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Analysis of Propagation Length for Nanowire Infused Hybrid Plasmonic Waveguide

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Abstract

In this work the mathematical modelling and detailed analysis of a dielectric based nanowire (NW) infused hybrid plasmonic waveguide (HPWG) with an aim to achieve high propagation length and increased effective area is reported in detail. Modal analysis is carried out to characterize modal parameters such as propagation length and energy confinement for various metal oxide metal (MOM) plasmonic waveguides combinations using commercial COMSOL Multiphysics 6.0. The research problem addressed in this work is propagation length of HPWG. Large propagation length is one of the major requirements in most of the SPR sensors and photonic circuits. In this direction, to enhance the propagation length this work presents a detailed modeling, optimization, and analysis of various MOM combinations are considered for optimizing the propagation length. Detailed analysis is carried out for various MOM combinations. The investigations shows that a propagation length of up to 2800 μm with high confinement is achieved for GaAs-SiO_2-Ag combination. HPWG having high propagation length reported in this work finds potentials applications in many SPR sensors, Photonic integrated circuits and CMOS silicon (Si)-based photonics technology.

Keywords

Plasmonics, Hybrid plasmonic waveguides, Propagation length, SPR sensors

Introduction

The present semiconductor technology is able to fabricate and processes integrated circuits with a size lesser than 3 nm. Modern electronic integrated devices and semiconductor integrated circuit technologies are reaching their speed and data transmission rate limits. The CMOS Si based photonics technology has provided us with excellent IC designs, but further reduction in the size of ICs is limited by the reduced diffraction of light [1]. SPPs (surface plasmon polaritons) that are electromagnetic excitation existing at metal dielectric interface can alleviate the problem of limit on diffraction and localize energy in regions which are insignificant than the incident light's wavelength in the material [2]. Recent advancements in the field of plasmonic, the study and application of SPPs have concluded that the current limitations in the CMOS photonic technology can be solved by integrating SPP based devices. Due to its significant properties such as high mode confinement and low loss, plasmonics has found innumerable applications ranging from science and engineering to cellular biology.

Appearing in the vicinity of metal and dielectric coherence, SPPs are potential candidates for deep subwavelength confinement. Due to its unusual features and potential uses in optics, surface-enhanced Raman spectroscopy [3], solar cells, data storage and sensors, research and development in the field of

SPP sensor and systems has gained interest in recent years [4]. The characteristics of SPPs such as their interaction with light depends on their structure which can be controlled easily just by altering it. This opens the door for creating a wide range of novel photonic devices. The characteristics of SPPs such as their interaction with light depends on their structure which can be controlled easily just by altering it.

Controlling lights having considerably insignificant wavelengths is achieved due to the SPP phenomenon. A waveguide is a perfect device to guide the SPP based electromagnetic excitations with low energy loss and maximum confinement in one direction. Within these years a lot of research has been put into this area to develop an efficient model of a SPP based plasmonic waveguide. Numerous types and models have been experimentally proposed and developed including metal films, metal/insulator/metal (MIM) slabs [5] nanoparticle chains [6], metal grooves [7], MIM gaps, metal wedges, hybrid Bragg waveguide, wire/spacer/film MIM structures [8] and NWs, metal strips [9]. The majority of them suffer from the trade-off between losses and mode confinement, despite the fact that they appear to be superior to conventional waveguides. A sizeable confinement is hard to achieve in these circuits attributing to the substantial ohmic losses in the metal [10]. Therefore, a negotiation between mode confinement and ohmic losses appears to be a practical method for creating efficient models. The substantial propagation losses present, especially at the visible and near-infrared wavelengths, have made it hard to compensate losses in subwavelength SPPs [10].

By combining the light directed by a plasmonic as well as a dielectric waveguide, the HPWG is an optical waveguide that can produce high light confinement. It is created by creating a small gap between a metal surface and a substance with a suitable high refractive index. Normally Si is used as the high refractive index medium whereas gold or silver is used as the metal. The HPWG works on the principle of mode coupling. The high refractive index region such as Si supports the dielectric mode, which is primarily contained inside the region itself. The metal structure supports SPP which is constrained to the surface of metallic region. The dielectric mode connects to the surface plasmon mode when these two structures are combined. Consequently, the light becomes confined in this dielectric metal interface.

