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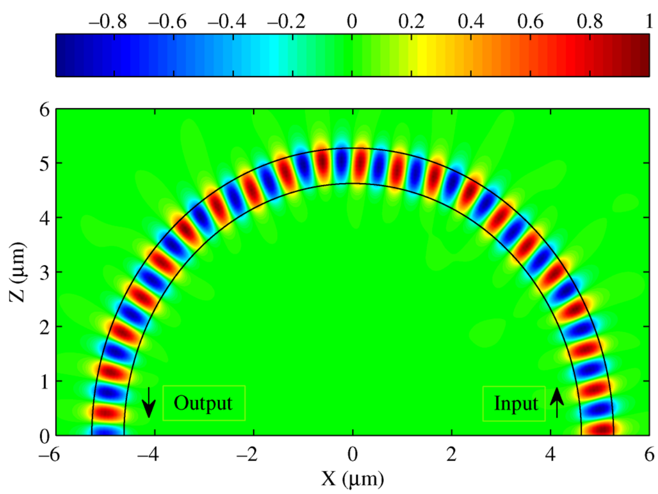

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Abstract: In a previous work, we reported a novel optical waveguide named silicon nanowire optical waveguide (SNOW), which consists of arrayed silicon nanowires acting like an effective-index medium. In this paper, we analyze bend properties of the waveguide and show that small radii bends can be achieved in SNOW structures with low radiation losses. For bend radii of 5 and 2 μm at a wavelength of 1550 nm, the radiation loss per 360° turn is 5×10^{-4} and 0.05 dB, respectively. Furthermore, we study the losses for changing the pitch between the nanowires and show that the loss behavior follows effective-index bulk waveguide approximation. Consequently, we show that the bending losses can be optimized by arranging the nanowires pitch size such that the density is higher in the inner side of the bend as compared with the outer side. Effects of wavelength and sidewall roughness on propagation loss are also investigated.

Index Terms: Integrated nanophotonic, silicon nanophotonics, waveguides.

1. Introduction

Nanoscale devices in silicon nanowires (SiNWs) bring new physical phenomena because of quantum effects providing new possibilities for optoelectronics devices. SiNWs with diameters smaller than 10 nm become direct bandgap [1] because four of the conduction band isosurfaces fold into the center of the Brillouin band. Due to direct band gap transitions, silicon nanostructures exhibit optical amplification [2] and spontaneous emission [3]. Besides, the bandgap can be changed from direct to indirect by applying compressive strain [1], allowing for optomechanical switches. SiNWs also exhibit interesting optical nonlinear properties, including three orders higher spontaneous Raman scattering for diameters smaller than 130 nm [4]. However, an SiNW with a diameter below 100 nm is a poor optical waveguide with optical confinement factors less than 1% for a diameter of 50 nm [5]. Furthermore, SiNWs exhibit high anisotropy with increased optical properties that are only observed when the electric field is polarized along the length of the nanowires [6]. Accordingly a single SiNW cannot be used as a photonic wire waveguide if one wants to use the increased material properties. Hence, improved performance in nanowire devices has not been observed in spite of the improved material characteristics [7].

In a previous work, we proposed and analyzed a novel waveguide consisting of vertical SiNWs in close proximity on a silicon-on-insulator (SOI) wafer [5]. The nanowires act like an effective-index medium, and the waveguiding was achieved, provided the electric field was polarized along the length of the nanowires as it is desirable from the anisotropy point of view. Radiation loss due to

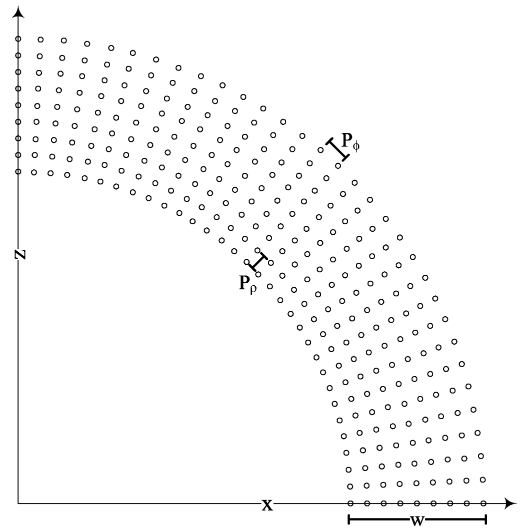

Fig. 1. Top-view schematic diagram of bend waveguide with SNOW.

