

# 90°-turns with polarization-independent single-mode waveguide on silicon-on-insulator for telecommunication wavelengths

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Three-dimensional Finite Difference Time Domain simulation is used to study the optical properties of waveguide 90°-turns in single-mode silicon-on-insulator rib and strip waveguides at telecommunication wavelengths.

**Keywords:** Rib and strip waveguides, Silicon-On-Insulator, Single-mode waveguides, Polarization independence, 90°-turns

## Introduction and purpose

Silicon-on-insulator (SOI) material is of interest for integrated microphotonics since it offers the potentiality of monolithic integration of optical and electronic functions on a single substrate. Moreover, silicon is transparent at telecommunication wavelengths, around 1.55  $\mu\text{m}$ . The silicon film of SOI substrates can be used as a low-loss waveguide [1]. The main advantages of the SOI arise from the strong light confinement in very small waveguides, due to the large refractive index difference between silicon and silicon oxide ( $\Delta n \approx 2$ ), and from the possibility of using established silicon microelectronics technology. In addition to the low cost of silicon technology and the availability of large wafers, SOI allows to significantly miniaturize the optical devices. Within this photonic technology, laterally confined optical waveguides can be mainly obtained either by a partial etching of the silicon film (rib waveguides), or by a full etching of the silicon film down to the buried oxide (strip waveguides).

Wavelength Division Multiplexing (WDM) is one of the technologies that is rapidly evolving to increase transmission capacity and flexibility in broadband optical fiber telecommunication networks. An important point is that most of the devices for telecommunication applications require polarisation insensitivity at wavelengths ranging from 1.53  $\mu\text{m}$  to 1.61  $\mu\text{m}$  [2] for single-mode waveguides. The problem is that for most SOI waveguide dimensions, there is a strong birefringence effect between the quasi-TE and quasi-TM optical modes, that is basically quantified by the effective index mismatch  $\Delta n_{\text{eff}}$  between the two light polarizations.

In the case of SOI rib waveguides, polarization independence was demonstrated for height larger than several microns [3]. Such solutions obviously pose problems of compactness. Recently, we made an analysis of the influence of geometrical parameters on the polarization sensitivity properties for smaller single-mode silicon-on-insulator rib waveguides [4]. We showed that a proper design of the rib waveguide dimensions ensure polarization independence, with rib heights ranging from 2  $\mu\text{m}$  to 0.5  $\mu\text{m}$ . The SOI rib-waveguide dimensions (height, width and etching depth) leading simultaneously to single mode propagation and polarization independence were calculated for telecommunication wavelengths, from 1.53  $\mu\text{m}$  to 1.61  $\mu\text{m}$ . The minimum etching depth is obtained for a nearly constant value of the ratio of the rib width over the waveguide height, within the considered height range, and is close to the rib width.

In the case of SOI strip waveguides, polarization independence can be obtained with waveguides having a square section, which theoretically ensures a degeneracy between the quasi-TE and quasi-TM optical modes. Single-mode propagation at telecom wavelengths requires waveguides with square section below 0.35  $\mu\text{m} \times 0.35 \mu\text{m}$ . Whereas such small dimensions obviously constitute an advantage for the compactness of devices, they make light coupling from a single-mode optical

fiber into SOI microwaveguides more difficult than for rib waveguides. Even if solutions for efficient light coupling into such strip SOI waveguide have been recently pointed out [5], such guides potentially suffer from increased losses, if compared with rib guides, due to the larger sensitivity to sidewall roughness.

For these reasons, both rib and strip waveguides are considered in this work. The basic question that is addressed is the following: how is it possible, with SOI polarization-insensitive waveguides, to make light take a 90°-turn ?

### SOI waveguide-based 90°-turns

Intrinsically, rib waveguides suffer from a lower confinement of light if compared with the strip geometry. For this reason, 90°-bends based on rib SOI waveguides generally require high radii to minimize losses, due to the light leakage into the SiO<sub>2</sub>/partially-etched Si film/SiO<sub>2</sub> slab waveguide. It has recently been shown that fully-etched corner mirrors offer an interesting alternative solution, in terms of both compactness and losses [6]. Even if the rib waveguides considered in ref 6 were not polarization insensitive, these results have encouraged us to evaluate the properties of fully-etched mirrors for SOI single-mode polarization-insensitive waveguides.

Optical modes have been calculated with a three-dimensional full-vectorial mode solver [7], for both quasi-TE and quasi-TM polarizations. Field distributions determined by this solver are then used as input conditions in a three-dimensional FDTD calculation [8]. Power transmittance is calculated for a range of wavelengths by a discrete Fourier transform of the field components recorded during the whole temporal simulation.