The further sections of the paper are systematically organized and presented in three sections. Section II gives theoretical aspects of SPPs and mathematical design considerations for HPWGs. Section III, gives a detailed analysis of a dielectric based nanowire infused HPWG.

Experimentation

Theoretical aspects of SPPs and propagation length

SPPs are coherent electromagnetic excitation that are predominantly prevalent amid the vicinity of dielectric-metal contact (Figure 1). They help the light to get coupled with electrons and hence, confine them at the interface. Investigations by researchers have shown that these oscillations possess spatially decaying fields which are perpendicular to the interface penetrating metal [11].

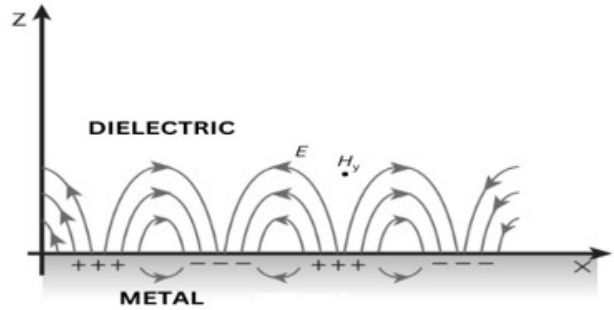


Figure 1: Coupling and oscillations of SPP electromagnetic waves.

Several methods, including total internal reflection of light, light scattering on nano-objects, and light diffraction have been employed for SPP excitation. According to Otto configuration or Kretschmann configuration, total internal reflection of light is the most popular method for connecting light wave with plasmon wave [12]. In the Otto setup, a prism is used, but it is set back from the metal surface. The incident light experiences absolute internal reflection, bringing about the arrangement of a transitory wave in the gap, assuming the refractive index of the space existing amidst the prism and the metal is not exactly equal but lesser than the prism and on the off chance that the point of frequency of the photon on the crystal surface is sufficiently enormous. If the principles of conservation of energy and momentum are satisfied, this transitory (evanescent) field can trigger SPP [13]. Even in the Kretschmann design, a prism is employed; however, a metal film which is sufficiently thin enough is applied to the surface of the prism rather than a dielectric one. The incident photon's energy and momentum match those of the surface plasmons at one particular angle of incidence on the prism surface, activating SPPs [14].

When using a light diffraction technique, wave vectors of incident wave and SPP wave are matched via the diffraction phenomena. The Bragg scattering ensures the matching. The best method for energizing SPP waves is this [15, 16]. Slits, nanoholes, waveguides, and other types of nanostructures that are produced on metal surfaces, as well as molecules or a nearfield microscope probe, can all employed excite SPP waves. By utilizing a plasmonic crystal comprising of nanohole arrays in a silver film covered by a daint layer of gold, Kalmykov et al., have developed a new technique for SPP excitation through the photoluminescence [17]. The key benefits of this method include the following: (1) detection of SPP on zero background; (2) additional structures are non-compulsory to trigger SPP waves; (3) contamination-free; and (4) optical stability.

The properties of SPPs are obtained by solving Maxwell's equations for electromagnetic waves in vacuum. The electric and magnetic fields are given by [13].

$$E_{x,n}(x,y,z,t) = E_0 e^{ik_x x + ik_{z,n}|z| - i\omega t} \quad (1)$$

$$E_{z,n}(x,y,z,t) = \pm \frac{k_x}{k_{z,n}} E_0 e^{ik_x x + ik_{z,n}|z| - i\omega t} \quad (2)$$

$$H_{y,n}(x,y,z,t) = H_0 e^{ik_x x + ik_{z,n}|z| - i\omega t} \quad (3)$$

Where, ω is the angular frequency, + and – for metal and dielectric respectively, and k is the wave vector and n signify the material (dielectric or metal). The dispersion relation which derives a relation between the wavenumber of a wave to its frequency purely depends on the relative permittivity of the materials included. This is obtained as [13],

$$k_x = k_0 \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (4)$$

Where, k = ω/c is the wave number in vacuum. The dielectric function of a metal is expressed as:

$$\varepsilon_m = \varepsilon_m^{'} + i\varepsilon_m^{"} \quad (5)$$

Where, ε_m' is the real component and ε_m" is the imaginary component of the relative permittivity of the metal whereas ε_d is the permittivity of dielectric material. Substituting for from equation 5, we get [18]:

$$k_x = k_x^{i} + ik_x^{"} = \left[\frac{\omega}{c}\left(\frac{\varepsilon_m^{'}\varepsilon_d}{\varepsilon_m^{'} + \varepsilon_d}\right)^{1/2}\right] + i\left[\frac{\omega}{c}\left(\frac{\varepsilon_m^{'}\varepsilon_d}{\varepsilon_m^{'} + \varepsilon_d}\right)^{3/2} \cdot \frac{\varepsilon_m^{"}}{2\left(\varepsilon_m^{'}\right)^2}\right] \quad (6)$$

