Highly efficient crossing structure for silicon-on-insulator waveguides

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A compact waveguide crossing structure with low transmission losses and negligible crosstalk is demonstrated for silicon-on-insulator circuits. The crossing structure is based on a mode expander optimized by means of a genetic algorithm leading to transmission losses lower than 0.2 dB and crosstalk and reflection losses below 40 dB in a broad bandwidth of 20 nm. Furthermore, the resulting crossing structure has a footprint of only $6\times 6\ \mu\text{m}^2$ and does not require any additional fabrication steps. © 2009 Optical Society of America

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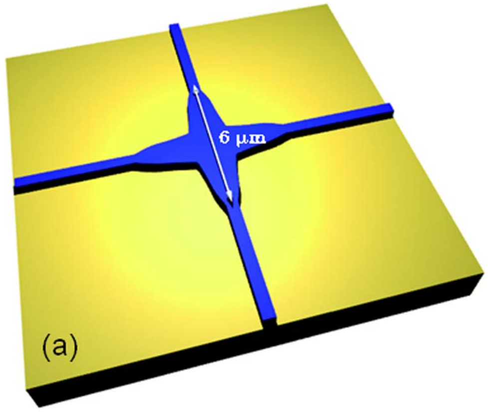
Silicon-on-insulator (SOI) is currently considered a suitable technology for enabling ultra high density integration of photonic devices owing to its high-index contrast and compatibility with high volume fabrication processes. Exciting progress has been made in the field during the past few years with significant advances in the development of key components such as modulators, photodetectors or lasers [1]. However, inefficient waveguide crosses can seriously limit the performance of advanced photonic devices, such as optical routers [2]. Waveguide crosses can be avoided in multilevel photonic devices by means of vertical waveguide couplers [3]. However, an efficient crossing structure would significantly decrease fabrication complexity in dense circuits with a high number of crosses.

Conventional 90° waveguide crosses have typically around 1.5 dB transmission losses and 12 dB crosstalk for wavelengths close to 1550 nm. Crosstalk can be minimized by choosing the optimum crossing angle so that it can be improved up to 20 dB when the crossing angle is 60° or 120° instead of 90° [4]. However, transmission losses do not decrease what imposes a serious limitation for complex photonic circuits with a high number of crosses. Recently, waveguide crosses optimized by reducing up to 20° the crossing angle and designing an offset between waveguides at the crossing point have been proposed to reduce transmission losses, but to our knowledge the resulting structure has not been demonstrated experimentally [5]. In any case, a special design of the waveguide crossing structure must be carried out when low losses and a 90° crossing angle are required.

Multimode-interference structures can be used to achieve low-loss and low-crosstalk waveguide crossings. Transmission losses around 0.4 dB and crosstalk losses below 30 dB have been experimentally demonstrated for a multimode-interference-based SOI crossing structure [6]. However, the size of the crossing structure, with a $13\times 13\ \mu\text{m}^2$ footprint, becomes rather large. Highly efficient waveguide crosses are also achieved by expanding the mode by means of elliptical or parabolic mode expanders in order to reduce the diffraction at the crossing point [2,7]. However, larger crossing lengths are also required to minimize transmission losses. Therefore, a waveguide crossing structure with a double etch was recently proposed to reduce the size of the crossing structure [8]. Transmission losses of 0.16 dB and crosstalk losses of 40 dB were experimentally demonstrated for a compact crossing structure of only $6\times 6\ \mu\text{m}^2$ footprint. However, the main limitation of this approach is that the required double etch increases the complexity and cost of the fabrication process. Highly efficient waveguide crosses have also been proposed in a periodic configuration to achieve a low-loss Bloch mode [9]. Very low transmission losses of only 0.04 dB have been theoretically obtained; however, the proposed approach is not optimum if only one cross is required. In this Letter, a waveguide crossing structure with a mode expander optimized by means of a genetic algorithm is proposed and demonstrated. Similar performance as compared with [8] is obtained, but no double etching process is required.