scattering was less than 0.12 cm^{-1}. An optical confinement factor of 32% within the silicon region could be achieved even for nanowires with diameters smaller than 10 nm. The optical confinement factor depended on the ratio of the diameter to the pitch of the nanowires. Hence, silicon nanowire optical waveguide (SNOW) structures provide for a solution to use the increased material properties of SiNWs while achieving the optical confinement and mode shapes of conventional bulk waveguides. We have proposed the use of SNOW for optical biosensors where it increases the bulk sensitivity by a factor of 4 compared with SOI photonic wire waveguide and a factor of 20 for surface attachment. Further, optical nonlinearities increase for SiNWs as compared to bulk silicon. So there is a promise for increased efficiency in optical nonlinear devices for signal processing and logic. As SNOW is a hollow core waveguide, it can also act as a compact host waveguide for low refractive index organic polymers where the polymers can be introduced between the SiNWs. This way the guidance can be achieved with SNOW while the optoelectronic properties of the polymers can be used for optical signal processing, optical logic, modulation, etc. It should also be mentioned here that the optical mode of the SNOW is larger than that for the SOI 200-nm-wide photonic wire waveguide and allows for ease of input and output coupling to the waveguide. Assuming a Gaussian spot size of 2 μm, the coupling efficiency to a 650-nm-wide SNOW is 63%, whereas it is 39% to a 200-nm SOI waveguide.

Since the SNOW structures consist of small inclusions; there is a concern of increased radiation through the bend due to scattering of light from the nanowires. In this paper, we show that bend waveguides with small radii can be achieved and the SNOW region acts like an effective-index medium even over a bend. We analyze the radiation loss through the bend for varying radii of the bend, and pitch between the nanowires and compare the loss with a conventional bulk waveguide with core equal to the effective-index for the SNOW. Interestingly, the bend waveguide can be optimized for loss by arranging the nanowires appropriately. Furthermore, the effects of wavelength and sidewall roughness on propagation loss are also studied. Bend waveguides are important building block for implementations of various photonic components such as ring resonators, power splitters, array waveguide gratings, and Mach–Zehnders. Low loss bends in SNOW allow for these structures to be used in integrated optics.

2. Device Description

Fig. 1 shows the top-view schematic of the SNOW structure with a bend. Vertical SiNWs are etched into a SOI wafer. Since we are interested in high optical confinement, we have considered the length of the SiNWs to be larger than 500 nm, providing more than 95% optical confinement in the

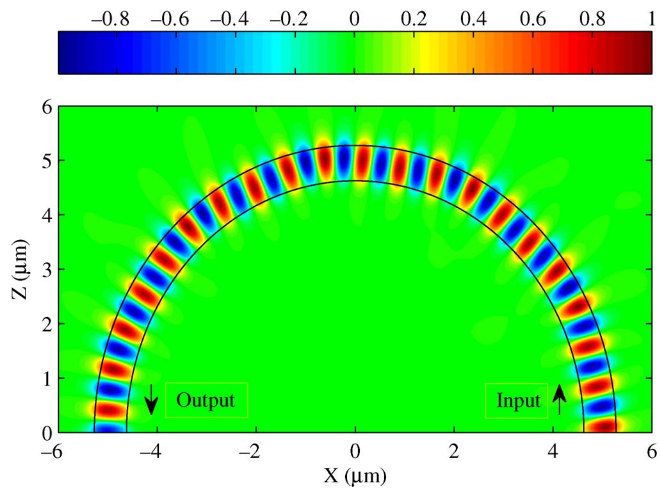

Fig. 2. Lateral electric field distribution for a bend SNOW with a radius of 5 μm at a wavelength of 1550 nm. SiNWs have diameter of 50 nm and pitch of 75 nm for both P_ρ and P_ϕ. The electric field is polarized along the length of the nanowires.