As the SPP excitations traverse along the surface of material, they end up losing a certain amount of energy to the metal owing to absorption. As a result, their intensity decreases by a factor of $exp\left(2k_x^{"}x\right)$ at a distance of x [13]. This distance for which the total intensity drops by 1/e of the original value is known as the propagation length. This requirement is met at [17].

$$L_{spp} = \frac{1}{2k_x^{"}} \quad (7)$$

Another important characteristic parameter for SPP is the mode confinement. It is characterized as the ratio of total mode energy to the peak energy density given as [13].

$$A_{eff} = \frac{1}{\max\{W(r)\}} \int_{-\infty}^{+\infty} W(r) d^2 r \quad (8)$$

Where, W(r) is the electromagnetic energy density along the direction in which the wave propagates, given as [19].

$$W(r) = \frac{1}{2}\left(\frac{d\left(\varepsilon(r)\omega\right)}{d\omega}\left|E(r)\right|^2 + \mu_0\left|H(r)\right|^2\right) \quad (9)$$

The detailed analysis of hybrid plasmonic waveguide for various MOM combinations discussed in section III shows that a propagation length of up to 2800 μm with confinement factor of 0.0095 is achieved for GaAs-SiO_2-Ag combination. The detailed analysis is presented in section III.

Results and Discussion

Analysis of a NW infused HPWG

This section comprises a detailed analysis of existing HPWGs for optical confinement. The simulation and results were obtained using the commercial COMSOL Multiphysics 6.0. Oulton et al., have proposed a HPWG for subwavelength confinement and enhanced propagation based on a dielectric based NW structure [18]. Figure 2 shows the front view of proposed structure. A metal surface (Ag) and a dielectric nanowire (GaAs) are separated from one another by a nanoscale dielectric gap SiO_2 to form the hybrid optical waveguide. Owing to the fact that both plasmonic as well as waveguide modes have coupled, it is feasible to store energy across the gap similar to what a capacitor does which allows efficient subwavelength transmission in non-metallic areas. As opposed to SPPs, which are just emphatically obliged in one dimension, the mixture mode can be unequivocally compelled to sizes in excess of multiple times less compared to the region of a diffraction-restricted spot while keeping propagation lengths more noteworthy than those of SPPs of the same dielectric - metal contact region [18].

The relative electric permittivity of GaAs, SiO_2 and Ag are $\varepsilon_c = \varepsilon_d$ and ε_m = -129 + 3.3, respectively, at an optical frequency of f = 193T Hz. Figure 3 shows the energy confinement in waveguide for different values of h and r. This hybrid structure supports a low loss mode appearing similar to a cylindrical waveguide mode whose energy is strongly confined in the

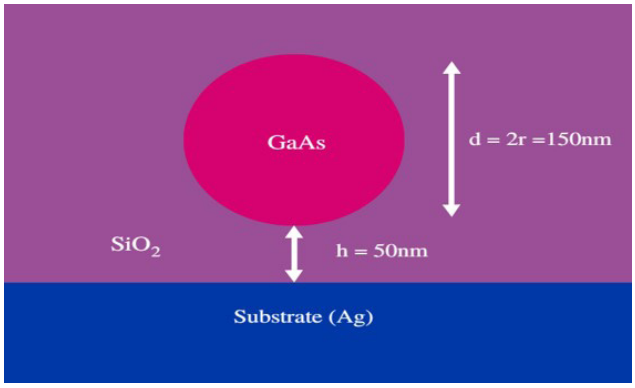


Figure 2: NW infused HPWG structure [18].

