Polarization mode converter based on hybrid integration of nanowires on a silicon waveguide

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We present a novel technique to realize polarization mode conversion in silicon waveguides via hybrid integration of InP nanowires. A total TE to TM polarization conversion can be achieved by a proper selection of the nanowire dimensions, whose impact on the conversion efficiency, bandwidth and insertion losses is discussed. The proposed approach allows post fabrication trimming and opens the way to reconfigurable polarization-controller circuits.
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INTRODUCTION

The precise and dynamic control of the state of polarization of light is essential for the development of complex integrated photonic circuits (PICs). Several demonstrations on polarization manipulation in integrated waveguides have been reported in the literature, for example, based on asymmetric waveguide geometries, tapered waveguides, plasmonic effects, metamaterials and grating-assisted structures [1-7]. Even though these devices show relatively low insertion losses (typically <1 dB) and relatively high polarization extinction ratios (>15 dB), they typically require complex fabrication processes such as multiple lithography steps. Furthermore, the degree of polarization conversion is a priori determined by the initial design and fabrication processes and it cannot be modified or tailored at a post-processing stage. In this paper, we report on a new approach for polarization conversion in integrated devices, based on hybrid integration of semiconductor nanowires (NWs) on standard silicon waveguides. The proposed scheme allows both full TE-TM polarization conversion and an easy reconfiguration of polarization manipulation functions after fabrication. Indeed, NWs can be placed, moved or removed according to the designer needs, as previously reported in [8], enabling post-fabrication trimming and ultimately leading to a novel approach for the realization of reconfigurable polarization-coded integrated circuits. We note that such a hybrid approach can be extended to a vast range of 2D materials that can be deposited on PICs after fabrication.

RESULTS

Polarization conversion in integrated waveguides can be achieved by introducing a periodical variation of the waveguide effective birefringence [9]. In our design, this effect is obtained by placing an array of NWs on the top of a silicon waveguide, in a configuration able to periodically break the waveguide symmetry. We numerically studied the polarization rotation induced by an InP NW array integrated on top of a standard single mode silicon on insulator (SOI) waveguide (cross section of 450 nm x 220 nm), as shown in Fig. 1. Device performance in terms of polarization conversion efficiency was simulated by 3D Finite-Difference Time-Domain (FDTD) simulations using a commercial solver. The input beam was set to the linear TE polarization state at the input of the waveguide.

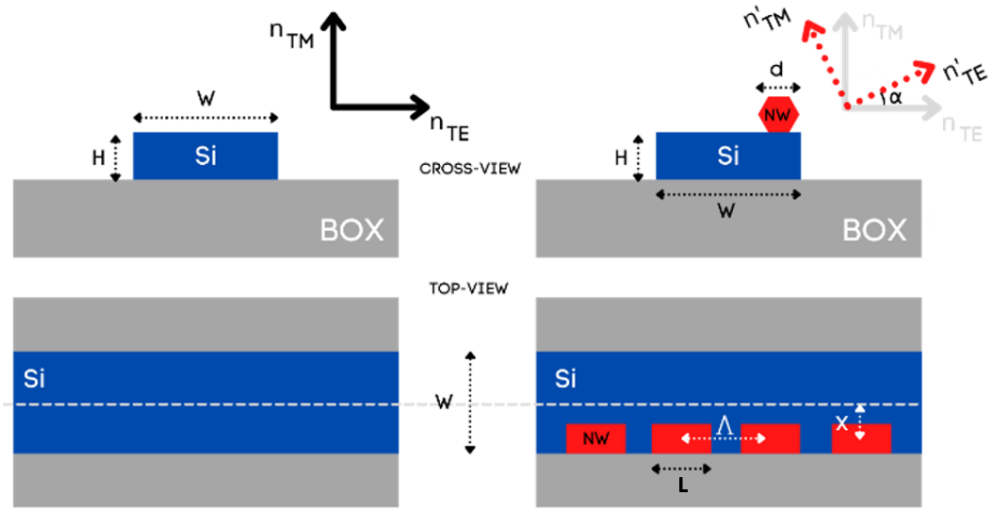

Figure 1: Cross- and top-view of a silicon waveguide being integrated with an array of NWs. The insertion of a NW results in a rotation of the waveguide effective principal axes of birefringence by an angle α. Parameters definition: W: waveguide width; H: waveguide height; d: NW diamenter; Λ: NW period; L: NW length; x: offset position between waveguide and NW centres.