vertical direction. Cylindrical coordinates are used to define the bend in the structure. The parameters defining the structure include the width of the SNOW region (W), the diameter of the nanowires (D), the pitch in the radial direction (P_ρ) and the pitch in the angular direction (P_ϕ). For this paper, we consider a nanowire diameter of 50 nm for all the structures because of the possibility of fabricating long SiNWs on SOI wafers with current technology [8]. The width of the SNOW region is 0.65 μm for $P_\rho = 75$ nm, which is the same as what we considered earlier for straight waveguides [5]. The wavelength of operation is 1550 nm and the electric field is polarized along the length of the nanowires, polarization for which we have previously shown guidance through straight waveguides. This corresponds to quasi-TM mode for conventional waveguides. The bends are analyzed using finite-difference time-domain method with a grid size of 2 nm for SNOW structure and 10 nm when it is substituted by an effective-index medium. Between the grid points, the refractive index is linearized to decrease the effect of grid size. We varied the grid by a factor of 2 to see the numerical accuracy of the results and beyond 2 nm, there was minimal change in loss calculation. Continuous wave (CW) excitation was used to analyze the structures. In the following, the performance of device is analyzed numerically.

3. Simulation Results and Discussion

3.1. Bend Loss

For the first simulations, we considered that P_ρ and P_ϕ are equal to 75 nm. This pitch provided the lowest loss in straight waveguides [5]. The effective-index of the SNOW region is approximately 2.2 that still provide a high index contrast waveguide and thus, small bend radius should be possible with low loss. Fig. 2 shows the lateral distribution of electric field in the bend SNOW for a radius of 5 μm. The excitation is a CW source located at the beginning of the right side of the 180° bend SNOW and the light propagates counterclockwise. The figure demonstrates that the SNOW structures can bend the optical wave. Radiation loss was calculated by monitoring the decay of power along the bend and is plotted in Fig. 3 for varying radius of the bend for a 360° turn. For a radius of 5 μm, the radiation loss per turn is less than 5×10^{-4} dB and increases to 0.05 dB for a bend radius of 2 μm. Also, plotted in the same figure is the radiation loss if the SNOW region was substituted by an effective-index waveguide. The effective-index is calculated by a weighted average of the silicon permittivity and the surrounding medium (air), where the weights are equal to the area of the individual materials [5]. As seen, a good agreement between SNOW and effective-index waveguide is achieved. This shows that the SiNW inclusions do not create much scattering, even over a bend, and the losses mainly come from the radiation through the bend itself.

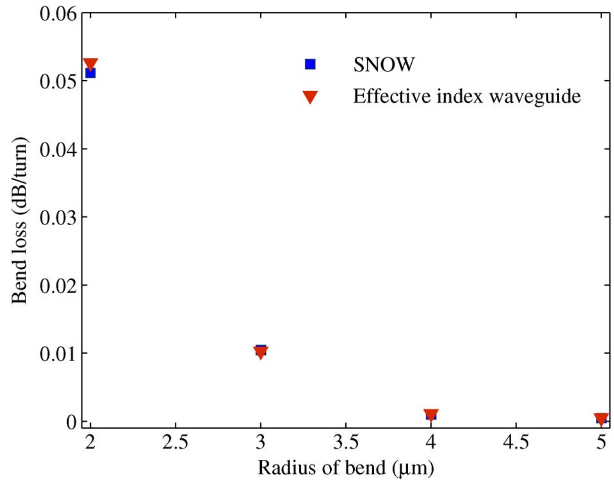

Fig. 3. Loss for various radii of bend SNOWs over a 360° turn.

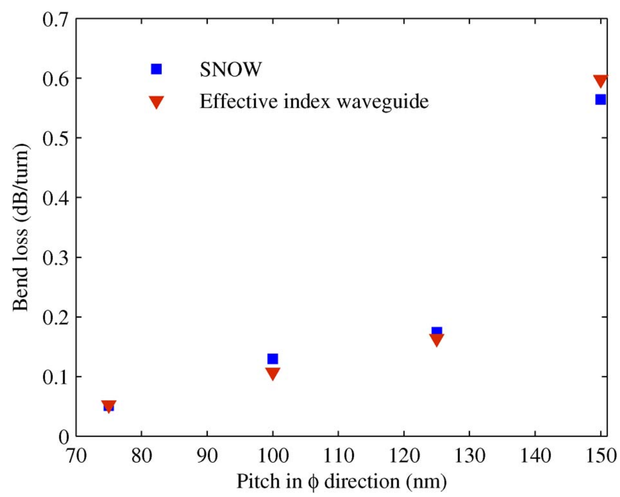

Fig. 4. Loss for various pitches in ϕ direction of bend SNOWs over a 360° turn. P_ρ is kept constant at 75 nm. The loss for effective-index waveguide is also plotted showing that the loss mainly comes from reduced waveguide confinement.

