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Research Article

Keywords: Effective index analysis, Finite element analysis, Nanotechnology, Photonic integrated circuit, Photonic waveguide, Silicon nanowire, Silicon-on-insulator, Silicon Photonics, Quasi mode

Posted Date: August 20th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-473168/v1>

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Analytical Prediction for Quasi-TE mode in Silicon Nanowire Optical Rectangular Waveguide

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Abstract—Theoretical and numerical mode estimation performed on Silicon Nanowire Optical Rectangular Waveguide (SNORW) is presented for on-chip communication in photonic integrated circuits. The propagation behavior of electric and magnetic fields is investigated, where zeroth order mode is found dominating inside the nanoslot region of SNORW for the circularly symmetric quasi-TE mode to propagate. This SNORW structure supports hybrid mode, which derives its behavioral root from the rectangular waveguide and functional root from the slot waveguide. In periodic silicon nanowire-based waveguide, it is found that the envelope of mode field intensity closely matches with rectangular waveguide and the guiding properties closely matches with slot waveguide. The type of mode is analyzed by full vectorial Finite Element Method (FEM) and the analytical expression is derived using Effective Index Method (EIM). Analytical expressions are used to express Quasi-TE mode in term of material profile and waveguide physical parameters. The results obtained for SNORW in S, C and L wavelength bands are compared with the earlier reported work on slot waveguide, and the field intensity obtained with the theoretical equations is also compared with that of FEM results.

Index Terms— Effective index analysis, Finite element analysis, Nanotechnology, Photonic integrated circuit, Photonic waveguide, Silicon nanowire, Silicon-on-insulator, Silicon Photonics, Quasi mode.

I. INTRODUCTION

IN the past two decades, optical waveguides using Silicon-On-Insulator (SOI) technology are attracting many researchers of Photonic Integrated Circuits (PICs). Among various types of optical waveguides, the rectangular waveguide is the mostly used PIC structure, due to its guiding phenomenon inside the high Refractive Index (RI) region surrounded by low RI material, as similar to the optical fiber. In further studies, the guiding phenomenon inside low RI material surprised various researchers [1], as the guiding principle of optical waves is found to be the opposite of optical fibers. The vast application of smaller waveguide and design components exploration have attracted numerous researchers to work in the area of low refractive index guided photonics. Thereafter, a new category of waveguide called ‘slot waveguide’ had been evolved, which is now under intense research with its application over all the areas of PIC’s. Many researchers have since worked on the theoretical investigation of optical slot waveguide proposing wave solutions [1]–[4], where the guiding phenomenon inside low RI slot region is proven with its diverse applications. This slot waveguide is classified into various category which mainly depends on its structural configuration. Orientation based classification is known as vertical/horizontal slot waveguide. The guidance of quasi-TE mode inside vertical slot waveguide and quasi-TM mode inside horizontal slot waveguide is also been investigated by various researchers [1], [3], [5], [6]. It is proven that the guiding phenomenon is directly dependent on the physical dimension of waveguide and its material compositions. As time moves on, the evolution of a very special type of waveguide based on the working property of slot waveguide evolved, which is silicon nanowire-based waveguide [7]–[9]. The waveguide formation using vertically aligned silicon wires makes it more susceptible with high surface to volume ratio of guiding mode pattern [10], [11]. This motivated to investigate wave solution of silicon nanowire-based structure, which is not appeared in any literature so far.

The silicon rods inside waveguide known as silicon nanowires (SiNWs) which ranges from 2 nm to 200 nm in diameter. The fabrication of these silicon nanowires is carried out in a controlled manner. The resultant SiNWs should have appropriate orientation and accurate dimension to harness desired photonic characteristics when used in the silicon nanowire-based devices. Thus, silicon nanowire’s cost-effective and controlled manner production is a challenge for the scientific community. In general, ‘bottom-up’ and ‘top-down’ are two broadly categorized approaches for the fabrication of vertical SiNWs. Researchers have proposed several ‘bottom-up’ approaches such as the laser ablation technique [12], Molecular Beam Epitaxy (MBE) technique [13], thermal evaporation technique [14], metal-organic vapor-phase epitaxy [15] and Vapor-Liquid-Solid (VLS) method [16]–[18]. The various methods to grow SiNWs in ‘top-down’ approaches are Reactive Ion Etching (RIE) technique [19], Electro-less Wet Chemical Etching (EWCE) technique [20], [21], Metal-Assisted Chemical Etching (MACE) [22] and lithographic technique

Fig. 1. 3D view of a Silicon Nanowire Optical Rectangular Waveguide (SNORW).