Fig. 1 shows the field distribution in the rib waveguide for the quasi-TE and quasi-TM polarizations for a 1 μm-width rib waveguide at  $\lambda = 1.55 \mu\text{m}$ , which is typical of the obtained fields for all considered waveguide geometries. Despite effective indices of the polarizations differ from only  $10^{-5}$  ( $n_{\text{eff}} = 3.38117$  at  $\lambda = 1.55 \mu\text{m}$ ), it is obvious from fig. 1 that the quasi-TE field slightly expands in the thinner silicon film region, whereas the quasi-TM mode appears to be better confined in the central part of the rib waveguide.

Fig. 2 shows the power transmittances obtained at  $\lambda = 1.55 \mu\text{m}$  for fully-etched corner mirrors based on polarization-insensitive rib waveguides, with heights ranging from 0.5 μm to 1.75 μm. Two tendencies can be drawn from fig. 2.

On the one hand, the larger the waveguide dimensions, the higher the power transmittance. Moreover, power transmittance variation with wavelength is weak. Fig. 3, which is a plot of the field obtained at half-height for the 1.75 μm-high rib waveguide for a quasi-TE polarization, confirms the weak level of losses depicted in fig. 2 for this waveguide height. 3D-FDTD simulations we have performed have proved that excessive losses obtained for small waveguides mainly originate from an excessive field compression in the corner region area. This effect does not occur in the case of slightly-etched rib waveguides, for which losses of corner mirrors below 0.1 dB can be obtained [6]. To our knowledge, this effect is reported for the first time. Small polarization-independent rib waveguides are approximately obtained by a reduction of all dimensions from larger waveguides. Small rib waveguides thus remain deeply-etched devices, i.e. they keep a strong lateral optical confinement. With the reduction of the height, corner mirrors based on polarization independent rib waveguides then tend to have properties similar to those of simple corner mirrors based on strip waveguides, which typically present power transmittances about 0.4 [9].

On the other hand, it is noticeable from fig. 2 that losses obtained for a quasi-TE or a quasi-TM polarization are close to each other, in spite of the different field extensions observed in fig. 1. This result is due to the fact that corner mirror device operation basically relies on total reflection, whatever the field is. Power transmittances obtained at  $\lambda = 1.55 \mu\text{m}$  for the 1.75 μm-high rib waveguide for the quasi-TE and quasi-TM polarizations are 0.945 and 0.942, respectively, which represents a loss difference between the two polarizations of only 0.014 dB

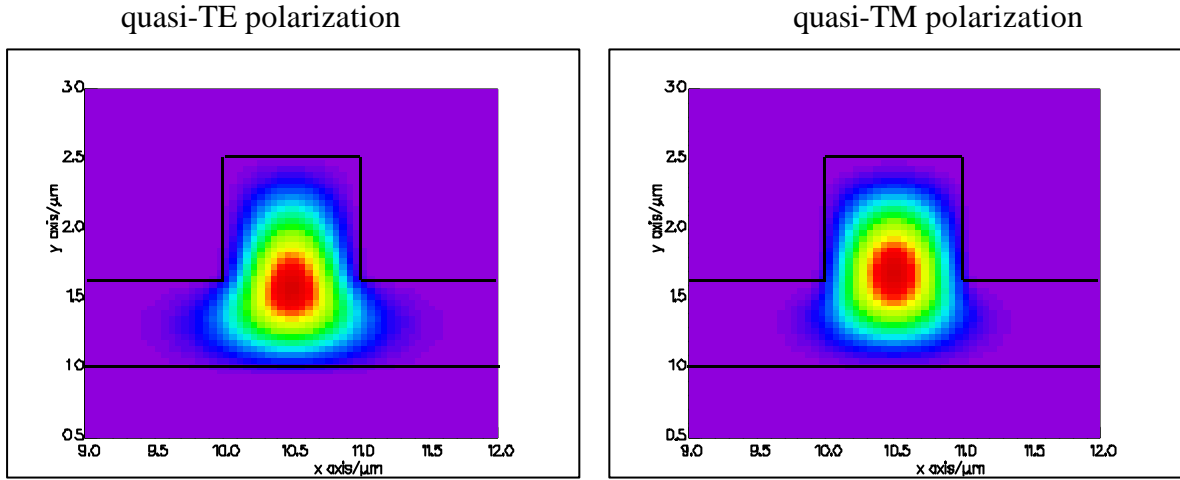
90°-turns for strip SOI waveguides have been studied in details [9]. Design of corner mirrors are possible, but efficient 90°-turns are obtained with mirrors having several slopes. Alternatively, it has been shown that 90°-bends with curvature radius of only few  $\mu\text{m}$  with strip waveguides have very low losses [10]. Following this latter approach, we have focused our study on the properties of 90°-bends based on SOI strip waveguides, using 3D-FDTD. To ensure independence to polarization, the considered waveguides have square sections.

