A Hybrid Plasmonic Waveguide for the Propagation of Surface Plasmon Polaritons at 1.55μm on SOI Substrate

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***Abstract*—A hybrid plasmonic waveguide (HPW) has been numerically investigated, based on silicon-on-insulator structure near the telecom wavelength λ=1550nm using the finite element method. The HPW consist of metal cap placed on Silicon on insulator (SOI) rib which has a trench with a semi-circle interface at the bottom of the trench. With the proper choice of waveguide sizes, our proposed HPW can support hybrid long-range surface plasmon which have strong mode confinement ($A_{eff}/A_0 \cong$ 0.0035-0.035) and long propagation length ($L_{eff} >$ 525 μm) simultaneously. In addition, for the proposed hybrid plasmonic waveguide, the calculated coupling length for two parallel identical waveguides which is separated by distant (d=250 nm) is approximately 1.3 μm , which is very helpful in realizing photonic integration circuits with ultra-high integration density.**

***Index Terms*—Surface Plasmon Polaritons, Plasmonic Waveguides, Coupling Length.**

I. Introduction

In the recent years, Nano-scale optical waveguides based on surface plasmon polariton have become a promising solution to achieve photonic integrated circuits (PICs) with a high-integration density. Due to their ability to break the diffraction limit they have the ability of true Nano-scale waveguiding and confinement of light. Till now, a variety of plasmonic structures have been investigated, including long-range SPP (LRSPP) [1],[2], metal-insulator-metal (MIM) [3], dielectric-loaded SPP (DLSPP) [4]. However, due to the large ohmic loss of metals, all these waveguides suffer from a trade-off between the confinement ability and the propagation length. In general, the SPP confinement is achieved primarily by decreasing the SPP spatial extension into the dielectric. On the other hand, this increases the portion of SPP power being absorbed by the metal which increases the loss. Hence, the choice of optimum guiding configuration is subject to trade-off with many intricate issues.

It has been shown that, covering the metal strip with two thin layers of lower index material can be a way to reduce the loss and increasing the propagation length significantly. However, the tradeoff is that it also increases the mode size [5], [6]. Therefore, to solve this problem to some extent, a hybrid waveguiding mechanism was proposed recently [7],[8]. In these structures the mechanism consists of a high-index-contrast dielectric waveguide placed close to a plasmonic structure. In this regard, one of the important structures that attracted a lot of attention is the hybrid waveguide consisting of a high index medium separated from a metal surface by a low index spacer [7]-[10]. It has been shown that this waveguide can have a good confinement and propagation distance at the same time [7]. Other kinds of hybrid plasmonic waveguide for TM polarization can be created by placing a metal cap [8] or metal plate [11] on top of a SOI (silicon-on-insulator) rib waveguide with SiO2 on the surface, or by incorporating air Nano-trench at the interface of metal and Silicon layer [12].

In this paper, we present a novel hybrid plasmonic waveguide, which consists of metal cap placed on the SOI rib, with a hole in Silicon layer under the metal, which has a semi-circle interface at its bottom. With this idea we basically incorporate both idea of using circular geometry [13] to have very tight confinement and long propagation length and SOI rib platform to ensure compatibility to CMOS technology, simultaneously. By introducing this new low-index region, the present hybrid plasmonic waveguide provides a very high power density in the region of low-index hole, due to the field-enhancement resulting from the effects of electric-field discontinuity and surface plasmonic. The simulation results show a very small effective mode area in the proposed structure. It will be shown that, this novel structure, also has very small decoupled separation for two parallel identical waveguides, which is helpful in realizing high density photonic integrated circuits.

II. Waveguide Structure

Figure 1 shows the cross section of our proposed hybrid plasmonic waveguide. The main feature of this geometry is the semi-circle silicon interface at the bottom of the trench. The wavelength is set at λ=1550 nm, and permittivity of SiO_2, Si and Ag are ϵ_{Sio_2}=2.25 , and ϵ_{Si}=12.25, and $\epsilon_{Ag} = -129 + 3.3i$ [14], respectively. The minimum distance between top of the semi-circle and the metallic layer is h. This helps to confine electromagnetic field in a very small area, which leads to a very small effective mode area. By proper choice of the waveguide dimensions, it also provides a large propagation length at the same time. In our simulations through this paper,

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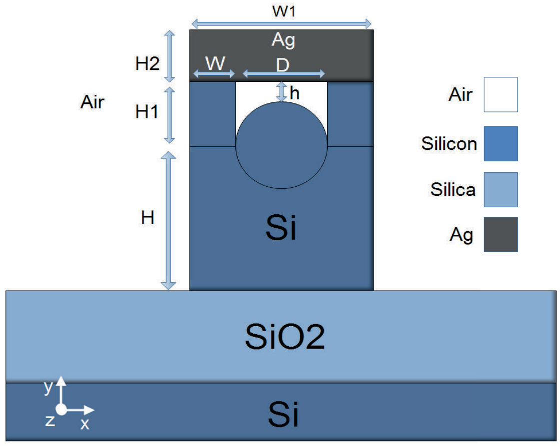

Fig. 1. The cross section of our proposed hybrid plasmonic waveguide with a Nano hole at the interface of metal and silicon layer.

