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 field 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 match 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. Analytical expressions are used to express Quasi-TE mode in terms of material profile and waveguide physical parameters. The results obtained for SNORW are in S, C and L wavelength bands and 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.

Keywords Effective index analysis · Finite element analysis · Nanotechnology · Photonic integrated circuit · Photonic waveguide · Silicon nanowire · Silicon-on-insulator · Silicon photonics · Quasi-mode

1 Introduction
In the past two decade, optical waveguides using silicon-on-insulator (SOI) technology are attracting many researchers of photonic integrated circuits (PICs) [1, 2]. Among various types of optical waveguides, the rectangular waveguide category is the typical PIC structure having wave-guiding phenomenon inside the high refractive index (RI) region surrounded by low RI material, which is similar to the optical fiber working phenomenon. In further studies, the guiding phenomenon inside low RI material surprised various researchers [3], 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 has given momentum to work in the area of low refractive index guided photonics [4, 5]. 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 [6]. Since then, many researchers have worked on the theoretical investigation of optical slot waveguide proposing wave solutions [3, 7–9], where the guiding phenomenon inside low RI slot region is proven with its diverse applications. This slot waveguide is classified into various categories 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 [3, 8, 10, 11]. It is proven that the guiding phenomenon is directly dependent on the physical dimension of waveguide and its material compositions. With the moving span of time, the evolution of a very special type of waveguide based on the working property of slot waveguide evolved, which is silicon nanowire-based waveguide [12–9]. The waveguide formation using vertically aligned silicon wires makes it more susceptible with
high surface to volume ratio of guiding mode pattern [15, 16]. This motivates to investigate wave solution of silicon nanowire-based structure, which is not appeared in any literature so far.

The diameter of silicon nanowires (SiNWs) for the waveguide formation ranges from 2 to 200 nm. The finned structured fabrication of nanowires should be in appropriate orientation with accurate dimension to harness desired photonic characteristics when used in the silicon nanowire-based devices. Hence, the production is very costly, which becomes challenging task 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 [17], Molecular Beam Epitaxy (MBE) technique [18], thermal evaporation technique [19], metal–organic vapor-phase epitaxy [20] and Vapor–Liquid–Solid (VLS) method [21–23]. The various methods to grow SiNWs in ‘top-down’ approaches are reactive ion etching (RIE) technique [24], electro-less wet chemical etching (EWCE) technique [25, 26], metal-assisted chemical etching (MACE) [27] and lithographic technique [28]. 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.

Nanowires-based photonic devices are smaller in dimension with excellent operational performance [29–32]. Silicon nanowires can be used in solar cell, due to its broadband absorption capacity along with very low reflectance [33, 34]. Nanowires on a large surface exhibit excellent light trapping property and demonstrate great potential in the use of absorber and photovoltaic applications [35]. The surface of nanowire bed acts as anti-reflectance for light-intensity and a good option for carrier photon collections [36]. Silicon nanowire with its applications is explored in various fields of photonics, such as photovoltaic cells [33], lithium batteries [37], field effect transistors [38], and photo-detectors [39]. Apart from applications in photonics, silicon nanowires are also applicable in various chemical [40], gas [15], and biosensor devices [16, 41]. In addition, a closely packed bunch of silicon nanowires are preferred for guiding of optical waves, which has been demonstrated 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 gives a brief introduction, and the second section gives the detailed structural modeling of SNORW. In the third section, numerical simulation of SNORW structure is performed, and in the fourth section, a theoretical investigation of SNORW structure for the guiding phenomenon is explored. In the last section, the theoretical analysis is justified with finite element technique.

2 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 works 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 Fig. 1. 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, and 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 height of each silicon nanowire is ‘h,’ and the effective waveguide width is ‘w_w.’

\[
w_w = (s_v \times N) + w_v \times (N + 1)
\]

(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.