Figure 1(a) shows the proposed waveguide crossing structure. The size of the crossing structure is $6\times 6\ \mu\text{m}^2$. The SOI substrate consists of a 250-nm-thick silicon layer placed on top of a 3-μm-thick silica layer. The waveguide width is 500 nm to ensure single-mode transmission for TE polarization. The optimization wavelength is fixed to 1550 nm. The geometry of the arms of the crossing structure was optimized in order to achieve maximum transmission and minimum crosstalk and reflection. For that purpose the width at several points equally spaced along the arm is specified by the optimization algorithm, as it can be observed in Fig. 1(b). The actual shape of the arms is defined by a spline function that interpolates the points calculated. Optimization is carried out with a genetic algorithm. This method is especially suited for multiparametric



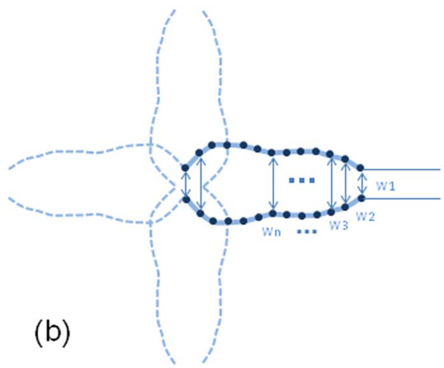


Fig. 1. (Color online) (a) Schematic of the optimized waveguide crossing structure and (b) width parameters employed in the optimization process.

optimizations. The genetic algorithm is a technique that searches the optimum in the solution space following an intelligent way that emulates the theory evolution [10]. The method starts by generating a random population of individuals. Each individual consists on an abstract representation of a point in the solution space. In this particular case the individuals are defined by arrays containing a given value for each of the width parameters at the optimization points mentioned before. Therefore, each individual corresponds to a given implementation of the crossing structure. The measure of the suitability of each individual, called the fitness, is calculated by means of 2D finite-difference time-domain (FDTD) simulations and the effective index method to save computation time. For each individual the transmission and reflection power and the crosstalk are obtained from the simulations in order to evaluate the fitness. By means of stochastic sampling and specific modification rules on the individuals of the population, new generations of potential solutions are formed in order to search for the optimum. Table 1 summarizes the obtained optimum width values of the arm of the crossing structure.

It is important to point out that the use of 2D-FDTD can be considered as a good approximation of the 3D problem, as was demonstrated in our previous

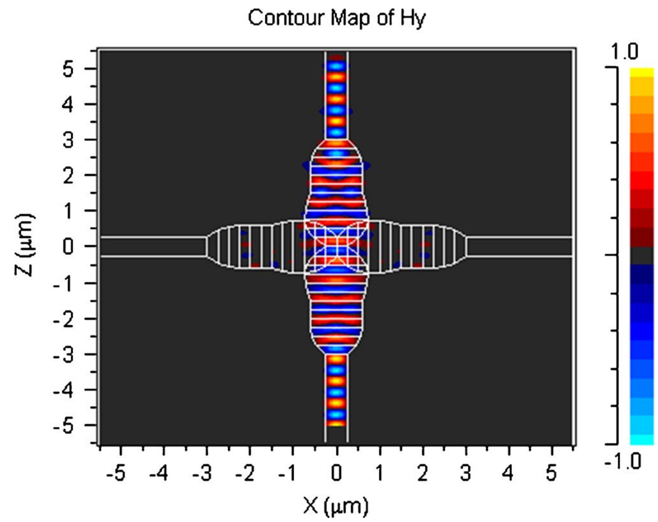


Fig. 2. (Color online) Electric field distribution of the waveguide crossing structure.

work [4]. Moreover, the resulting structure, shown in Fig. 1, was also simulated by 3D-FDTD to validate the obtained results. Transmission losses of 98.27% (0.07 dB) were obtained by 3D-FDTD simulations. Crosstalk and reflection losses were also calculated by 3D-FDTD yielding to values below 40 dB. Figure 2 shows the electric field distribution of the optimized crossing structure. It can be seen that crosstalk is negligible and that the input field is perfectly coupled to the output waveguide. The influence of width variations of the input, output, and cross waveguides by maintaining unaltered the crossing structure was also analyzed. Transmission, crosstalk, and reflection losses are almost constant when the waveguide width is varied between 450 and 550 nm.

Once the complete design was optimized, the structure was fabricated and measured. The fabrication process was carried out by using electron beam lithography over hydrogen silsequioxane (HSQ) negative resist. The electron dose was adjusted in order to achieve the optimized dimensions. After developing the sample, the patterned resist was employed as a mask in the following fabrication step consisting of a dry etching by using an inductive coupled plasma system. This process was also optimized in order to reach the right structures dimensions and profiles. Figure 3 shows a scanning-electron microscope image of the fabricated structure. Characterization was carried out by using an end-fire technique. Light from a tunable laser source was coupled into the SOI sample using a lensed fiber, and the output light was collected by an objective onto a power detector. Waveguides with up to 20 crosses were fabricated to obtain accurate results of transmission losses.