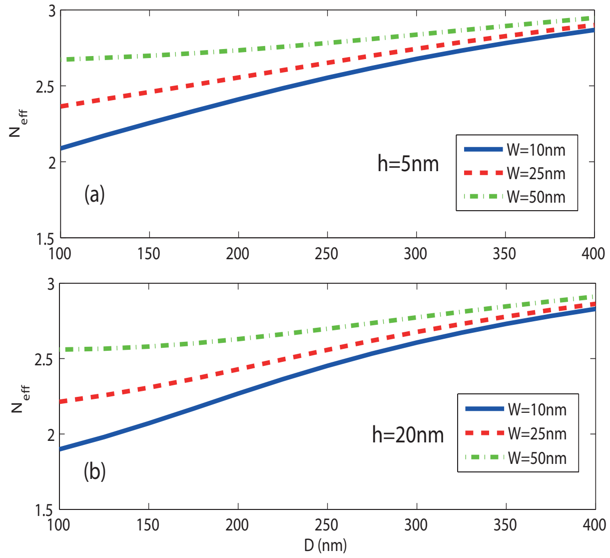

Fig. 2. Real part of effective mode index, for different h and W parameters as D varies (a)h=5nm (b)h=20nm.

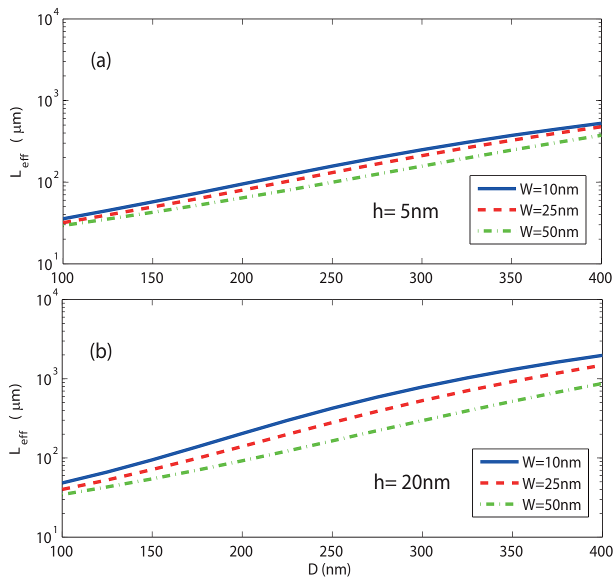

Fig. 3. Propagation length for different values of W, as D varies when h=5, 20nm, (a)h=5nm (b)h=20nm.

we use the waveguide parameters such as diameter of the semi-circle (D), silicon height (H) , distance between the tip of the semi-circle part of the trench to the conductor (h) and the width of the trench walls (W) to optimize the characteristic properties of our proposed waveguide.

The main characteristic parameters of plasmonic waveguides are effective mode index, N_{eff}, propagation length, L_{eff}, and effective mode area, A_{eff}. The modal properties are investigated by means of the finite-element method using COMSOL@ software. The eigenmode solver is used with the scattering boundary condition. Convergence tests are done to ensure that the numerical boundaries and meshing do not interfere with the solutions. In addition, to make sure there is no disturbance from the boundaries of the computational domain, we choose the calculation domain to be large enough, $(-2\mu m < y < 2\mu$m and $-2\mu m < x < 2\mu m)$. Throughout this paper we set $H = D/2$,$H_1 = D/2+h$ and $H_2 = 100$nm and we use other parameters of the waveguide in the optimization process.