3 Numerical simulation

In this proposed structure, the x–y cross section of SNORW is considered for illustration of waveguide mode, and the x–z top view cross section is considered for illustration of wave-guiding capability. The geometrical parameters of this SNORW structure are optimized for its confinement factor and feasibility. Confinement factor of waveguide with respect to the number of nanowires arranged in one array of
x–y cross section, the diameter of individual nanowire, and the cavity spacing between two adjacent nanowires is represented in Fig. 2a, b, and c, respectively. ‘N’ number of cavities with ‘N + 1’ number of nanowires are arranged in one array of x–y cross section. The value of ‘N + 1’, ‘wv’, and ‘sv’ is chosen as 34, 10 nm and 5 nm, respectively. These optimum values are the minimum possible waveguide geometrical parameters after which confinement factor will show a constant behavior. The ratio of ‘sv’ and ‘wv’, known as pitch ratio, is calculated as 0.5. This arrayed pattern is repeating itself in z-direction with constant pitch ratio of 0.5. For illustrative purpose, optimized 34 nanowires and 33 nanogaps are considered in one array of SNORW along x-axis. Thus, the x–y cross section consists of 33 nanogaps and leads to effective waveguide width of 505 nm as per Eq. 1. The effective waveguide width of ~ 0.5 μm will be comparable to various single-mode supported waveguides, such as bulk SOI rectangular waveguides [42] and slot waveguides [43]. 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 (SiO₂) material is used in substrate as well as cladding portion, and nanowires are made-up of silicon (Si) material.

Validation of mode type and filed 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 analyzed for its electric and magnetic field distribution pattern to judge its supported mode category. For this, the mode properties of this SNORW structure are studied and analyzed using full-vectorial finite element method. The wavelength chosen for this analysis is 1550 nm, which is mostly used wavelength in all types of optical communication scenarios [44]. The refractive index used for SiO₂ and Si at 1550 nm wavelength is calculated through Sellmeier’s equation as 1.4444 [14,45] and 3.4752 [46], respectively. The height of all silicon nanowire is chosen as 220 nm to meet the current standard height for SOI structures [47]. The computation of electric and magnetic fields guiding inside SNORW structure is simulated by taking minimum triangular mesh element size of 0.1 nm and maximum element size of 1 nm. The minimum mesh element size is 1/50th the size of smallest SNORW parameter, that is sv. Also, the maximum element size is 1/50th the smallest waveguide parameter. Therefore,

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

Fig. 2 Confinement factor with respect to a ‘N + 1’, b ‘Wv’, and c ‘sv’, of SNORW
the precision and effectiveness of the achieved results are expected to be higher as compared to structure with large mesh size. The computed results for x, y and z components of electric and magnetic fields are represented in Figs. 3, 4 and 5, respectively.

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 direction of wave propagation, then transverse electric (TE) field means absence of electric field in z-direction. For a pure TE mode, guided wave has only longitudinal magnetic field (i.e., \( H_z \neq 0, \ E_z = 0 \)). Also, in TE mode, \( H_x, E_x \) and \( H_y \) are non-vanishing, but \( E_x, H_y \) and \( E_z \) are vanishing because the electric field has only a transverse component. Therefore, 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 Figs. 3, 4 and 5. On the other hand, transverse magnetic (TM) field represents the absence of magnetic field in z-direction. Pure TM field has 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 \( E_y \), but \( H_x, E_z \) and \( H_z \) are vanishing. Again, due to the presence of all the field components, mode of SNORW is not similar to perfect TM mode. However, the intensity of fields such as \( E_x, H_y \) and \( E_y \) is much higher than that of \( H_x, E_z \) 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 Figs. 3, 4 and 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.

![Fig. 3 X-component of a Electric field, and b Magnetic field; profile of SNORW](image)

![Fig. 4 Y-component of a Electric field, and b Magnetic field; profile of SNORW](image)
and will often have weak guiding capability. However, in case of SNORW, the two materials used are silicon and fused silicon, which have refractive index of 3.4752 and 1.4444 at 1550 nm, which is having large refractive index difference of 2.0308. 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 into 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 [48]. Dominating mode component in EH and HE modes is $H_z$ and $E_z$, respectively [49]. 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, and thus, this waveguide is satisfying the conditions for existence of hybrid mode. The intensity of $E_z$ and $H_z$ is much higher than that of $E_y$ and $H_x$, respectively, which shows that this SNORW behaves like TM mode. However, with the presence of all field component with dominancy of $E_z$ over $H_z$ field component, this SNORW will work as HE (quasi-TE mode).