Figure 4 shows experimental and 3D-FDTD simulation results of the transmission losses as a function of the transmission wavelength, while Fig. 5 shows

Table 1. Optimum Width Values in Micrometers of the Arm of the Crossing Structure

$W1$	$W2$	$W3$	$W4$	$W5$	$W6$	$W7$	$W8$	$W9$	$W10$	$W11$	$W12$	$W13$
0.5	0.92	1.1	1.18	1.2	1.2	1.24	1.34	1.44	1.48	1.38	1.08	0.5

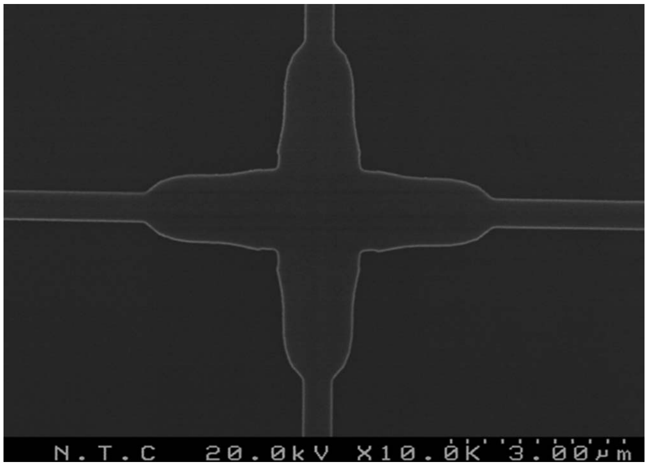


Fig. 3. Fabricated waveguide crossing structure.

3D-FDTD simulation results of crosstalk and reflection losses as a function of the transmission wavelength. In Fig. 4, it can be seen that experimental transmission losses are lower than 0.2 dB in a 20 nm bandwidth. Furthermore, it can also be observed that there is very good agreement between experimental and simulation results. Crossing losses were also characterized. Almost no output light was observed in the cross waveguides with the IR camera, as shown in the inset of Fig. 5, confirming the negligible crosstalk. Crosstalk power could not be measured, as it was below the noise floor of the power detector.

In summary, a highly efficient waveguide crossing structure with a footprint of only $6 \times 6\ \mu\mathrm{m}^2$ has been demonstrated for SOI circuits. The crossing structure, designed by means of a genetic algorithm, has transmission losses lower than 0.2 dB and crosstalk

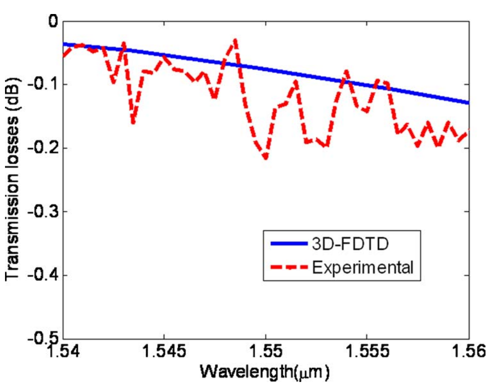


Fig. 4. (Color online) Experimental and 3D-FDTD simulation results of the transmission losses as a function of the transmission wavelength.

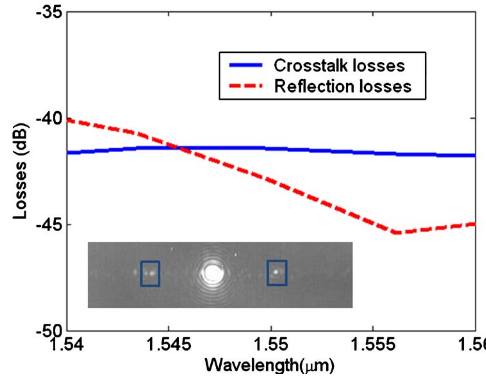


Fig. 5. (Color online) 3D-FDTD simulation results of crosstalk and reflection losses as a function of the transmission wavelength. The inset shows the output light from the direct waveguide and, in rectangles, the output light from the cross waveguides.

and reflection below 40 dB in a broad bandwidth of 20 nm. Furthermore, it does not require any additional fabrication step.

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