

# Single-mode-fiber-matched waveguide by silver/sodium ion-exchange and field-assisted ion-diffusion

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Single-mode-fiber-matched glass based waveguide is manufactured by silver/sodium ion-exchange, and field-assisted ion-diffusion subsequently, in specially melted sodium-rich silicate glass substrate of optical quality. Propagation loss and coupling loss respectively of  $\sim 0.10$  dB and  $0.20\sim 0.30$  dB/facet is achieved, based on this process, integrated optic  $1\times 8$  power splitter has been fabricated, with insertion loss (IL) and polarization dependent loss (PDL) being respectively lower than  $11.0$  dB and  $0.1$  dB, over wavelength range of  $1520\sim 1570$  nm.

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## 1. Introduction

Glass-based waveguide made by ion-exchange technology has long been deemed as one of most promising candidate for building integrated optic devices, due to its compatibility with optical fiber, low propagation loss, and most distinguishingly, potentially cost-effectiveness[1]. Therefore, ion-exchange technology for glass waveguide fabrication have been intensively investigated since 1972, when Izawa and Nakagome[2] demonstrated the first ion-exchanged waveguide of  $Tl^+$  ions in silicate glass containing oxides of sodium and potassium. Up to recent years, glass integrated optic devices made by ion-exchange have been brought out from the laboratory into the realm of practical application, and exhibit unique competence among optical communication and sensing devices[3].

Among specifications of glass waveguide devices for optical communication network application, the most important one is insertion loss (IL), which could be improved effectively by burying the waveguide core into underneath the glass substrate surface. Buried waveguide could be fabricated through pure thermal ion diffusion[4,5], or field-assisted ion diffusion[6]. Application of DC electric field in field-assisted ion diffusion provides another degree of freedom to achieve the required depth, and thus an elaborately optimized waveguide structure, enabling high performance waveguide. In a buried waveguide, scattering loss of guided light due to irregularities at glass surface could be eliminated completely. On the other hand, a more symmetrical refractive index profile would be achieved at the same time, which ensures low polarization dependent loss (PDL), and low coupling loss with single-mode fiber as well.

Fundamental principles of ion-exchanged and field-assisted ion-diffusion waveguide process have been demonstrated shortly after rising of ion-exchanged waveguide technology. While up to present days, papers on buried waveguide give few detailed discussion on buried waveguide structure and the corresponding experimental process. Using specially melted glass substrate, deeply buried and single-mode fiber matched waveguide has been manufactured in our laboratory. In this paper, we report a channel waveguide manufacturing process and device based on this process.

## 2. Experimental

Glass substrate material is of critical importance in manufacturing of deeply buried waveguide. Being not optimized for ion-exchanged process, optical glass brands commercially available are hardly suitable for buried waveguide manufacturing, having been experimentally proved. In our experiment, Glass material used for ion exchange is specially prepared which is highly pure sodium-rich silicate glass ( $Na_2O$  content  $\sim 15$  mol%) of optical quality. Glass substrate used for waveguide device is disc-shaped, with diameter and thickness  $75$  mm and  $1.2$  mm, respectively.

Buried channel waveguide is manufactured by two steps: In the first step, surfaced channel waveguides are formed by purely thermal ion exchange at  $290^\circ C$  in melted salt mixture of  $AgNO_3/NaNO_3/Ca(NO_3)_2$ ,  $n[AgNO_3]:n[NaNO_3]:n[Ca(NO_3)_2]$  being  $3:500:500$ , with  $Ca(NO_3)_2$  being induced to lower salt mixture molten point. The waveguide structure is delineated by photolithographically defined “windows” in the vacuum evaporated aluminum masking film. In the second step,