The hybrid HE (quasi-TE) mode is propagating inside this nanowire structure with dominancy of $E_z$ over the other $z$-component of field, and the presence of non-vanishing $E_z$, $H_z$. The resultant pointing vector after cross product of $E_z$ and $H_z$ will support optical intensity to propagate in z-direction. The homogeneous repetition of silicon nanowire pattern along z-axis is simulated, and result for intensity guiding in SNORW structure is shown in Fig. 6. In SNORW, high optical power is confined inside the low RI nanoslots between silicon nanowires, which obey the same principle of wave guidance as of slot waveguide. However, the overall mode guiding pattern is quite similar to bulk rectangular waveguide. Therefore, it can be inferred from all the above-simulated results that this SNORW structure has hybrid working phenomenon of both slot waveguide as well as rectangular waveguide.

### 4 Theoretical analysis

The wave solutions are calculated using the effective index method. The two dimensions of SNORW x–y cross section are 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. 7. The case of TM mode is then solved, where \( H_y \) is characterized as governing wave and the Helmholtz equation can be formed as:

\[
\frac{\partial^2 H_y}{\partial x^2} + \kappa^2 H_y = 0
\]

(2)

where \( \kappa \) is replaced by \( \kappa_h, \gamma_s, \) and \( \gamma_c \) 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 \( n_{\text{eff}} = \frac{\beta}{k_0} \). The relation of \( \beta \) 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 \( \beta \) and \( n_{\text{eff}} \) entirely different for each of them. 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. 7 are represented with its generalized coordinates as:

\[
a_i = \left(\frac{2i-1}{2}\right)sv + (i-1)w_v \quad i = 1, 2, \ldots \left(\frac{N+1}{2}\right)
\]

(3)

\[
b_i = \left(\frac{2i-1}{2}\right)sv + (i)w_v \quad i = 1, 2, \ldots \left(\frac{N+1}{2}\right)
\]

(4)

Here ‘\( a_i \)’ and ‘\( b_i \)’ are the depiction for beginning and leaving coordinate of SiNWs from center of cross section toward x-axis. ‘\( w_v \)’ is the diameter of individual nanowire, and ‘\( sv \)’ is the cavity spacing between two adjacent nanowires. ‘\( N \)’ is the total number of cavity spacing 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 solution for the transverse magnetic (TM) field is region-wise derived by using the solution of Eq. 2 as:

![Fig. 7 SNORW cross-section for theoretical analysis](image-url)
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-spacing, \( 2 \) \( N+2 \) 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 \( i = 1, 2, 3 \ldots (N+1)/2 \) as shown in Fig. 7, and the resulting variables \( B_1, B_{i+1}, C_1, C_{i+1}, D_i \) and \( F \) are calculated as:

\[
\begin{align*}
B_1 &= A_1 \cosh(\gamma_s a_i) \quad |x| < a_1 \\
B_1 \cos(\kappa_h |x - a_1|) + C_1 \sin(\kappa_h |x - a_1|) \quad a_1 < |x| < b_1 \\
D_i \cosh(\gamma_s |x - (\frac{a_i + b_i}{2})|) \quad b_1 < |x| < a_{i+1} \quad i = 1, 2, \ldots (\frac{N-1}{2}) \\
B_{i+1} \cos(\kappa_h |x - a_{i+1}|) + C_{i+1} \sin(\kappa_h |x - a_{i+1}|) \quad a_{i+1} < |x| < b_{i+1} \quad i = 1, 2, \ldots (\frac{N-1}{2}) \\
F \exp(-\gamma_c |x - b_{i+1}|) \quad |x| > b_{i+1} \quad i = N
\end{align*}
\]