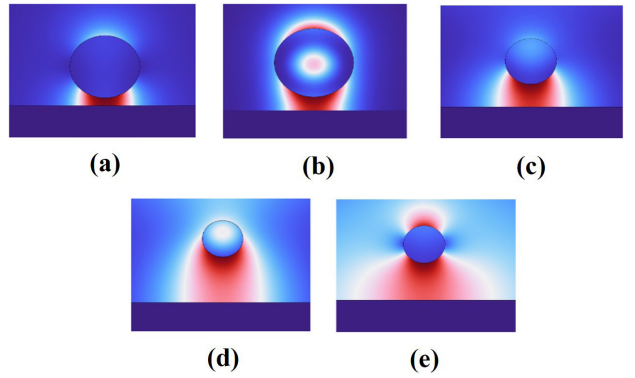


Figure 3: Plots of energy confinement. **(a)** r, d = 100 nm, 25 nm, **(b)** r, h = 250 nm, 100 nm, **(c)** r, h = 100 nm, 100 nm, **(d)** r, h = 100 nm, 200 nm, and **(e)** r, h = 50 nm, 100 nm.

dielectric layer for large values of r and h. On the other hand, a small-diameter cylinder generates an SPP-like mode with loss equivalent to that of uncoupled SPPs and extremely poor localization parallel to the metal surface. For a mediocre range of values for h and r, the mode coupling gives rise to a hybrid mode comprising the characteristics of both cylindrical mode and SPP mode. By tuning the parameters of the waveguide appropriately, one can achieve propagation distances up to few millimetres in addition to high energy confinement.

An important parameter in modal analysis is the propagation length which is very much essential in determining the practicality of a waveguide. Figure 4 depicts the variation of propagation length in response to a change in radius of NW for fixed values of h. The results reveal that increasing the height of NW from material increases the propagation length substantially. The maximal propagation length for h = 25 nm is 1200 μm, whereas it is 2750 μm for h = 200 nm. The propagation length increases up to a certain value of r and then decreases. As a result, an optimal values of radius 120 nm < r < 190 nm results in longer propagation lengths. This effectively proves that for r << 120 nm the waveguide supports a SPP mode whereas for r >> 190 nm the waveguide supports cylindrical mode. For values of r in the range 120 nm < r < 190 nm a hybrid mode comprising of both cylindrical and SPP modes is supported by the waveguide.

The variation of h for r = 170 nm is shown in figure 5. As evident from the plot, propagation length increases as the height of nanowire from the substrate increase. For r = 170 nm a propagation length of 2400 μm was achieved.

Further investigations were carried to determine the effective mode area of the waveguide. The plot of normalised mode area in response to an increase in the radius of cylinder for certain fixed values of h is shown in figure 6. As we can see, the normalized mode area is highest confinement at h = 150 nm and r = 192 nm with a confinement factor of 0.0095. A linear relationship between radius, r and effective mode area is difficult to establish. But it is definite that mode index and propagation length do not go hand in hand with each other. Therefore, it is practical to negotiate among the structural parameters to achieve longer propagation lengths along with a strong confinement.

Further investigations were conducted by considering different metals in the place of silver for the substrate layer. Since gold, silver and copper come under the same period, they exhibit similarity in certain characteristics which can act as a substitute of silver. These noble metals possess unique characteristics which can be explored in numerous ways. Figure 7 shows the propagation lengths for different substrate metals as a function of radius of the cylinder, r for h = 150 nm. As evident from the plot, propagation length for silver is very high than gold and copper.

Figure 8 shows the normalized effective mode index for different substrates. As evident from the plot, the normalised values of A_{eff}/A_0 for gold and copper are exactly identical and have overlapped while for silver, it is quite different. Although the normalised mode index for these substrates differs with

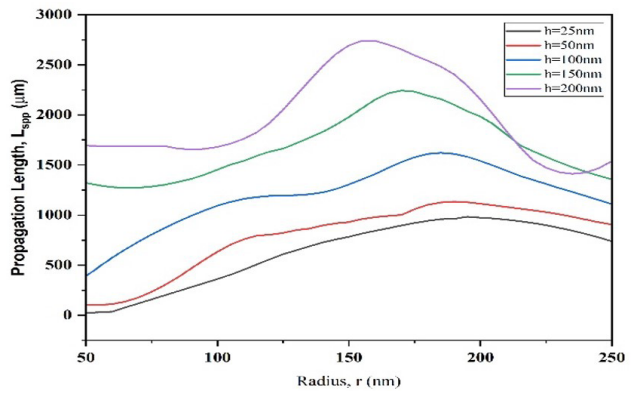


Figure 4: Propagation length vs r for various values of h.

