On-chip realization of quantum circuits by using waveguides on Si₃N₄

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Abstract. In this paper we consider the dependence of the supported modes and the type of its polarization on the profile of the waveguide. Investigated possibility of production of beam splitters designed on the conventional waveguide.

1. Introduction
In the present the issue of creating quantum chip [1-3] is very important, in view of the fact that all possible technological solutions are moving in the direction of reducing the size, which means that we need to find ways to implement it. In particular, quantum chips are essentially nanoscale objects, which gives a considerable gain in size. Thus, the possible transfer of various linear quantum optical systems is a very important technological problem. In this work will be considered acceptable and optimal size to create waveguides in Si₃N₄, and the possibility of making structures based on waveguides and optical modes overflow between them.

2. Method
In the first part of this work we will be consider how different modes in different waveguides are supported, and why in different sizes dominant modes of the waveguides can be displayed. Also we will give an explanation how to reduce the size of the waveguide for solving this problem. On the Figure 1 you can see the waveguide’s profile without cladding.

\[ \text{Figure 1. Waveguide without cladding. Refractive indexes are: } n(\text{Air}) = 1, n(\text{SiN}_4) = 2.02, n(\text{SiO}_2) = 1.553 \]

We assume that \( E_y \) and \( E_x \) - it's vertical and horizontal polarization, respectively, if we look at the profile of the waveguide. To find the number of supported modes used Mode Solver tool from OptiFDTD package. In the second part we will explain the possibility of constructing some linear optical elements such as beam splitters (Figure 2) in Si₃N₄ using only waveguides. We obtained optimal sizes for these elements and investigated any arbitrary deviation from this values. Furthermore we will show which different circuits from different beam splitters can be realized this way and show all optimal values for its sizes.
For modeling the process of the light propagation we use the next method, which is known as FDTD. In the 2D TE case, only $H_x$, $E_y$, and $H_z$, and have nonzero components. In lossless media, Maxwell's equations take the following form:

$$\begin{align*}
\frac{\partial E_y}{\partial t} &= \frac{1}{\varepsilon} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial z} \right), \\
\frac{\partial H_x}{\partial t} &= \frac{1}{\mu_0} \frac{\partial E_y}{\partial z}, \\
\frac{\partial H_z}{\partial t} &= -\frac{1}{\mu_0} \frac{\partial E_y}{\partial x},
\end{align*}$$

(1)

where $\varepsilon = \varepsilon_0 \varepsilon_r$ is the dielectric permittivity of the material, $\mu_0$ is the magnetic permeability of free-space. The refractive index of the material is defined by:

$$n = \sqrt{\varepsilon_r}. \quad (2)$$

Each field is represented by a 2D array: $E_y(i, k)$, $H_x(i, k)$ and $H_z(i, k)$. The indices $i$ and $k$ account for the number of space steps in the X and Z direction, respectively. In the case of TE (Figure 3), the location of the fields in the mesh is shown below.

Figure 2. a) The general scales of the coupler. b) The gap between waveguides.

Figure 3. Location of the TE fields components in the computational domain
3. Results and conclusion

The number and polarization of modes, supported by the waveguide, depends on its profile and materials, surround the waveguide. In the Table 1 dimensions of the waveguide are given in micrometres. A dash indicates the absence of a supported modes. Stacked Recording format: <Ex>/<Ey>.

The following table indicates the kind of polarization is maintained waveguide. Presented that thin and wide waveguide supports horizontal polarization, but narrow and deep - vertical. At the same waveguide width of 0.5 microns and 0.2 microns reliably does not support any mode – for the light there is no waveguide structure.

The smallest waveguide observed in the symmetric case - when one is surrounded by single material on all sides. Also supported type of polarization depends on the proportions. It makes possible to make polarizers only with conventional waveguide. We have also demonstrated the possibility of constructing some linear optical elements such as beam splitters based on waveguides on Si₃N₄. We modeled directed beam splitters with different values of beamsplitting ratio (Figure 4), which are based on optical tunneling. Obtained parameters for the beam splitters with a few basic values: ½, ⅔, ¾. As an example you can see the distribution of the electric field in 50:50 beam splitter on the Figure 5. This work is extremely important because we can use such circuits to make controlled quantum networks.

| width | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 |
|-------|-----|-----|-----|-----|-----|-----|-----|
| thick | 0.2 | -/- | -/- | Ex/ | Ex/ | -/- | -/- |
| 0.25  | -/- | -/- | Ex/Ey| Ex/Ey| -/- | -/- | -/- |
| 0.3   | -/- | Ex/-| Ex/-| Ex/Ey| Ex/Ey| -/- | -/- |
| 0.4   | -/- | -/- | Ex/-| Ex/Ey| Ex/Ey| -/- | -/- |
| 0.5   | -/- | -/- | Ex/Ey| Ex/Ey| 1Ex/2Ey| -/- | -/- |
| 0.6   | -/- | -/- | Ex/Ey| Ex/Ey| Ex/Ey| -/- | -/- |
| 0.7   | -/- | -/- | Ex/Ey| Ex/Ey| Ex/Ey| -/- | -/- |

Table 1. Dependence of supported modes from waveguide’s scales.

Figure 4. Figure illustrating the amplitude on one input port at two outputs of beam splitter circuit modeled in Si₃N₄. This figure shows the amplitude distribution along cross-section for 50:50 beam splitter.
Figure 5. Figure illustrating the distribution of the electric field in 50:50 beam splitter. Waveguides presented by Si$_3$N$_4$ on SiO$_2$ substrate.

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