\[
\begin{align*}
\frac{d}{dx} \cosh(\gamma_s |x|) & \quad |x| < a_1 \\
\frac{1}{n_i} [B_1 \cos(\kappa_h |x - a_1|) + C_1 \sin(\kappa_h |x - a_1|)] & \quad a_1 < |x| < b_1 \\
D_i \cosh(\gamma_s |x - (\frac{a_i + b_i}{2})|) & \quad b_1 < |x| < a_{i+1} \quad i = 1, 2, \ldots (\frac{N-1}{2}) \\
\frac{1}{n_k} [B_{i+1} \cos(\kappa_h |x - a_{i+1}|) + C_{i+1} \sin(\kappa_h |x - a_{i+1}|)] & \quad a_{i+1} < |x| < b_{i+1} \quad i = 1, 2, \ldots (\frac{N-1}{2}) \\
F \exp(-\gamma_c |x - b_{i+1}|) & \quad |x| > b_{i+1} \quad i = N
\end{align*}
\]

\[
\begin{align*}
C_{i+1} &= D_i \left( \frac{\gamma_k}{\gamma_n} \right)^2 \sinh \left( \gamma_n a_{i+1} - \left( \frac{a_i + b_i}{2} \right) \right) \quad i = 1, 2, \ldots (\frac{N-1}{2}) \\
F &= B_{i+1} \cos(\kappa_h w_i) + C_{i+1} \sin(\kappa_h w_i) \quad i = N
\end{align*}
\]

To validate the fields inside SNORW structure, it is important to calculate the pointing vector profile \( (S_s) \). The pointing vector profile perpendicular to \( x-y \) cross section of SNORW along \( z \)-direction is calculated using \( |E_x \times H_z| \). 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.

## 5 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 are
presented in this section. SNORW having total effective waveguide width of 505 nm with 33 nanogaps, 34 wires and equal pitch ratio of $s/w_v = 0.5$ 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 are analyzed by using full-vectorial finite element method and illustrated using Fig. 8a. 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 8b presents a comparison between the theoretically calculated mode profile and FEM mode profile.

The results show that the SNORW structure supports guiding of wave as quasi-TE mode. The performance of this waveguide at wavelengths other than 1550 nm needs to be evaluated for sustainability of this structure as PIC component. Therefore, the effective refractive index ($n_{\text{eff}}$) and the mode propagation constant ($\beta$) of this SNORW are calculated from 1460 to 1625 nm wavelengths. The optical wavelength range from 1460 to 1625 nm is very important to utilize in the worldwide communication standards. The range of 1460–1625 nm wavelength is divided into three bands, i.e., S, C and L bands. The short (S)—band starts from 1460 nm and ends at 1530 nm, commonly used in passive optical network systems as a downstream wavelength. The conventional (C)—band starts from 1530 nm and ends at 1565 nm, mostly used in ultra-long-haul transmission systems with WDM and EDFA technologies. The long (L)—band starts from 1565 nm and ends at 1625 nm, mainly used to expand the capacity of DWDM optical networks. These wavelength bands are suitable to perform almost all the operations of a PIC in photonic domain. The wavelength ranging from 1460 to 1625 nm with 1 nm resolution is used for calculation of $n_{\text{eff}}$ and $\beta$, as shown in Fig. 9a. These solutions are then used for calculation of quasi-TE mode inside SNORW structure. The corresponding confinement
factor ($\Gamma_s$) of field intensity inside this structure is plotted in Fig. 9b. The confinement lies within range from 40.11% (at 1460 nm) to 30.98% (at 1625 nm), which shows linearly decreasing nature with increase in wavelength.

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 modes at wavelengths of S, C and L-bands. The pointing vector of SNORW at wavelength of 1460, 1550 and 1625 nm with x-cut coordinates is plotted in Fig. 10.

The center of the waveguide structure has the maximum intensity. As the wavelength increases from 1460 to 1625 nm, 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 interferes and increases 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.