To analyze the structure, we have to define the partial differential equation derived from Maxwell's equations that describes the light propagation in this waveguide which is

$$\nabla^2 E_t + \nabla\Big(\frac{\nabla n^2(x,y) \times E_t}{n^2(x,y)}\Big) + \Big(\frac{2\pi}{\lambda}\Big)^2 n^2(x,y)E_t = \beta^2 E_t, \quad (1)$$

$$\beta = \beta' - j\beta'', \quad (2)$$

Where E_t is the transverse electric field, λ is the wavelength, $n(x,y)$ is the refractive index distribution and β is the complex propagation constant (eigenvalue of the wave equation). Instead of using β itself usually the parameter N_{eff} which is defined as β/k_0 (k_0 is the wavenumber in vacuum $(k_0 = 2\pi/\lambda)$) is used. In Fig.2 we have plotted the real part of effective mode index $\Re\{N_{eff}\}$ versus circle diameter (D), for different h parameter values as D and W vary.

Normally it is desirable to design the waveguide with high real part of the effective mode index, which leads to higher concentration of the light. It is clear that the increasing the trench aperture increases $\Re\{N_{eff}\}$. Also with thicker trench walls (W) and smaller distance between the semicircle dielectric and the conductor (h), we can have larger real part of the effective mode index.

Another characteristic of the plasmonic waveguide, which plays an important role in the design process is propagation length (L_{eff}) which is defined as the distance that the energy (intensity) of the field attenuates to $1/e$, i.e.

$$L_{eff} = \frac{\lambda}{4\pi\Im\{N_{eff}\}}, \quad (3)$$

In Fig.3 we have plotted propagation length versus D as W varies for h=5nm and h=20nm, (logarithmic scale on the

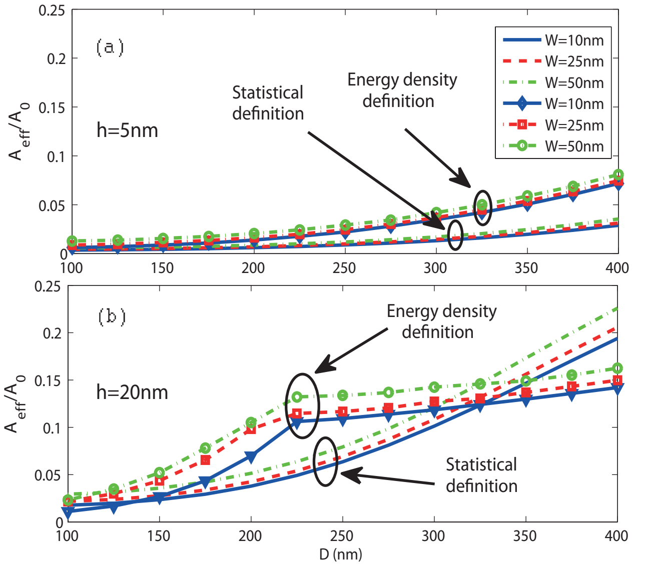

Fig. 4. the normalized effective mode area (A_{eff}/A_0) for h=5nm and 20nm, based on two definitions (a)h=5nm (b)h=20nm.

y-axis). According to Fig.3 longer propagation length in the range of millimeter, can be achieved by increasing the diameter (D) and distant (h) and decreasing the value of W, in the substrate. However, longer propagation length usually causes a problem in plasmonic waveguides, which is reduction in the effective mode index of the waveguide. To see that, we have plotted the normalized effective mode area (A_{eff}/A_0), for h=5nm and 20nm as W and D vary, in Figs.4(a) and (b). In each plot, we have calculated the effective mode area based on two different definitions, one according to statistical measurement definition and one according to energy density definition. Based on the statistical definition of effective mode area.

$$A_{eff} = \frac{\left(\int\int E^2(r)dA\right)^2}{\int\int E^4(r)dA}, \quad (4)$$

Where $E(r)$ is the electric field [15], and in the energy density definition,

$$A_{eff} = \frac{\int W(r)dA}{Max\{W(r)\}}, \quad (5)$$

Where in this definition, $W(r)$ is the energy density [15]. To compare these definitions, we have normalized both of them to A_0, the diffraction-limited mode area defined as $\lambda^2/4$.

It is clear that as we increase the value of D confinement becomes worse, which is not desirable for the purposes of compact integration circuits. A good design must consider both A_{eff} and L_{eff} at the same time, which will be a trade-off between them. For h=5nm based on the statistical definition, we can see that for all values of D between 100 to 400 nm or even higher values we have a very good confinement (less than 0.035) which ensures a high localization of field in area between top of silicon semi-circle and metallic layer. Also

