Numerical modelling of an error of manufacturing of ion-exchange waveguide for the tasks of quantum computations

V S Gerasimenko¹, N D Gerasimenko¹, F D Kiselev¹
¹Saint Petersburg National Research University of Information Technologies, Mechanics, and Optics, Kronverkskiy 49, St. Petersburg, 197101, Russia

Abstract. This paper describes modeling of single-mode waveguide and 3dB directional coupler for integrated optical quantum circuits manufactured by ion-exchange process. We present results of diffusion ion exchange simulation for Na⁺ ↔ K⁺ in the R₂O-Sn₂O₃-SiO₂ glass and optical elements modeling performed by the beam propagation method. There was demonstrated that the refractive index profile in the overlapping area of directional coupler can be calculated by summing two separate profiles, and error would not exceed 3%. We were able to minimize light propagation losses in the device with about 20 mm length. It was done by reducing interaction length to zero and adjusting width of the bend. After that fabrication tolerance of the device was looked. The overall transmittance of the proposed directional coupler was evaluated as 0.96

1. Introduction
It is well known that quantum information processing can be implemented on linear optics. Distribution of a photon between two modes, that can be spatial, polarization or temporal, is suitable to encode a qubit. Photonic integrated circuits are primary physical platform for quantum computations due to dimensional stability over time and compact form factor in comparison with bulk optics. Modern devices of integrated quantum optics are manufactured commonly by growing on a crystal surface or using lithography [1-5]. Both these methods are expensive and complicated. In addition, grown waveguides are often unsuitable for thermal or electric control because of the requirement of optical insulation. In this research we consider ion-exchanged waveguides in glass. This process provides a relatively easy way to get quantum chip with buried waveguide [6]. In addition light effective mode area in such device is similar to one in a single-mode optical fiber, so it is suitable for fiber-to-chip coupling with no additional device.

2. Method
In the process of ion exchange, the longest stages are the diffusion of substituting ions into glass and the substituted ones from it [7].

The first task was to simulate these processes at the stages of forming (first stage) and burying (second one) of a waveguide. It was done by solving diffusion equation for concentration (C) of substituting ions for only in-glass area near the surface (Fig. 1a) with constant diffusion coefficient (D) due to high ions similarity:
\[ \frac{\partial C}{\partial t} = D \nabla^2 C \]

Sources was simulated by boundary conditions. For first stage they were:

\[
\begin{align*}
C &= 1, \quad \text{for non-masked area} \\
\frac{\partial C}{\partial t} &= 0, \quad \text{for masked area} \\
\frac{\partial C}{\partial t} &= DC, \quad \text{for inner boundaries}
\end{align*}
\]

and for second one:

\[
\begin{align*}
C &= 0, \quad \text{for melt-glass boundary} \\
\frac{\partial C}{\partial t} &= DC, \quad \text{for inner boundaries}
\end{align*}
\]

After it concentration distribution was converted to refractive index profile \( (n) \) [8,9]:

\[
n = n_0 + \Delta n_{\text{max}} C,
\]

where \( \Delta n_{\text{max}} \) is the change in the refractive index at \( C = 1 \) (and \( \Delta n = \Delta n_{\text{max}} C \)), \( n_0 \) is refractive index of the glass before ion exchange (at \( C = 0 \)).

We achieved desired refractive index profile with 2 \( \mu \text{m} \) wide mask (Fig. 1b).

Figure 1(a, b). (a) Simulated area. Space only inside white rectangle was modelled. 1 is a mark for non-masked area, 2 for masked one when waveguide is manufacturing. When it is burying both of the marks denote melt-glass boundary. 3 is a mark for inner boundaries (regardless of manufacturing stage); (b) The result of modeling the profile of refraction. The step of counts on the axes is 0.1 \( \mu \text{m} \).

We also showed that modelling of the overlapped region can be performed by directly summing two separate refractive index profiles (Fig. 2 a,b).
Figure 2(a, b). (a) The result of diffusion simulation for interaction area; (b) The comparison of diffusion simulation and single profiles summing. The steps of counts on the axes is 0.1 μm.

Since refractive index difference between the core of the waveguide and the substrate is quite small we used beam propagation method [10] to simulate the performance of our device.

At the beginning a linear waveguide was modelled. Single-mode regime was observed for the whole infrared telecommunication range. Important result about fundamental mode in an ion-exchanged waveguide is that this mode has a profile duplicates the refraction index gradient (Fig. 3).