### 6 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 pointing vectors in the waveguide. In SNORW, the strength of $E_x$ field component vanishes exponentially at the boundary and the strength of $H_y$ field component is continuous with material change at boundaries. Also, the presence of electric and magnetic fields is found to have high intensity in the direction of $E_z$ and $H_y$, than that of $E_x$ and $H_z$. In addition, both electric and magnetic field components in the z-direction are present with the dominancy 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 nanoslots between silicon nanowires. The envelope of optical mode in SNORW resembles the conventional rectangular waveguide; however, the mode

| Waveguide type | Effective waveguide width | Waveguide height | Operating wavelength ($\lambda$) | Low RI | High RI | $\Gamma_s$ |
|----------------|---------------------------|-----------------|-------------------------------|-------|--------|---------|
| Slot waveguide | 420 nm                    | 320 nm          | 1550 nm                       | 1.53  | 3.476  | ~10% [50]|
| Slot waveguide | 410 nm                    | 300 nm          | 1550 nm                       | 1.46  | 3.48   | ~31% [3] |
| Slot waveguide | 500 nm                    | 220 nm          | 1550 nm                       | 1.444 | 3.4752 | 25.02% [11]|
| Slot waveguide | 516 nm                    | 220 nm          | 1550 nm                       | 1.70  | 3.48   | 21.6% [7] |
| 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%  |
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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**Declarations**