Fig. 5 shows the power transmittances obtained for a 0.35  $\mu\text{m}$ -square waveguide, for two curvature radii ( $R = 1 \mu\text{m}$  and  $R = 4 \mu\text{m}$ ), and for the quasi-TE and quasi-TM polarizations. This waveguide dimension has been chosen because it is close to the largest one that ensures single-mode propagation at  $\lambda = 1.55 \mu\text{m}$ . We see from fig.5 that losses are weaker for the  $R = 4 \mu\text{m}$ -based than for the  $R = 1 \mu\text{m}$ -based 90°-bend, as waited. We also see from fig.5 that losses are weak in all cases, with the lowest level obtained for the quasi-TM polarization of the  $R=4 \mu\text{m}$ -based 90°-bend ( $T=98.2\%$ ), whereas  $T=97.35\%$  for the quasi-TE polarization. The loss difference between the two polarizations is about 0.04 dB for the two considered 90°-bends. It is slightly more than those obtained with the largest polarization-independent rib waveguides (0.014 dB), which have yet lower power transmittance.

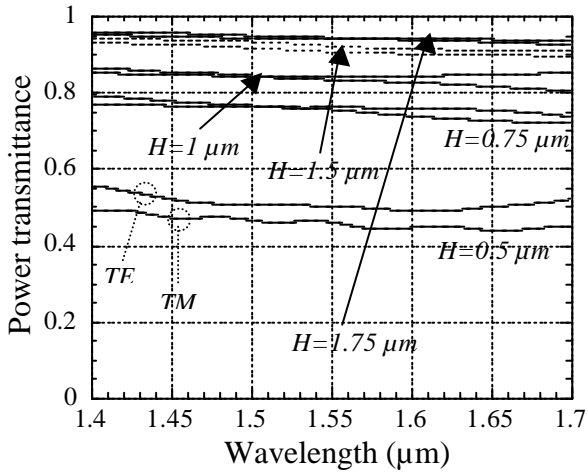
A comparison between 90°-turns based on the two kinds of SOI waveguides, i.e. rib and strip waveguides, will be presented in the full contribution, including a discussion of other important aspects for telecommunication purposes, as the magnitude of propagation losses and coupling efficiency from a single-mode fiber.

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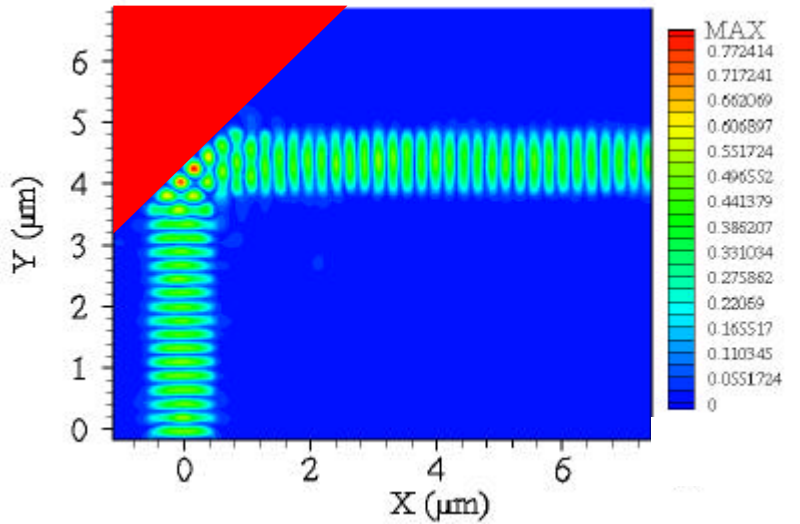
**Figure 1:** Intensity map for 1.5  $\mu\text{m}$  high rib waveguide  
Height = 1.5  $\mu\text{m}$ , Width = 1  $\mu\text{m}$  and Etching depth = 0.8925  $\mu\text{m}$



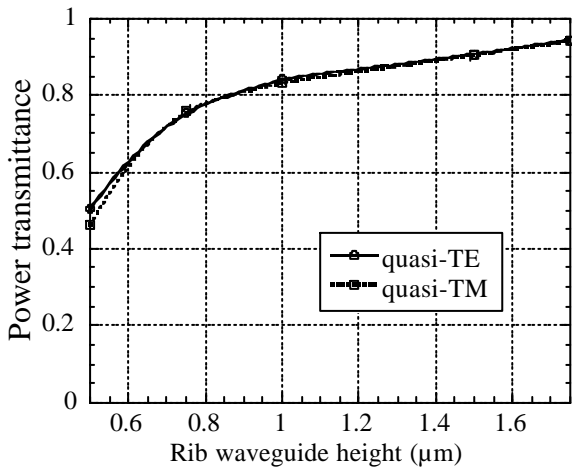
**Figure 2:** Power transmittances of corner mirrors based on polarization-independent rib waveguides



**Figure 3:** Field map obtained for the fully-etched mirror based on the 1.75  $\mu\text{m}$ -high rib



**Figure 4:** Power transmittance of rib waveguide-based corner mirrors at  $\lambda = 1.55 \mu\text{m}$  versus waveguide height



**Figure 5:** Power transmittances of SOI strip waveguide-based 90°-bends