masking film on glass substrate is chemically etched-off, after which field-assisted ion diffusion is performed to bury the surface channel waveguide into the glass substrate. Experimental apparatus for field-assisted ion diffusion is schematically shown in Fig. 1, the glass substrate is glued to a quartz barrel using temperature resistant silicone sealant to hold cathode melted salt mixture, a quartz container is used to hold anode melted salt mixture, both cathode and anode melted salt mixture are  $\text{NaNO}_3/\text{Ca}(\text{NO}_3)_2$ , with  $n([\text{NaNO}_3]:n[\text{Ca}(\text{NO}_3)_2])=1:1$ , two platinum disk-shaped electrodes are immersed in the melted salt mixture and connected respectively to the cathode and anode of a DC power supply. Field-assisted ion diffusion is performed at 240, much lower than that in the first step. Low temperature and high electric field applied across the glass substrate makes electromigration (drift) velocity prominent with respect to the thermal diffusion velocity.

The DC power supply used could operate in two modes, i.e. constant voltage (CV) mode, or alternatively, constant current (CC) mode. Considering resistance of glass substrate decreasing with time at constant voltage, a

CV-CC two-step field-assisted regime is applied, in which CV phase enables rapid increasing of current in glass substrate, while the subsequently CC phase ensures a constant ion diffusion velocity and protected the glass substrate from being broken-down under excessively strong current.

Insulation property of the field-assisting apparatus used is experimentally verified. Replacing the glass substrate by a silica substrate, and maintaining voltage same as that for waveguide manufacturing, very weak current on the order of micro Ampere is observed.

After end surfaces being lapped and polished, Scanning electron microscope (SEM) with backscattered electrons (BSE) wavelength-dispersive X-ray spectroscopy (WDS) was utilized to obtain the ion concentration map in the diffusion region. IL and PDL characteristics of straight and bended channel waveguide are measured, and furthermore, as a demonstrative device, IL and PDL characteristics of  $1\times 8$  splitter based on cascaded Y branch configuration over wavelength range of 1520~1570 nm are measured.

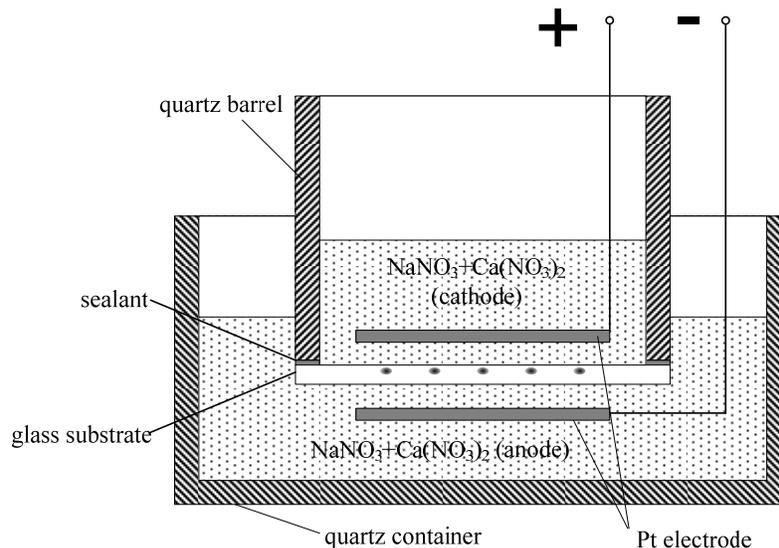


Fig. 1. Configuration of field-assisted ion diffusion.

### 3. Results and discussion

Fig. 2 (a) shows the electric field and current density in the substrate during the field-assisted ion diffusion process. The CV phase lasts 30 minutes before the CC phase commences.

Resistivity of glass substrate in the process of field-assisted ion diffusion is shown in Fig. 2 (b), from which it can be seen clearly that in the process of field-assisted ion diffusion, glass substrate resistivity experiences a significant decrease before reaching a stable value.