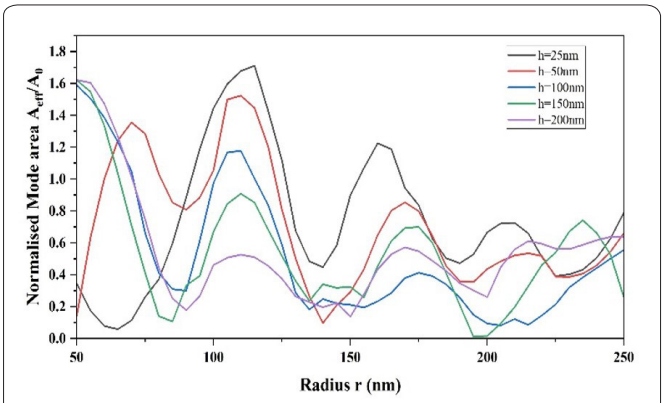


Figure 6: Normalized effective mode area for different values of h.

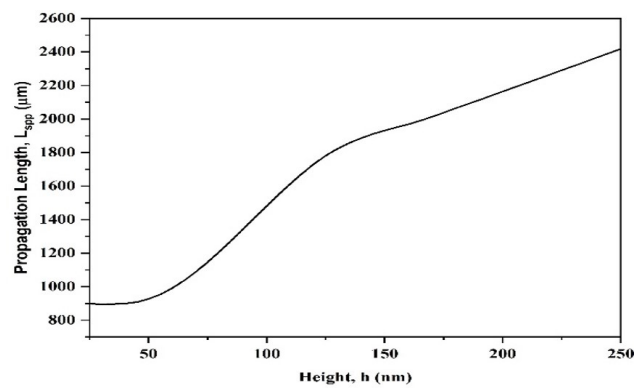


Figure 5: Propagation length vs h for r = 170 nm.

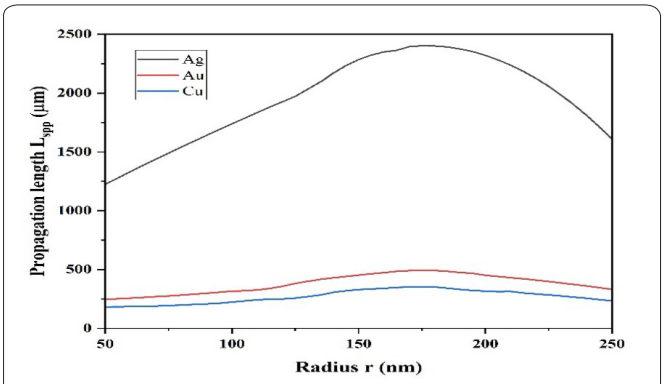


Figure 7: Propagation lengths for different substrates with GaAs nanowire (h = 150 nm).

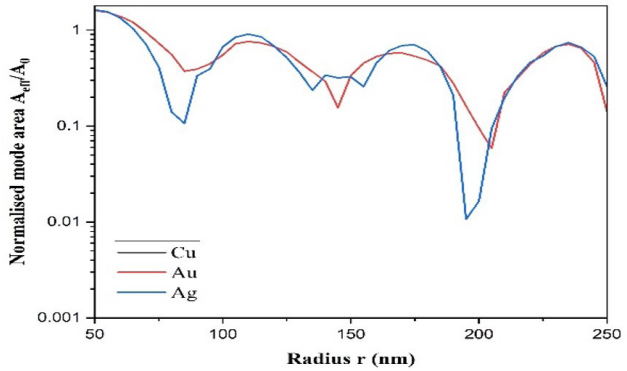


Figure 8: Normalized mode area for different substrates (h = 150 nm, r = 100 nm).

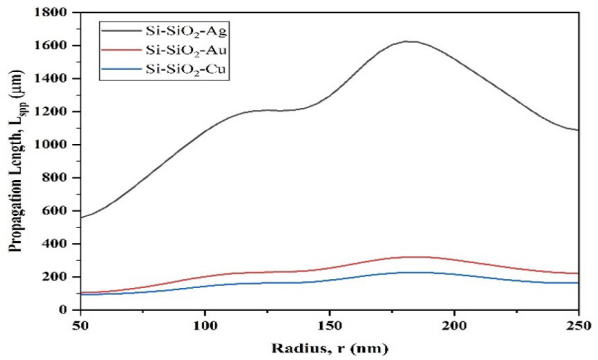


Figure 9: Propagation length for Si NW.