Figure 3. Calculated fundamental mode of the ion-exchange glass waveguide with refractive index profile shown on Fig. 1b.

After waveguide, the directional coupler was simulated. Geometry of the mask in general represents geometry of the device (Fig. 4). To reach correct coupling coefficient we need to overlap two waveguides, but refractive index profile complexity in interaction area might cause high order modes excitation. This process occur with light leaking from the device. We optimized our structure by adjusting width of the s-bends and reducing interaction length between the waveguides to zero for losses prevention (Fig. 5).
Figure 4. Geometry of the mask for the 3dB directional coupler. $S_{\text{inp/out}}$ is initial and $S_{\text{int}}$ is the interaction region separations, $w$ is a width of slits in the mask which is 2 μm. Each of the two slits correspond to left and right optical channels of the device.

Figure 5. Simulation of the optimized 3dB directional coupler. Initial separation - 160 μm, separation in the interaction region – 15.82 μm, interaction length – 0 μm. Left is the field contour map along the device and right picture shows power in the left channel (blue), power in the right channel (green) and overall power in the region (red).
As a final stage we performed simulations of the directional coupler with some errors in manufacturing process to determine scheme fabrication tolerance (Table 1).

Table 1. Effect of manufacturing errors on splitting coefficient.

| Type of error                        | Value  | Splitting coefficient difference |
|--------------------------------------|--------|----------------------------------|
| Separation                           | +5%    | -0.140                           |
| Separation                           | -5%    | +0.125                           |
| Mask thickness                        | +5%    | -0.057                           |
| Mask thickness                        | -5%    | -0.057                           |
| Exposure time (first stage)           | +5%    | -0.042                           |
| Exposure time (first stage)           | -5%    | -0.025                           |
| Exposure time (second stage)          | +5%    | -0.018                           |
| Exposure time (second stage)          | -5%    | -0.060                           |

3. Results and conclusion

We performed diffusion, optical and fabrication tolerance modeling of the 3dB directional coupler based on ion-exchanged waveguides in glass. It was shown that the refractive index profile in the regions where two waveguides overlap can be simulated by summing two separately calculated profiles which gave us a significant speed up in the optimization process. One of important ideas was to reduce coupler interaction length to zero to prevent light leaking from device. The only drawback is high sensitivity of the coupler to separation width error. Proposed optimized device has length of 20mm with maximum and minimum separation distances of 160 µm and 15.82 µm respectively. Its overall transmittance was evaluated as 0.96.

References
[1] Matthews J C F, Politi A, Stefanov A, O'Brien J L 2009 Nat. Photonics 3(6) 346-350
[2] Crespi A, Ramponi R, Osellame R, Sansoni L, Bongioanni I, Sciarrino F, Vallone G, Mataloni P 2011 Nat. Commun 2 566
[3] Politi A, Matthews J C F, Thompson M G, O'Brien J L 2009 IEEE J. Sel. Top. Quantum Electron. 15(6) 1673-1684
[4] Politi A, Cryan M J, Rarity J G, Yu S, O'Brien J L 2008 Science 320(5876) 646-649
[5] Zhang Y, McKnight L, Engin E, Watson I M, Cryan M J, Gu E, Thompson M G, Calvez S, O'Brien J L, Dawson M D 2011 Appl. Phys. Lett. 99(16) 161119
[6] Hallett D, Foster A P, Hurst D L, Royall B, Kok P, Clarke E, Itskevich I E, Fox A M, Skolnick M S, Wilson L R 2018 Optica 5 644-650
[7] Nikonorov N V, Aseev V A, Zhukov S N, Ignatiev A I, Kiselev S S, Rokhmin A S 2008 WAVEGUIDE PHOTONICS (St. Petersburg: SPSU ITMO)
[8] West B R, Madasamy P, Peyghambarian N, Honkanen S 2004 J. Non-Cryst. Solids Nov 1 347(1-3): 18-26.
[9] Zhabrev V A 1987 Obtaining and applying protective coatings: proceedings of the 12th All-Union Conference on Heat-Resistant Coatings, Leningrad April 16-18, 1985 (Leningrad: Science) p 14-18
[10] Yevick D, Hermansson B 1990 J. Quantum Electron. 26 109