[23]. These silicon nanowire growth approaches require a clean chamber and are performed under very high temperature inside vacuum. However, these fabrication approaches are time consuming and expensive procedures to attain the most requisite criteria of having accurate orientation and precise dimension.

Vertically aligned nanowires on a large surface exhibit excellent light trapping and low reflectance properties which demonstrates great potential in the use of effective absorber, solar-cells, and photovoltaic applications [24]. Silicon nanowires can be used in the case of solar cells, due to its broadband absorption capacity along with very low reflectance [25], [26]. The surface of vertically grown silicon nanowire acts as anti-reflectance for light-intensity and a good option for carrier photon collections [27]. Silicon nanowire with its applications is explored in various fields of photonics, such as photovoltaic cells [25], lithium batteries [28], field effect transistors [29], and photo-detectors [30]. Apart from applications in photonics, silicon nanowires are also applicable in various chemical [31], gas [32], and biosensor devices [33], [34]. In addition, a closely packed bunch of silicon nanowires are preferred for guiding of optical waves, which is been studied in this research paper with theoretical justification.

In this manuscript, the modal investigation of silicon nanowire waveguide's geometry is statistically studied and organized into five sections. The first section above, provided a brief introduction towards the application of silicon nanowire and various fabrication approaches to grow vertical SiNWs for a photonic integrated circuit. The second section gives the detailing of structural modelling of Silicon Nanowire Optical Rectangular Waveguide (SNORW). In the third section, numerical simulation of SNORW structure is performed to identify the supporting mode inside the waveguide structure. Further, in the fourth section, a detailed theoretical investigation of SNORW structure for the guiding phenomenon is explored. Finally, in the fifth section, the theoretical analysis of SNORW is justified with the help of finite element technique.

II. STRUCTURE MODELING OF SILICON NANOWIRE WAVEGUIDE

A Silicon nanowire-based waveguide structure is fabricated using two major steps. In the initial step, an array of silicon nanowire is grown over a layer of silicon oxide substrate by maintaining its desired physical parameters. After achieving the desired height of SiNWs, the final step is to remove the undesired portion of the SiNWs by the etching process. Consequently, the remaining bunch of vertical SiNWs work as a waveguide, which have a continuous constant aperture within all the silicon nanowires. The SiNWs having a vertical rod-shaped sub-wavelength structure, when arranged in an array pattern forms a waveguide known as 'Silicon Nanowire Optical Rectangular Waveguide' (SNORW). A 3D view of silicon nanowire optical rectangular waveguide without any cladding material is shown in Figure 1. In SNORW, high optical power is confined inside the low refractive indexed (RI) nano-slots found between silicon nanowires, which obey the same principle of wave guidance as of slot waveguide.

A SNORW consists of an array of high refractive indexed silicon wires/rods, which are arranged periodically along x and z direction above substrate. These rods are few nanometers in diameter, thus known as nanowires. The SNORW, when used for PIC based communication, the cavity between nanowires are filled with low refractive indexed material such as fused silica. The substrate material is also taken as fused silica, thus making the whole structural arrangement compatible with Silicon-On-Insulator (SOI) technology. The cross-sectional view of SNORW with substrate, cladding and cavity material as fused silica is shown in Fig. 2. The height of each silicon nanowire is ' h ' and the effective waveguide width is ' w_w '.

$$w_w = (s_v \times N) + w_v \times (N + 1) \quad (1)$$

Where, ' W_v ' is the diameter of individual nanowire and ' S_v ' is the cavity spacing between two adjacent nanowires and ' N ' is the number of cavity spacings along x-axis of SNORW cross-section. The combination of SiNWs and the cavity filled with fused silica, collectively make this structure as buried SNORW.