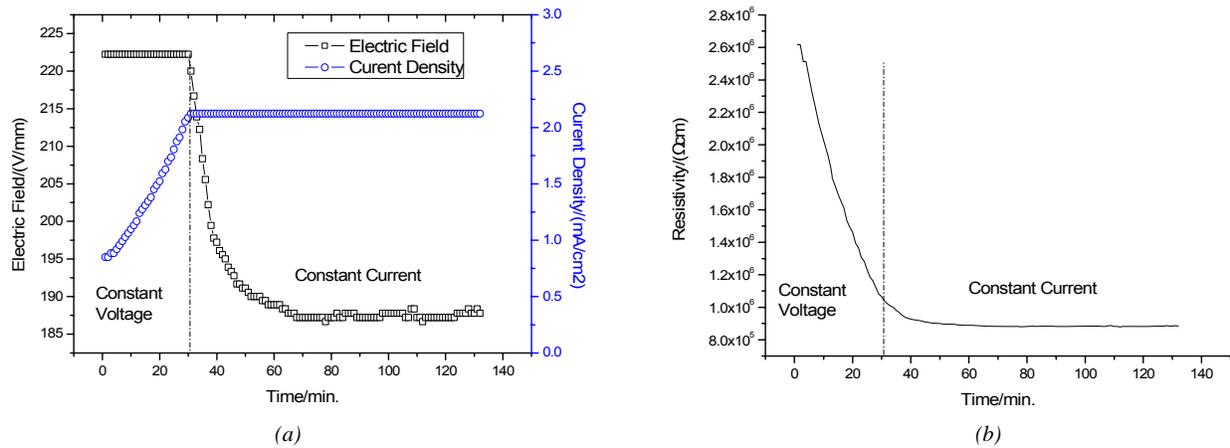


Fig. 2. (a) Electric field in the glass substrate and current density in the substrate during the field-assisted ion diffusion process; (b) and resistivity of glass substrate during ion diffusion.

Fig. 3 gives the cross section of buried waveguide acquired with BSE by SEM (left), silver element concentration map by WDS spectroscopy (middle), and calcium element concentration map (right). From which we can see clearly that the silver ions diffusion zone has been buried deeply and completely under the glass

substrate surface, burying depth of the Ag<sup>+</sup> diffusion being approximately 18 $\mu$ m.

Dimension of silver rich zone is approximately 8 $\mu$ m $\times$ 8 $\mu$ m, matching well with single-mode fiber core. There are no calcium element having been driven into the glass substrate, for bivalent possess much lower mobility with respect to univalent element.

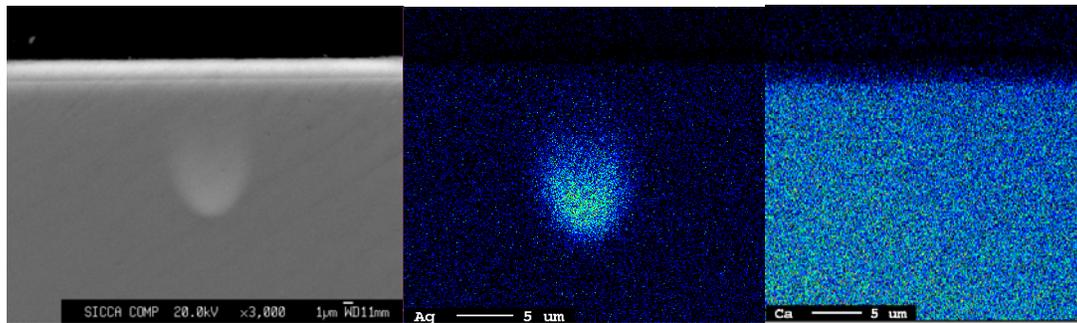


Fig. 3. Cross section of buried waveguide acquired with BSE by SEM (left), and silver element concentration map by WDS spectroscopy (middle), and calcium element concentration map (right).