We also analyzed the structures for varying P_ϕ. Fig. 4 shows the loss for a bend radius of 2 μm when P_ϕ is varied and P_ρ is kept constant at 75 nm. The loss is low till a value for P_ϕ of 125 nm but increases appreciably after that and is equal to 0.56 dB per 360° turn for P_ϕ of 150 nm. It is to be noted that the effective-index reduces as the value of P_ϕ increases. For a value of P_ϕ of 150 nm, the effective-index reduces to 1.7 instead of 2.2. The loss for the bend if an effective-index bulk waveguide is used is also plotted, where the effective-index is calculated for the corresponding pitch. The loss increases in the same fashion suggesting that the increased loss is due to decreased waveguide confinement and not due to scattering from individual SiNWs as they are placed further apart.

The loss further increases if both P_ρ and P_ϕ are changed simultaneously because of reduced confinement. As an example for $P_\phi = P_\rho = 100$ nm, the loss increases to 1.81 dB for a bend radius of 2 μm. Since SNOW structures do not need the SiNWs to be arranged in an ordered fashion [5] and since the inclusions work as an effective-index waveguide, one can think of designing the bend for reduced loss by improved waveguide design. The idea is to have the increased effective-index in

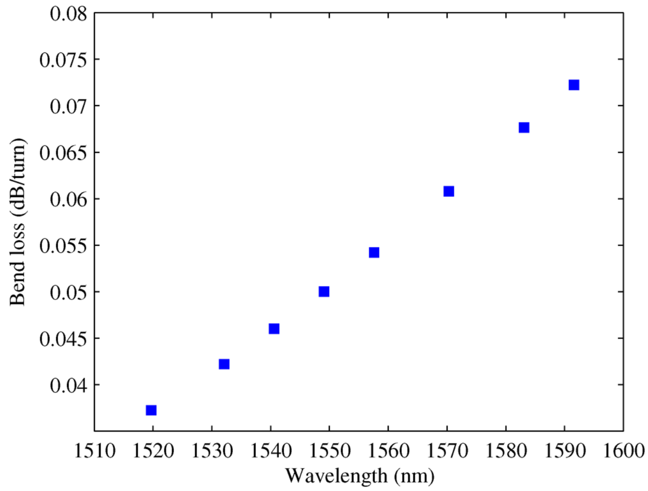

Fig. 5. Loss for various wavelengths for a SNOW with bend radius of 2 μm.

the inner part of the bend while having a reduced effective-index on the outer part. This should result in pushing the optical wave toward the inner part of the waveguide counteracting the effect of the bend which pushes the optical wave to the outside. The change of the effective-index can be achieved by changing either of P_ρ or P_ϕ over the waveguide width. We calculated the loss for a bend radius of 2 μm when the P_ϕ changed from 80 nm to 120 nm over the waveguide width in a linear fashion and P_ρ was kept constant at 100 nm. The average of P_ϕ was 100 nm. The radiation loss was 1.41 dB per 360° turn compared to a value of 1.81 dB if the both pitches were kept constant at 100 nm.

3.2. Effect of Operational Wavelength

Fig. 5 shows the bend loss versus wavelength for a bend radius of 2 μm. Both pitch sizes are 75 nm. By increasing the wavelength, optical confinement decreases because of reduction in the normalized frequency and reduction in refractive index of silicon. Consequently, the bend loss increases due to reduced optical confinement. However, the loss is still low over a wide wavelength region spanning 100 nm. This also clearly shows the SNOW bends are not working like photonic band gap (PBG) structures.

3.3. Effect of Sidewall Roughness

A main area of concern for the SNOW devices is the scattering of the light due to sidewall roughness. Sidewall roughness in photonics band gap structure is a major source of optical loss [11]. Similarly, in silicon photonics devices, owing to the high index contrast between a silicon waveguide and its surrounding medium, sidewall roughness results in significant scattering losses [12]. For example it has been shown that for a 200-nm-wide SOI waveguide, the loss due to roughness of 2 nm is 2.6 dB/cm [14]. Besides, the propagation loss may change strongly from one waveguide to another on the same wafer. Such variations are inevitable due to the manufacturing process fluctuations. Therefore, this is important to consider these variations in the designs.

