional K^+–Na^+ ion-exchanged process. The index profile of a channel waveguide is expressed by [14]

$$n(x,y)=n_s+\Delta n_{\max}\exp(-y^2/d_y^2)erfc(x/d_x),\quad x\geq 0 \tag{1}$$

where n_s is the substrate refractive index, x is the depth coordinate, $\Delta n_{\max}$ is the maximum index change, d_y is the half-width of channel waveguide, and d_x is the diffusion depth. The peak index of the channel waveguide is given by $n_f=n_s+\Delta n_{\max}$. In the case of K^+ ion-exchange slab waveguide, Eq. (1) shows that the measured refractive index profile of the slab waveguide may be modeled by a complementary error function in the x direction. The more general form by the use of Wentzel–Kramers–Brillouin (WKB) approximation is written by [15],

$$2V_d\int_0^{\xi_t}\sqrt{erfc(\xi)-b}\,d\xi=(2m+\frac{3}{2})\pi \tag{2}$$

where $\xi=x/d_x$, V_d is the normalized diffusion depth, and $V_d=k_0d\sqrt{n_f^2-n_s^2}\approx k_0d\sqrt{2n_s\Delta n_{\max}}$, the mode number $m=0$, 1, 2,…, b is the normalized mode index, and $b=(n_{eff}^2-n_s^2)/(n_f^2-n_s^2)$,

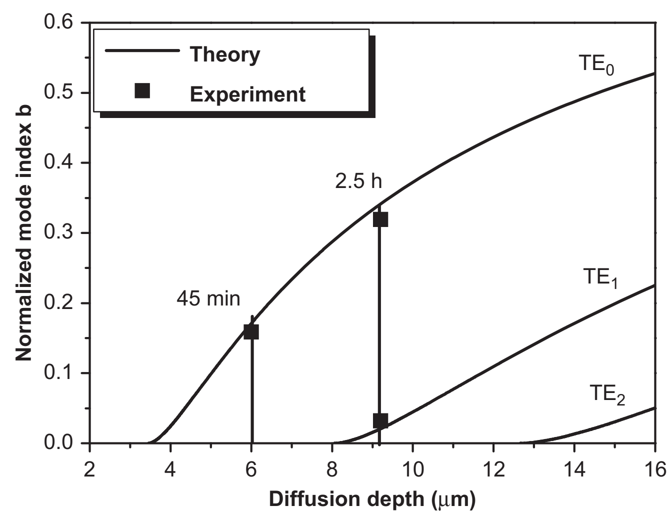

Fig. 2. Theoretical dispersion curves and measured effective indices of TE modes in the slab waveguides at a wavelength of 1550 nm (T=385 °C, t=45 min to 2.5 h).

here n_{eff} is the effective indices of guided modes. Fig. 2 shows the theoretical dispersion curves of TE modes for the slab waveguides at a wavelength of 1550 nm.

In order to analyze an ion-exchanged channel waveguide, the effective index method is used here [15]. The channel waveguide is divided into a slab waveguide I with light confinement in the x direction and a slab waveguide II with light confinement in the y direction, as shown in Fig. 3. In the slab waveguide I, the normalized mode index, b_I, can be obtained graphically using the dispersion curves in Fig. 2 at 1550 nm wavelength. Thus,

$$N_I=\sqrt{n_s^2+b_I(n_f^2-n_s^2)} \tag{3}$$

The normalized expression for an optical channel waveguide is written as.

$$2V_{dII}\int_0^{\xi_t}\sqrt{\exp(-\xi^2)-b_{II}}\,d\xi=(m+\frac{1}{2})\pi \tag{4}$$

where $V_{dII}=k_0d_y\sqrt{N_I^2-n_s^2}$ is the normalized frequency, and $b_{II}=(N^2-n_s^2)/(N_I^2-n_s^2)$ is the normalized mode index of the channel waveguide.

Fig. 4 shows the dispersion curves of the ion-exchanged channel waveguide for a fixed waveguide width of 6.0 μm, and the quasi-TE modes are illustrated. As the waveguide width is