Fig. 2. Cross-sectional schematic view of SNORW.

Nanowires based photonic devices are smaller in dimension with excellent operational performance. This waveguide is a newly developed class of waveguides that has received significant attention by many researchers worldwide, due to its promising applications [35]–[38]. Recently, nanowire based waveguide was reported, in which a vertical array of SiNWs were used to transmit the optical signal from one end to another in Silicon-on-Insulator (SOI) platform [7], [32] and having low as well as flat dispersion profile [9]. Also, silicon nanowire based waveguides having high waveguide surface to waveguide volume ratio, thus it can be used as a gas sensing devices [7], [8], [32].

III. NUMERICAL SIMULATION

The x-y cross-section of SNORW shown in Fig. 2 is considered for illustration of wave guiding capability in this proposed structure. The value of ' S_v ' and ' W_v ' are chosen as 5nm and 10nm, respectively. The ratio of ' S_v ' and ' W_v ', known as pitch ratio, is calculated as 0.5. ' N ' number of cavities with ' $N+1$ ' number of nanowires are arranged in one array of x-y cross-section. This arrayed pattern is repeating itself in z-direction with constant pitch ratio of 0.5. For illustrative purpose, 34 nanowires and 33 nanogaps are considered in one array of SNORW along x-axis. Thus, the x-y cross-section consists $N = 33$ nanogaps and leads to effective waveguide width of 505nm as per Eqn. 1. The effective waveguide width of $\sim 0.5\mu\text{m}$ will be comparable to various single mode supported waveguides, such as bulk SOI rectangular waveguides [39] and slot waveguides [40]. This waveguide is designed mainly for silicon photonic integrated device-to-device communication on chip level. The whole SNORW structure is compatible with SOI technology. Therefore, fused silica (SiO_2) material is used in substrate as well as cladding portion and nanowires are made-up of silicon (Si) material.

Fig. 3. X-component of (a) Electric field, and (b) magnetic field; profile of SNORW.

Validation of mode type and field distribution of the waveguide structure is crucial before evaluating its performance as a communicating integrated device. Thus, the x-y cross-section of SNORW is analysed for its electric and magnetic field distribution pattern to judge its supported mode category. For this, the mode properties of this SNORW structure is studied and analyzed by using full-vectorial finite element method. The wavelength chosen for this analysis is 1550nm, which is mostly used wavelength in all types of optical communication scenarios [41]. The refractive index used for SiO_2 and Si at 1550nm wavelength is calculated through Sellmeier's equation as 1.444 [9], [42] and 3.4752 [43], respectively. The height of all silicon nanowire is chosen as 220nm to meet the current standard height for SOI structures [44]. The computation of electric and magnetic fields guiding inside SNORW structure is simulated by taking minimum triangular mesh element size of 0.1nm and maximum element size of 1nm. The minimum mesh element size is 1/50 times the size of smallest SNORW parameter, that is S_v . Also, the maximum element size is 1/5 times the smallest waveguide parameter. Therefore, the preciseness and effectiveness of the achieved results is expected to be higher. The computed results for x, y and z components of electric and magnetic fields are represented in Fig. 3, Fig. 4 and Fig. 5, respectively.

Fig. 4. Y-component of (a) Electric field, and (b) magnetic field; profile of SNORW.

Fig. 5. Z-component of (a) Electric field, and (b) magnetic field; profile of SNORW.