**Conflict of interest** The authors have not disclosed any competing interests.

**References**

1. Li, R., Zhao, Y., Li, R., Ge, Y., Xu, Z.: Silicon-on-insulator slot waveguide design for C band optical amplification confinement. Opt. Mater. Expr. **11**(7), 1989 (2021). https://doi.org/10.1364/OME.427415
2. Li, L., et al.: Bright field structural colors in silicon-on-insulator nanostructures. ACS Appl. Mater. Interfaces **13**(3), 4364–4373 (2021). https://doi.org/10.1021/acsami.0c19126
3. Almeida, V.R., Xu, Q., Barrios, C.A., Lipson, M.: Guiding and confining light in void nanostructure. Opt. Lett. **29**(11), 1209 (2004). https://doi.org/10.1364/OL.29.001209
4. Cam Hoang, T.H.: Analysis on slotted photonic crystal cavity and waveguide combination in silicon-on-insulator platform. Optik (Stuttg) **251**, 168465 (2022). https://doi.org/10.1016/j.ijleo.2021.168465
5. Kazanskiy, N.L., Butt, M.A., Khonina, S.N.: Silicon photonic devices realized on refractive index engineered subwavelength grating waveguides-a review. Opt. Laser Technol. **138**, 106863 (2021). https://doi.org/10.1016/j.optlastec.2020.106863
6. Iqbal, M., Zhao, D., Ma, Y., Zhong, K.: Designing optical waveguides: myth and reality. Brazilian J. Phys. **50**(6), 857–873 (2020). https://doi.org/10.1007/s13538-020-00763-w
7. Steglich, P.: “Silicon-on-insulator slot waveguides: theory and applications in electro-optics and optical sensing emerging waveguide technology. InTech (2018)
8. Xu, Q., Almeida, V.R., Panepucci, R.R., Lipson, M.: Experimental demonstration of guiding and confining light in nanometer-size low-refractive-index material. Opt. Lett. **29**(14), 1626 (2004). https://doi.org/10.1364/OL.29.001626
9. Priye, V., Malviya, N., Mickelson, A.: Analytical predictions for nonlinear optical processes in silicon slot waveguides. J. Comput. Electron. **17**(2), 857–865 (2018). https://doi.org/10.1007/s10825-018-1150-8
10. Sun, R., et al.: Horizontal single and multiple slot waveguides: optical transmission at λ = 1550 nm. Opt. Express **15**(26), 17967 (2007). https://doi.org/10.1364/OE.15.017967
11. Singh, R.R.: Structural optimization and parametric analysis of SOI optical slot waveguides. J. Comput. Electron. (Feb. 2020). https://doi.org/10.1007/s10825-020-01473-x
12. Khorasaninejad, M., Saini, S.S.: Silicon nanowire optical waveguide (SNOW). Opt. Express **18**(22), 23442 (2010). https://doi.org/10.1364/OE.18.023442
13. Khorasaninejad, M., Saini, S.S.: Bend waveguides on silicon nanowire optical waveguide (SNOW). IEEE Photonics J. **3**(4), 696–702 (2011). https://doi.org/10.1109/JPHOT.2011.2160527
14. Singh, R.R.: Dispersion tailoring of silicon nanowire optical rectangular waveguide (SNORW). SN Appl. Sci. **2**(3), 502 (2020). https://doi.org/10.1016/j.sna.2020.02.009-z
15. Singh, R.R., Malviya, N., Priye, V.: Parametric analysis of silicon nanowire optical rectangular waveguide sensor. IEEE Photonics Technol. Lett. **28**(24), 2889–2892 (2016). https://doi.org/10.1109/LPT.2016.2624501
16. Singh, R.R., Priye, V.: Silicon nanowire optical rectangular waveguide biosensor for DNA hybridization. IEEE Photonics Technol. Lett. **30**(12), 1123–1126 (2018). https://doi.org/10.1109/LPT.2018.2835152
17. Yang, Y.-H., Wu, S.-J., Chiu, H.-S., Lin, P.-I., Chen, Y.-T.: Catalytic growth of silicon nanowires assisted by laser ablation. J. Phys. Chem. B **108**(3), 846–852 (2004). https://doi.org/10.1021/jp030663d
18. Fuhrmann, B., Leipner, H.S., Höche, H.-R., Schubert, L., Werner, P., Gösele, U.: Ordered arrays of silicon nanowires produced by nanosphere lithography and molecular beam epitaxy.Nano Lett. **1**(12), 2524–2527 (2005). https://doi.org/10.1021/nl051856a
19. Pan, H., et al.: Growth of Si nanowires by thermal evaporation. Nanotechnology **16**(4), 417–421 (Apr. 2005). https://doi.org/10.1088/0957-4484/16/4/014
20. Dick, K.A., Deppert, K., Mårtensson, T., Mandl, B., Samuelson, L., Seifert, W.: Failure of the vapor−liquid−solid mechanism in Au-assisted MOVPE growth of InAs nanowires. Nano Lett. **5**(4), 761–764 (2005). https://doi.org/10.1021/nl050301c
21. Wagner, R.S., Ellis, W.C.: Vapor-liquid-solid mechanism of single crystal growth. Appl. Phys. Lett. **4**(5), 89–90 (1964). https://doi.org/10.1063/1.1753975
22. Westwater, J.: “Growth of silicon nanowires via gold/silane vapor−liquid−solid reaction. J. Vac. Sci. Technol. B Microelectron. Nanom. Struct. **15**(3), 554 (1997). https://doi.org/10.1116/1.589291
23. Ziau-Romain, L., Mouchet, C., Cayron, C., Rouviere, E., Simonato, J.-P.: Growth parameters and shape specific synthesis of silicon nanowires by the VLS method. J. Nanoparticle Res. **10**(8), 1287–1291 (Dec. 2008). https://doi.org/10.1007/s10742-010-0135-0
24. Fu, Y.Q., et al.: “Deep reactive ion etching as a tool for nanostructure fabrication. J. Vac. Sci. Technol. B Microelectron. Nanom. Struct. **27**(3), 1520 (2009). https://doi.org/10.1116/1.3065991
25. Qu, T., Wu, X.L., Siu, G.G., Chu, P.K.: Intergrowth mechanism of silicon nanowires and silver dendrites. J. Electron. Mater. **35**(10), 1879–1884 (2006). https://doi.org/10.1007/s11664-006-0171-4
26. Sohi, P.A., Kahrizi, M.: Formation mechanism of silicon nanowires using chemical/ electrochemical process. IEEE Trans. Nanotechnol. **16**(3), 507–513 (2017). https://doi.org/10.1109/TNANO.2017.2694428
27. Han, H., Huang, Z., Lee, W.: Metal-assisted chemical etching of silicon and nanotechnology applications. Nano Today **9**(3), 271–304 (2014). https://doi.org/10.1016/j.nantod.2014.04.013
28. Martínez, R.V., Martínez, J., García, R.: Silicon nanowire circuits fabricated by AFM oxidation nanolithography. Nanotechnology **21**(24), 245301 (2010). https://doi.org/10.1088/0957-4484/21/24/245301
29. Fathi Aghdam, F., Liao, H., Huang, Q.: Modeling interaction in nanowire growth process toward improved yield. IEEE Trans.
Autom. Sci. Eng. 14(2), 1139–1149 (2017). https://doi.org/10.1109/TASE.2015.2499210