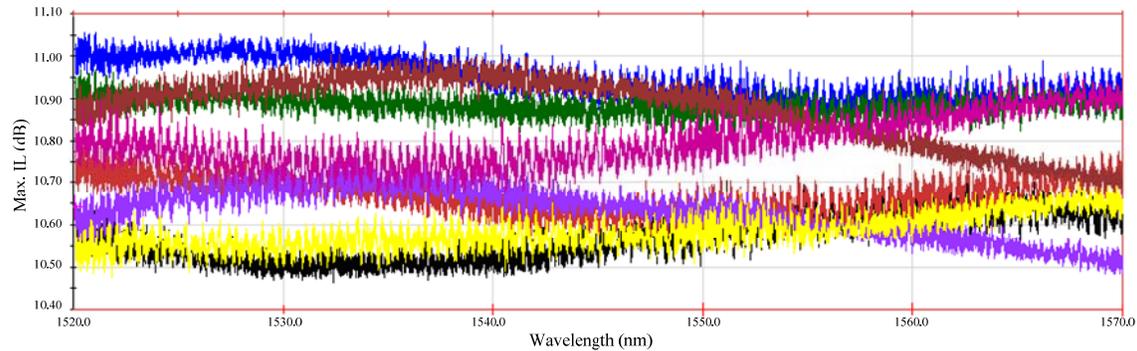
IL of straight channel waveguide with length of 32mm is typically  $\sim$ 0.80dB, PDL being 0.07dB. Further measuring on channel waveguide of different length shows that propagation loss and coupling loss of channel waveguide is  $\sim$ 0.10dB and 0.20 $\sim$ 0.30dB/facet, respectively. Bended channel waveguide with radius of curvature of 50mm show no significant difference in IL and PDL, compared with straight waveguide of approximately the same length on the same chip. It can be concluded that based on the current waveguide

manufacturing process, bending loss of waveguide with radius over 50mm is neglectably low.

IL of 1 $\times$ 8 splitter over wavelength range of 1520 $\sim$ 1570nm made by the process stated above is given in Fig. 4, Maximum value of IL and PDL being listed in Table 1. Bended waveguide radius is designed to be 80mm, to minimize bending loss. From which we know that excess loss of 1 $\times$ 8 splitter is below 2dB, comparing with loss characteristics of channel waveguide stated above, splitting loss at Y junction is estimated to  $\sim$ 0.4dB.

Table 1. *il and Pdl characteristics of 1×8 splitter made on glass substrate.*

Channel	1	2	3	4	5	6	7	8
IL(max) (in dB)	11.96	10.68	10.76	11.02	10.96	11.05	10.78	10.72
PDL(max) (in dB)	0.06	0.04	0.05	0.06	0.06	0.09	0.08	0.07

Fig. 4. *IL of 1×8 splitter over spectrum range of 1520~1570nm.*

It is worthy to point out that, by integrate the current density with respect to time in Fig. 2, we can get the electric quantity passed the glass substrate during the field-assisted ion diffusion to be 15.38 Coulomb per square centimeter, which is equivalent to electric quantity carried by mobile ions in glass with volume of  $1.32 \times 10^{-2} \text{ cm}^3$ . Considering the channel occupies only a small fraction of the glass substrate surface, and the diffusion depth of silver ion to be approximately  $18 \mu\text{m}$ , it can be estimate that under the current condition,  $\text{Na}^+$  emigrates 7.3 time faster than  $\text{Ag}^+$ .

#### 4. Conclusions

In summary, single-mode fiber matched buried channel waveguide has been manufactured in specially melted glass substrate. In the field-assisted ion diffusion step, low temperature and strong electric field make deeply burying waveguide possible, and acquired symmetry of waveguide structure at the same time. Propagation loss and coupling loss respectively as low as  $\sim 0.10\text{dB}$  and  $0.20\sim 0.30\text{dB}/\text{facet}$  is achieved in channel waveguide. Based on this process, integrated optical  $1 \times 8$  power splitter is manufactured, with insertion loss (IL) and polarization dependent loss (PDL) being respectively lower than  $11.0\text{dB}$  and  $0.1\text{dB}$ , over wavelength range of  $1520\sim 1570 \text{ nm}$ . By optimizing experimental parameters, IL and PDL characteristics of waveguide device could be further improved.

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