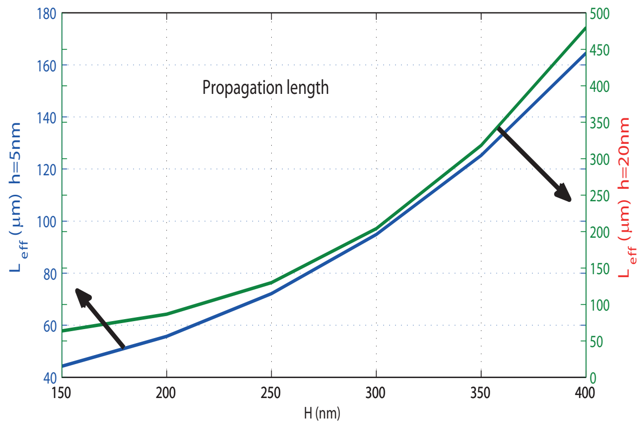

Fig. 5. Propagation length for h=5nm and h=20nm as H varies for fixed values of D=200nm and W=10nm.

based on the energy density definition, we obtained A_{eff}/A_0 below 0.08, which is also very good compared to other plasmonic waveguide structures. In Fig.4(b) by increasing D the effective mode area increases with a fast rate up to the point D=225nm and for D >225 nm it increases with slower rate. The reason is that around D=225nm, the structure behavior changes from hybrid structure to cylindrical mode waveguide mode[7].

Another parameter that can be used in the optimization process is the silicon rib height (H). By proper choice of H, we can achieve large propagation length with good mode confinement simultaneously. In Fig.5 a plot of propagation length for h=5nm and 20nm versus silicon height (H) is shown for D=200nm , W=10nm. From Fig.5 it is obvious that for larger H, longer propagation length can be achieved,(logarithmic scale on the y-axis).

To see the effect of the rib heights (H) on the effective mode area we have plotted the normalized effective mode area A_{eff}/A_0 versus H for different values of h using statistical and energy density definition in Fig.6. Based on the results effective mode area grows monotonically with H therefore better confinement is achieved with lower values of Si rib height. It should be mentioned that although we have used both the statistical and energy density definitions to calculate the effective mode area, the energy density definition, is not proper for our proposed structure because of two main reasons. First, since we have a hole in the Si layer, the peak of energy density distribution on side walls becomes so large, which leads to inaccurate calculated results [15]. Second, it has been shown that, the hybrid plasmonic waveguide is good for high energy density, rather than real energy confinement [16]. Hence, the best choice for analyzing A_{eff} and designing an optimum structure is using the statistical definition. For the final design, according to the presented results and explanations and based on the statistical definition the optimum structure should have the parameter values, H=350nm, H_2=100nm, W=10nm, D=200nm, h=5nm. The quasi-TM fundamental mode $|E_y|$ for these sizes is shown in Fig.7. We also have plotted the mode profile along x- and y-axis in Fig.8 and .9, respectively. In

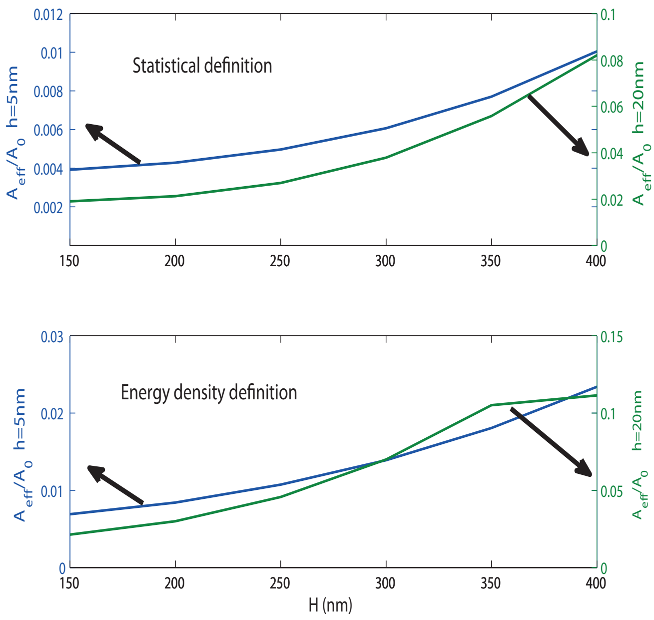

Fig. 6. Normalized effective mode area A_{eff} versus H for h=5nm and h=20 nm, based on statistical and energy density definitions.