30. Hsin, C.-L., Wu, M.-H., Wang, W.-C.: Thermoelectric devices by half-millimeter-long silicon nanowires arrays. IEEE Trans. Nanotechnol. 18, 921–924 (2019). https://doi.org/10.1109/TNANO.2019.2938624

31. Yoon, J.-S., Kim, K., Meyyappan, M., Baek, C.-K.: Optical characteristics of silicon-based asymmetric vertical nanowire photodetectors. IEEE Trans. Electron Devices 64(5), 2261–2266 (2017). https://doi.org/10.1109/TED.2016.2552973

32. Tong, J., et al.: Effects of the ambient medium and structure parameter on the optical properties of tapered silicon nanowire. Opt. Commun. 454, 124515 (2020). https://doi.org/10.1016/j.optcom.2019.124515

33. Peng, K., Xu, Y., Wu, Y., Yan, Y., Lee, S.-T., Zhu, J.: Aligned single-crystalline silicon nanowire arrays for photovoltaic applications. Small 11(11), 1062–1067 (2015). https://doi.org/10.1002/smll.20050137

34. Garnett, E., Yang, P.: Light trapping in silicon nanowire solar cells. Nano Lett. 10(3), 1082–1087 (2010). https://doi.org/10.1021/nl100161z

35. Venkatesan, R., Mayandi, J., Søndenå, R., Finstad, T.G., Venkatachalapathy, V.: Investigating antireflection properties of hybrid silicon nanostructures comprising rod-like nanopores and nano-textured surface. Mater. Lett. 275, 128087 (2020). https://doi.org/10.1016/j.matlet.2020.128087

36. Srivastava, S.K., Kumar, D., Singh, P.K., Kar, M., Kumar, V., Husain, M.: Excellent antireflection properties of vertical silicon nanowire arrays. Sol. Energy Mater. Sol. Cells 94(9), 1506–1511 (Sep. 2010). https://doi.org/10.1016/j.solmat.2010.02.033

37. Chan, C.K., et al.: High-performance lithium battery anodes using silicon nanowires. Nat. Nanotechnol. 3(1), 31–35 (Jan. 2008). https://doi.org/10.1038/nnano.2007.411

38. Goldberger, J., Hochbaum, A.I., Fan, R., Yang, P.: Silicon vertically integrated nanowire field effect transistors. Nano Lett. 6(5), 973–977 (May 2006). https://doi.org/10.1021/nl050166j

39. Bae, J., et al.: Si nanowire metal-insulator-semiconductor photodetectors as efficient light harvesters. Nanotechnology 21(9), 095502 (Mar. 2010). https://doi.org/10.1088/0957-4484/21/9/095502

40. Cui, Y.: Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species. Science 293(5533), 1289–1292 (2001)

41. Abdul Rashid, J.I., Abdullah, J., Yusof, N.A., Hajian, R.: The development of silicon nanowire as sensing material and its applications. J. Nanomater 2013, 1–6 (2013). https://doi.org/10.1155/2013/328093

42. T. T. Aalto, M. Harjanne, M. Kapulainen, P. Heimala, and M. J. Leppihalme (2004) “Development of silicon-on-insulator waveguide technology. 2014: 81, doi: https://doi.org/10.1117/12.537540.

43. Zengzhi, H., et al.: High confinement factor ridge slot waveguide for optical sensing. IEEE Photonics Technol. Lett. 27(22), 2395–2398 (Nov. 2015). https://doi.org/10.1109/LPT.2015.2466595

44. Zhou, F., Su, H., Joe, H.-E., Jun, M.B.-G.: Temperature insensitive fiber optical refractive index probe with large dynamic range at 1,550 nm. Sensors Actuators A Phys. 312, 112102 (2020). https://doi.org/10.1016/j.sna.2020.112102

45. Agrawal, G.P.: Fiber-optic communication systems, 4th edn. Wiley-Blackwell, Oxford (2010)

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