In the waveguide section without the NW (see Fig.1 (left panel)), the waveguide birefringence is essentially determined by the structure geometry. Therefore, the birefringence principal axes corresponded to the TE and TM directions and the effective refractive indices were equal to $n_{eff,\,TE} = 2.35$ and $n_{eff,\,TM} = 1.73$ respectively, as calculated at λ=1550 nm for a waveguide with W = 450 nm and H = 220 nm. As qualitatively shown in Fig. 1 (right panel), the insertion of a NW on top of the silicon waveguide induces the propagation of two hybrid quasi-TE and quasi-TM modes, with a rotation of the effective principal polarisation axes of the waveguide by an angle α. This results in coupling of the optical power in the unperturbed structure from the TE to the TM mode. The overall polarization conversion efficiency along the waveguide is determined by a phase matching (PM) condition that depends on the NW dimensions, array period and on the effective birefringence along the principal axes exhibited by the structure without or with the NWs. In simple periodic structures, this effect can be modeled by a sequence of identical waveplates with a fixed and alternate rotation of the principal axes. In this case, the PM condition can be easily calculated by imposing the period of the birefringence variation to be equal to ⍰/(⍰n), where ⍰n is the effective refractive index difference of the two hybrid modes.

The NW radius and length are critical to the conversion process, since they determine both the angle of rotation of the principal axes and the amount of birefringence perturbation. Fig. 2 shows the results of our numerical simulations. The polarization conversion efficiency is plotted as a function of the number of NWs and the NW length L for different values of the NW radius R. As can be seen from Fig. 2 (left panel), the use of larger NWs allows achieving a 100% TE-TM polarization conversion efficiency using a lower number of elements compared to the case of smaller NWs, suggesting that the NW radius has a significant impact on the effective angle of rotation α. On the other hand, NWs with larger radius require a longer interaction length L to get a complete polarisation conversion from the TE to the TM mode (see Fig. 2 (right panel)). Overall, this results in a greater device insertion loss, since the optical propagation losses increase as a function of the NW length L, essentially due to a stronger light scattering, as is shown in Fig. 2 (right panel). Another aspect worth noting is the bandwidth of the polarization conversion efficiency. As a result of our simulations, we observed that the use of NWs with larger radius allow achieving a broader operational bandwdith, with an almost-flat 100% TE-TM polarization conversion efficiency across the C band.

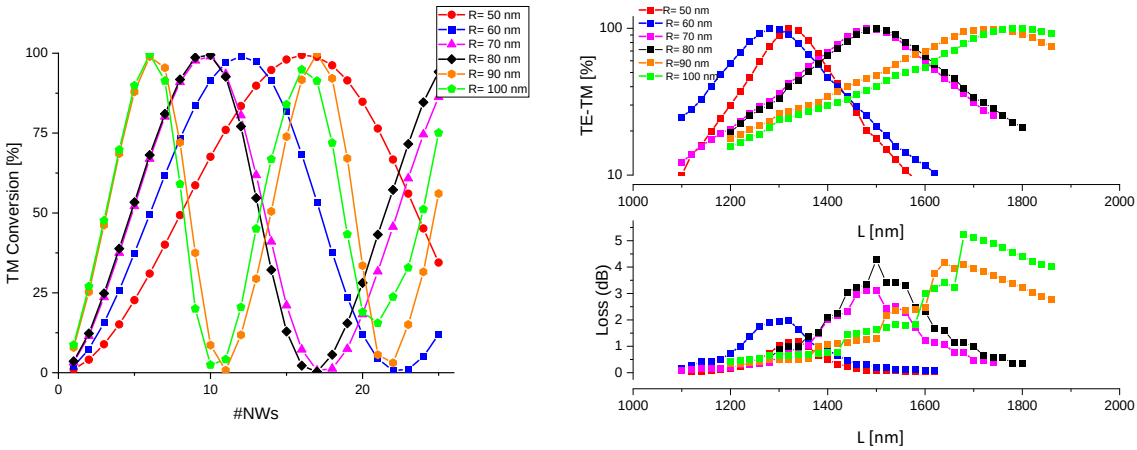

Figure 2: Left panel: TE-TM polarization conversion efficiency as a function of the number of NWs, calculated considering different NWs radius; Right panel: TE-TM polarization conversion efficiency (top) and device total insertion losses (bottom) as a function of the NWs length L.

DISCUSSION

In this paper, we report on a novel technique to realize polarization manipulation in integrated waveguides via hybrid integration of semiconductor NWs. Our results showed that TE-TM full polarization conversion can be achieved by using an array of InP NWs placed on a standard silicon waveguide. The impact of the different NW parameters was numerically investigated. The use of NWs with larger radius leads to a broader conversion bandwidth and full TE-TM polarization conversion with a smaller number of elements compared to NWs with lower radius, resulting in a reduced device footprint. However, the use of larger NWs increases the overall device insertion losses. Therefore, depending on the specific applications and their associated requirements, the NW parameters can be selected to obtain a proper balance between conversion efficiency, bandwdith, insertion losses and device footprint. The feasibility of such a scheme is already demonstrated by post-fabrication protocols [8] which allow for precise NW placing and physical manipulation onto a Si-photonics platform. Additionally, we note that the hybrid NW-waveguide integration approach can be generalized and applied to a variety of advanced photonic applications: NWs can be functionalized to perform advanced optical processing, therefore their integration to silicon devices is promising for the development of advanced integrated circuits.

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