The absence of electric or magnetic field in the direction of propagation shows the phenomena, known as pure transverse, which means that the components are perpendicular to some common reference. If z-direction is considered as wave propagation direction, then transverse electric (TE) field means absence of electric field in z-direction. For a pure TE mode, guided waves with only longitudinal magnetic field is present (i.e. $H_z \neq 0$, $E_z = 0$). Also, In TE mode H_x , E_y and H_z are non-vanishing, but E_x , H_y and E_z are vanishing because the electric field has only a transverse component. However, TE-mode is not the guiding case in SNORW, since all three components of E as well as H are present, which is clear from Fig. 3, Fig. 4 and Fig. 5. On the other hand, transverse magnetic (TM) field represent the absence of magnetic field in z-direction. Pure TM field having guided waves with only longitudinal electric field (i.e. $E_z \neq 0$, $H_z = 0$). Also, in TM mode, the magnetic field has only a transverse component which result to non-vanishing E_x , H_y and E_z , but H_x , E_y and H_z are vanishing. Due to presence of all the field components, mode of SNORW is also not similar to perfect TM mode. However, the intensity of fields such as E_x , H_y and E_z are much higher than that of H_x , E_y and H_z , thus, it can be inferred as partial TM type of mode, this is clear with the field intensity results for SNORW as shown in Fig. 3

to Fig. 5. Furthermore, transverse electromagnetic (TEM) mode is also a category, in which the z-component of both electric and magnetic field are absent (i.e. $H_z = 0, E_z = 0$). Generally, in TEM mode field distribution, the waveguides have very small refractive index difference between core and cladding, and will often have weak guiding capability. However, in case of SNORW the two materials used are silicon and fused silicon, having refractive index of 3.4752 and 1.444 at 1550nm, which is having large refractive index difference of 2.0312. Moreover, the z-component of both E and H field is present. Therefore, TEM mode is not a guiding mode inside SNORW structure.

In dielectric material-based waveguide where no metallic boundary exists, the evolution of hybrid modes comes in to picture. These hybrid modes having presence of both electric and magnetic field components in z-direction (i.e. $H_z \neq 0, E_z \neq 0$). Hybrid modes are mainly categorized in to EH (quasi-TM) and HE (quasi-TE) modes [45]. Dominating mode component in EH and HE modes are H_z and E_z , respectively [46]. In SNORW, the normal component of the electric field strength approximately vanishes at the boundary of SNORW as shown in Fig. 3. In addition, both electric and magnetic field components in z-direction are present as shown in Fig. 5, thus this waveguide is satisfying the conditions for existence of hybrid mode. The intensity of E_x and H_y is much higher than that of E_y and H_x , respectively, which shows that this SNORW behaves like TM mode. However, with presence of all field component with dominancy of E_z over H_z field component this SNORW will work as HE (quasi-TE mode).

IV. THEORETICAL ANALYSIS

Fig. 6. SNORW cross-section for theoretical analysis.

The wave solutions are calculated using the effective index method. The two dimensions of SNORW x-y cross-section is divided into its one-dimensional orthogonal components. The effective refractive index calculated from first orthogonal component along y-axis is taken as refractive index of denser material in second orthogonal component of SNORW along x-axis. The refractive index of material is varying for individual nanowire and nanoslot along x-axis of this one-dimensional problem. The assumption of variables to represent the generalized coordinates for overlapped two orthogonal components is shown in Fig. 6. The case of TM mode is then solved, where H_y is characterized as governing wave and the Helmholtz equation can be formed as:

$$\frac{\partial^2 H_y}{\partial x^2} + \kappa^2 H_y = 0 \quad (2)$$

Where, κ is replaced by κ_h, γ_s , and γ_c for silicon (high refractive index), nanoslot (cavity), and cover region (cladding), respectively. When a mode is propagating inside a SNORW waveguide, its effective index is defined as $n_{eff} = \beta/k_0$. The relation of β is $\beta^2 = k_0^2 n_h^2 - \kappa_h^2 = k_0^2 n_s^2 + \gamma_s^2 = k_0^2 n_c^2 + \gamma_c^2$, here, n_h, n_s and n_c are the refractive index of silicon, nanoslot, and cover region, respectively. In principle, more than one eigenmode can exist inside a waveguide, having β and n_{eff} entirely different for each of them individually. The existence of eigenmode strongly depends on the waveguide structural parameters. Thus, in this manuscript, SNORW parameters are chosen such a way that only zeroth order dominant mode will exist. To evaluate the wave solutions using Helmholtz equation for both E-field and H-field, the x-cut coordinates of SNORW with N nanoslots as shown in Fig. 6 is represented with its generalized coordinates as:

$$a_i = \left(\frac{2i-1}{2}\right)s_v + (i-1)w_v \quad i = 1, 2, \dots, \left(\frac{N+1}{2}\right) \quad (3)$$

$$a = \left(a_1, a_2, a_3, \dots, a_{\frac{N+1}{2}}\right)$$

$$a = \left(\frac{s_v}{2}, \frac{3s_v}{2} + w_v, \frac{5s_v}{2} + 2w_v, \dots\right)$$

$$b_i = \left(\frac{2i-1}{2}\right)s_v + (i)w_v \quad i = 1, 2, \dots, \left(\frac{N+1}{2}\right) \quad (4)$$

$$b = \left(b_1, \quad b_2, \quad b_3, \quad \dots \quad b_{\frac{N+1}{2}}\right)$$

$$b = \left(\frac{s_v}{2} + w_v, \quad \frac{3s_v}{2} + 2w_v, \quad \frac{5s_v}{2} + 3w_v, \quad \dots\right)$$

Here, ' a_i ' and ' b_i ' is the depiction for beginning and leaving coordinate of SiNWs from center of cross-section towards x-axis. ' W_v ' is the diameter of individual nanowire and ' s_v ' is the cavity spacing between two adjacent nanowires. ' N ' is the total number of cavity spacings along x-axis of SNORW cross-section.

The derivation of mode field equations is a challenge in this case as the interaction between field intensity is highly dependent on an overlapped mode region generated by the individual Si nanowires. The constructive interference evolved from the evanescent field of Si nanowires inside nanogap region will result into a low refractive index guiding waveguide. The resulting analytical solutions for the transverse magnetic (TM) field are region-wise derived by using the solutions of Eq. 2 as:

$$H_y = \begin{cases} A_1 \cosh(\gamma_s |x|) & |x| < a_1 \\ B_1 \cos(\kappa_h |x - a_1|) + C_1 \sin(\kappa_h |x - a_1|) & a_1 < |x| < b_1 \\ D_i \cosh(\gamma_s \left|x - \left(\frac{a_{i+1} + b_i}{2}\right)\right|) & b_i < |x| < a_{i+1} \\ & i = 1, 2, \dots, \left(\frac{N-1}{2}\right) \\ B_{i+1} \cos(\kappa_h |x - a_{i+1}|) + C_{i+1} \sin(\kappa_h |x - a_{i+1}|) & a_{i+1} < |x| < b_{i+1} \\ & i = 1, 2, \dots, \left(\frac{N-1}{2}\right) \\ F \exp(-\gamma_c |x - b_{\frac{N+1}{2}}|) & |x| > b_{\frac{N+1}{2}} \\ & i = N \end{cases} \quad (5)$$

$$E_x = \begin{cases} \frac{A_1}{n_s^2} \cosh(\gamma_s |x|) & |x| < a_1 \\ \frac{1}{n_h^2} [B_1 \cos(\kappa_h |x - a_1|) + C_1 \sin(\kappa_h |x - a_1|)] & a_1 < |x| < b_1 \\ \frac{D_i}{n_s^2} \cosh(\gamma_s \left|x - \left(\frac{a_{i+1} + b_i}{2}\right)\right|) & b_i < |x| < a_{i+1} \\ & i = 1, 2, \dots, \left(\frac{N-1}{2}\right) \\ \frac{1}{n_h^2} [B_{i+1} \cos(\kappa_h |x - a_{i+1}|) + C_{i+1} \sin(\kappa_h |x - a_{i+1}|)] & a_{i+1} < |x| < b_{i+1} \\ & i = 1, 2, \dots, \left(\frac{N-1}{2}\right) \\ \frac{F}{n_c^2} \exp(-\gamma_c |x - b_{\frac{N+1}{2}}|) & |x| > b_{\frac{N+1}{2}} \\ & i = N \end{cases} \quad (6)$$