We considered the effect of sidewall roughness on performance of SNOW. We assumed different amounts of perturbation from 2 nm to 7 nm on sidewall of each SiNW. Effect of sidewall roughness can be simulated by considering a systematic perturbation of the index profile. We did this by drawing the structure in a grid equal to value of the perturbation in a mask design software. The resulting structure is then converted to an index profile. To reiterate, the index is linearized between the grids. To visualize it, the profile index of a SiNW is shown in Fig. 6 for perturbations of 2 and 7 nm. Fig. 7 shows the calculated bending loss for various sidewall roughness. Bending loss for no sidewall

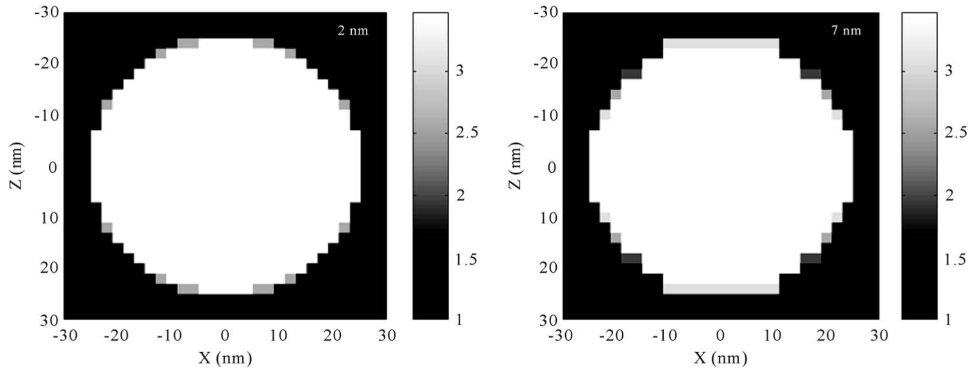

Fig. 6. Profile index of a SiNW by considering a sidewall roughness of 2 nm (left) and 7 nm (right).

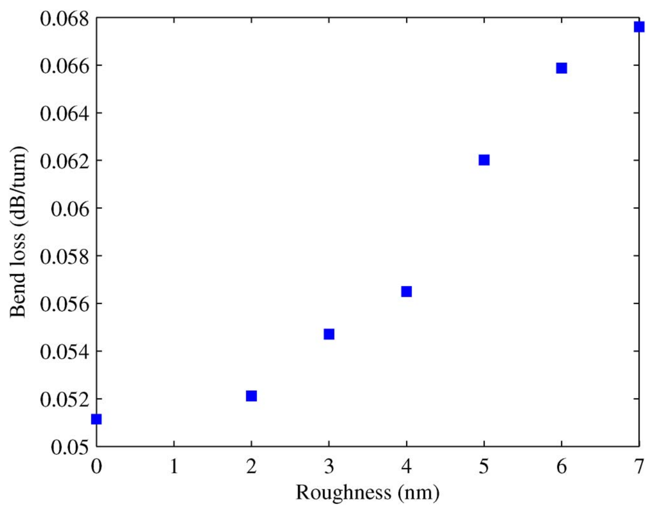

Fig. 7. Radiation loss for a bend radius of 2 μm for various sidewall roughness; the reference point of zero is provided for comparison.

roughness is also provided for comparison purposes. The excess loss due to sidewall roughness is quite small as opposed to what was achieved for photonics crystal showing another advantageous of SNOW. Further, this loss is lower than that for sidewall roughness of 2 nm in SOI waveguide. We believe the loss is low because each individual nanowire in the array has very low optical confinement, and a small perturbation in each individual nanowire does not change the phase. Further, since SNOW is acting as an average waveguide, the roughness on individual inclusions gets averaged out over many. A reduction in roughness-induced propagation loss due to decreasing optical confinement has been previously shown to occur as the waveguide width is reduced below 260 nm for SOI waveguides [14].

4. Conclusion

In summary, we propose bend waveguide using arrays of SiNWs. We also show that by adjustment of SiNWs distribution, the overall performance of this kind of bend waveguides could be improved. We analyzed the waveguide bends for different radii, different pitch between SiNWs, and also showed that the bend loss follows the effective-index approximation for the SNOW. Further, the loss is low over at least 100 nm bandwidth. We also showed that unlike PBG structures, SNOW bends are tolerant to sidewall roughness.

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