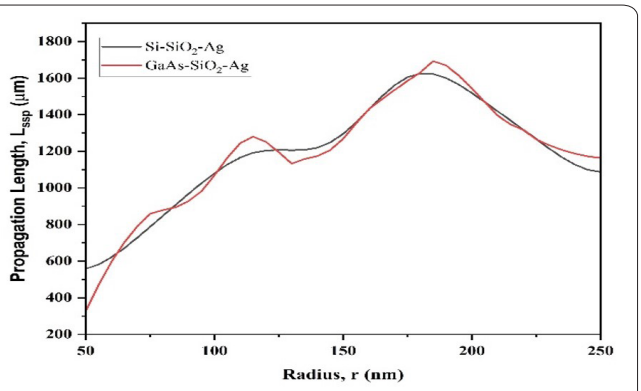


Figure 10: Propagation lengths for Si model and GaAs model (h = 150 nm).

Table 1: Comparison of propagation length and modal area.

Model	Maximum propagation length (μm)	Normalised mode area
Proposed NW infused HPWG	2800	0.0095
Existing conventional HPWG [20]	120	0.01

least differences, there is a huge difference with respect to their propagation lengths. The propagation lengths obtained for silver is the highest followed by gold and copper. Therefore, silver seems to be the perfect material for substrate.

To strengthen the model further, analysis is carried out by experimenting with various high permittivity dielectric materials used in nanowire to achieve high propagation length. Since the permittivity of GaAs and Si are approximately identical (ε_c = 12.08) at optical frequencies, the structure was simulated by infusing a Si NW into the dielectric medium. Figure 9 shows the plots of propagation length in accordance with the radius of cylinder for h = 150 nm with Si as the NW and for different substrates. The investigations show that though Si is suitable for the NW, the propagation lengths are lesser than that of GaAs NW model. The highest propagation length achieved for using Si based structure is 1600 μm at r = 180 nm, whereas it is 2400 μm for GaAs structure. This is shown in figure 10.

In comparison to existing plasmonic waveguides, HPWG offers substantial confinement of light at a lower loss [20]. Additionally, Si photonics technology is compatible with it. The combination of these alluring qualities has sparked interest in the use of this new guiding scheme throughout the world. Due to these features, the HPWG has numerous applications in the field of engineering and science. For instance, these are used in biosensing, optical computing and optical information processing [21], photonic integrated sensors and many more.

In comparison the nanowire infused HPWG model has shown significant increase in modal characteristics. Exceptionally high propagation lengths were achieved along with strong energy confinement in the metal dielectric interference. The nanowire infused model has been compared to an existing conventional SOI HPWG model proposed by Wang et al. [20]. Their model comprises of Si-SiO$_2$-Ag structure with the shape of the dielectric Si being triangular along a gap between the dielectric and the insulator. The table 1 shows the comparison results for both the models. There is a significant increase in the propagation length from 120 μm reported by Wang et al. [20] to 2800 μm using the proposed model. Also, the normalized mode area is approximately equal to that of the conventional waveguide having strong modal confinement. This eliminates losses and increases the overall efficiency of the waveguide. Owing to its simple structure this model can be integrated with other photonic devices and PICs with minimum complications in fabrication processes.

Conclusion

Plasmonics has been broadly concentrated on by different analysts all through the world and has acquired most extreme significance over the most recent couple of many years. Because of its light tuning properties, plasmonics find huge applications going from science and innovation to molecular biology. It has arisen to be a significant branch in nanophotonic. In this paper, a detailed discussion on the theoretical, modelling and simulation results pertaining to enhancing the propagating length aspects of HPWGs is provided. A NW infused HPWG is analyzed and the results are inferred. Also, a detailed analysis on a NW infused HPWG structure, and compiled its modal characters for various metal oxide insulator structural scenarios. The results obtained indicate that the propagation length can be further extended to the mm range with strong confinement. There is a significant increase in the propagation length from 120 μm reported by Wang et al. [20]

to 2800 μm using the proposed model. Also, the normalized mode area is approximately equal to that of the conventional waveguide having strong modal confinement. This eliminates losses and increases the overall efficiency of the waveguide. Owing to its simple structure this model can be integrated with other photonic devices and PICs with minimum complications in fabrication processes.

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Conflict of Interest

None.

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