As per boundary conditions, the magnetic field (H_y) and its derivative must be continuous at the interface between two materials. In case of SNORW with N number of odd cavity-spacings, $2N+2$ number of even boundary discontinuities are present between every nanowire and cavity interface. Thus, the boundary conditions are applied at $x = \pm a_i$ and $\pm b_i$, where $i = 1, 2, 3 \dots (N+1)/2$ as shown in Fig. 6, and the resulting variables $B_1, B_{i+1}, C_1, C_{i+1}, D_i$ and F are calculated as:

$$B_1 = A_1 \cosh(\gamma_s a_1) \quad (7)$$

$$C_1 = A_1 \left(\frac{\gamma_s}{\kappa_h}\right) \left(\frac{n_h}{n_s}\right)^2 \sinh(\gamma_s a_1) \quad (8)$$

$$D_i = \frac{B_i \cos(\kappa_h w_v) + C_i \sin(\kappa_h w_v)}{\cosh(\gamma_s \left|b_i - \left(\frac{a_{i+1} + b_i}{2}\right)\right|)} \quad i = 1, 2, \dots, \left(\frac{N-1}{2}\right) \quad (9)$$

$$B_{i+1} = D_i \cosh(\gamma_s \left|a_{i+1} - \left(\frac{a_{i+1} + b_i}{2}\right)\right|) \quad i = 1, 2, \dots, \left(\frac{N-1}{2}\right) \quad (10)$$

$$C_{i+1} = D_i \left(\frac{\gamma_s}{\kappa_h}\right) \left(\frac{n_h}{n_s}\right)^2 \sinh(\gamma_s \left|a_{i+1} - \left(\frac{a_{i+1} + b_i}{2}\right)\right|) \quad i = 1, 2, \dots, \left(\frac{N-1}{2}\right) \quad (11)$$

$$F = B_{\frac{i+1}{2}} \cos(\kappa_h w_v) + C_{\frac{i+1}{2}} \sin(\kappa_h w_v) \quad i = N \quad (12)$$

To validate the fields inside SNORW structure, it is important to calculate the pointing vector profile (S_z). The pointing vector profile perpendicular to x-y cross-section of SNORW along z-direction is calculated using $|E_x \times H_y|$. The guiding of optical power inside SNORW structure is validated in the next section by comparing the results of analytical technique and finite element method.

V. RESULT VALIDATION

To implement this vertical silicon nanowire structure as a waveguide, it is important to identify the propagation mode and the pattern of field intensity distribution inside this structure. To validate the possibility of guiding optical power inside SNORW structure, Finite Element Method (FEM) and theoretical study with contemplating analytical result is presented in this section. SNORW having total effective waveguide width of 505 nm with 33 nanogaps, 34 wires and equal pitch ratio of $s_v / w_v = 0.5$ is considered, utilizing previous sections of this manuscript. The modal properties of this SNORW structure in terms of optical power guiding inside the cross-section of structure is analyzed by using full-vectorial finite element method and illustrated using Fig. 7(a). The optical field intensity is strong inside low refractive indexed nanoslots by virtue of electric field discontinuity at the interfaces of low and high refractive indexed materials. Figure 7(b) presents a comparison between the theoretically calculated mode profile and FEM mode profile.

Fig. 7. Normalized mode intensity profile of quasi-TE mode for $N = 33$: (a) x-y plane pointing vector profile; and (b) x-cut S_z comparison.

The results shows that the SNORW structure supports guiding of wave as quasi-TE mode. The performance of this waveguide at wavelengths other than 1550nm need to be evaluated for sustainability of this structure as PIC component. Therefore, the effective refractive index (n_{eff}) and the mode propagation constant (β) of this SNORW is calculated for S, C and L wavelength bands. These wavelength bands are suitable to perform almost all the operations of a PIC in photonic domain. The wavelength ranging from 1460nm to 1625nm with 1nm resolution is used for calculation of n_{eff} and β , as shown in Fig. 8(a). These solutions are then used for calculation of quasi-TE mode inside SNORW structure. The corresponding confinement factor (Γ_s) of field intensity inside this structure is plotted in Fig. 8(b). The confinement is within range from 40.11% (at 1460nm) to 30.98% (at 1625nm), which shows linearly decreasing nature with increase in wavelength.

Fig. 8. (a) SNORW n_{eff} and β with wavelength; and (b) confinement factor of SNORW with wavelength.

TABLE I
CONFINEMENT FACTOR COMPARISON OF SOI WAVEGUIDES

Waveguide type	Effective waveguide width	Waveguide height	Operating wavelength (λ)	Low RI	High RI	Γ_s
Slot waveguide	420 nm	320 nm	1550 nm	1.53	3.476	~10 % [47]
Slot waveguide	410 nm	300 nm	1550 nm	1.46	3.48	~31 % [1]
Slot waveguide	500 nm	220 nm	1550 nm	1.444	3.4752	25.02 % [6]
Slot waveguide	516 nm	220 nm	1550 nm	1.70	3.48	21.6 % [2]
SNORW	505 nm	220 nm	1460 nm	1.4451	3.4823	40.11 %
SNORW	505 nm	220 nm	1550 nm	1.444	3.4752	34.88 %
SNORW	505 nm	220 nm	1625 nm	1.4431	3.4701	30.98 %

The value of SNORW confinement factor is compared to slot waveguides in Table-1, which shows that this SNORW structure is supporting the propagation of mode at wavelengths of S, C and L-bands. The poynting vector of SNORW at wavelength of 1460nm, 1550nm and 1625nm with x-cut coordinates are plotted in Fig. 9.

Fig. 9. SNORW Poynting vector profile for 1460nm, 1550nm and 1625nm.

The center of the waveguide structure is having maximum intensity. As the wavelength increases from 1460nm to 1625nm, the intensity decreases at the center region of SNORW structure. This shows that the lower wavelength is having high confinement in the waveguide region. In addition, lower wavelength is also having low evanescent field intensity outside the waveguide region. However, within the waveguide region, the evanescent field of individual silicon nanowire constructively interfere and increase the intensity inside nanoslot region. The mode intensity is discrete in all the nanogaps, with maximum being at the center of waveguide. The discreteness in mode intensity value is due to the discontinuity and disappearance of x component of electric field inside silicon nanowire. As a result, splitting occurs in oval-shaped field distribution profile. Also, the constructive interference at the center of structure is high as a result of high intensity at the central nanoslot as compared to other nanoslots. These results prove that the SiNWs in arrayed geometry can guide optical field intensity with excellent operational performance for SOI based PICs.

VI. CONCLUSION

The geometry based on periodically distributed vertical silicon nanowires structure is sandwiched between two fused-silica layers and having the compatibility with 220 nm silicon technology is presented in this paper. The structure is investigated for the propagation behavior of electric and magnetic fields. This structure named SNORW takes its functional root from the bulk rectangular waveguide and follows the basic guiding properties of vertical slot waveguide. Therefore, the envelope of mode field intensity closely matches with the bulk rectangular waveguide. However, the working phenomenon of guiding matches with slot waveguide, where most of the field intensity is found to lie in low refractive indexed material and discontinuity is found at material boundary. A theoretical analysis is carried out for SNORW to plot the behavior of electric and magnetic field distributions along with Poynting vectors in the waveguide. In SNORW, the strength of E_x field component exponentially vanishes at the boundary of SNORW and the strength of H_y field component is continuous with material change at boundaries. Also, the presence of electric and magnetic fields are found to have high intensity in the direction of E_x and H_y than that of H_x and E_y . In addition, both electric and magnetic field components in the z -direction are present with the dominance of E_z over H_z field. Therefore, the interaction of SNORW structure with optical waves shows the guiding behavior of quasi-TE mode. The results have been substantiated using

Finite Element Method (FEM) based technique. Both analytical and FEM techniques prove that, in SNORW, high optical power is confined in the low index nano-slots between silicon nanowires. The envelope of optical mode in SNORW resembles the conventional rectangular waveguide; however, the mode profile resembles the slot-waveguide, where wave guidance occurs in the voids created by low index region. The bulk material used in SNORW can be varied to alter the essential physical properties of nanowires and to achieve improved performance of different SNORW based devices. With all the above discussion, it can be inferred that nanowire based compact photonic devices have excellent operational performance, hence making it promising research on compact nano-optical devices.

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