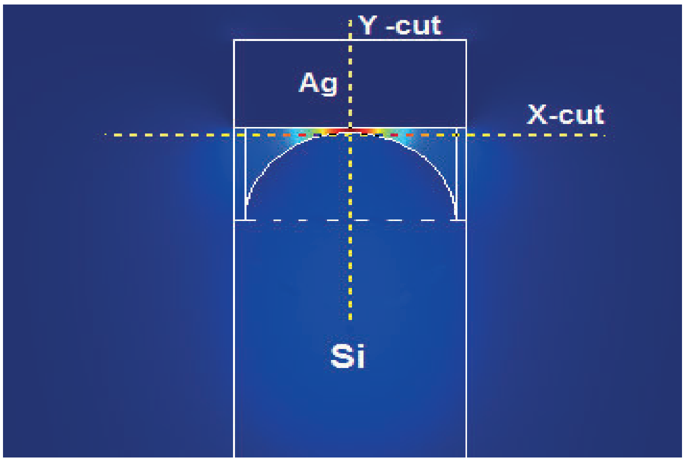

Fig. 7. The quasi-TM fundamental mode $|E_y|$ of proposed hybrid plasmonic waveguide, with a semicircle hole at the interface of metal and Si, (H=350nm, $H2$=100nm, W=10nm, D= 200nm, h=5nm)

Fig.8, the lateral confinement is almost 100nm, which is more proper than 500nm that was proposed in[13].

III. Directional coupler based on proposed hybrid plasmonic waveguide

In Fig.10 the cross section of our proposed directional coupler for a coupling system with two parallel identical hybrid plasmonic waveguides is shown. The distant between two waveguide is d.

Figure 11, shows the calculated coupling length L_c of two parallel hybrid plasmonic waveguides as the distant between them (d) varies from 250nm to 700nm for given separations h=5nm and h=20nm, (logarithmic scale on the y-axis).

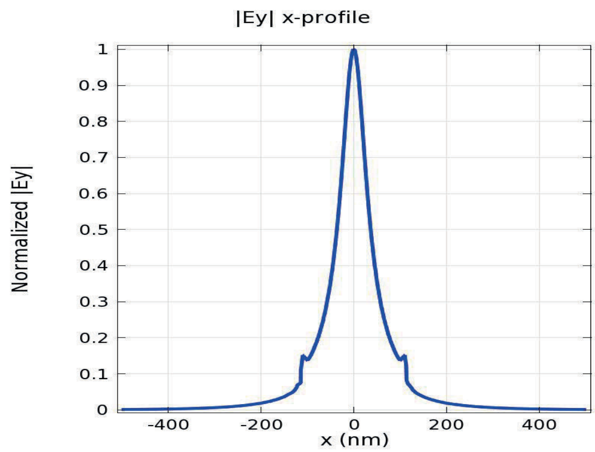

Fig. 8. $|E_y|$ distribution in the x direction along the dashed lines in Fig.7.

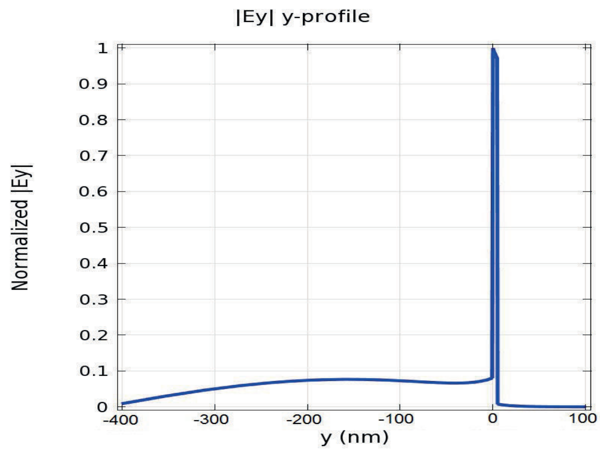

Fig. 9. $|E_y|$ distribution in the y direction along the dashed lines in Fig.7.

The other parameters are D=200nm, H_2=100nm, W=10nm, H=300nm. The coupling length is given by

$$L_c = \frac{\pi}{\beta_o - \beta_e}, \quad (6)$$

Where β_o and β_e are the propagation constants of the odd and even super modes of the two parallel waveguides, respectively. They can be calculated using a full vector FEM mode-solver.

According to Fig.11 the coupling length is almost increases exponentially as the separation d increases, which is similar to the conventional dielectric optical waveguides. When the separation is decreased to 250nm, the coupling length is as small as L_c= 1.30μm. On the other hand, the coupling length is only several microns, when a small separation is chosen. This is very useful for an ultra-compact directional coupler, which is a basic element for Nano photonic integration circuits.

In order to highlighting the limits of the proposed device in terms of fabrication process and fabrication tolerances, we have simulated our structure based on situations, when an accurate and fine semicircle cannot be fabricated. For this condition,in Fig .12 we have assumed that during the fabrication process, the semicircle edges on the rib part associate with unexpected tolerance. Table I, will show that a very fine

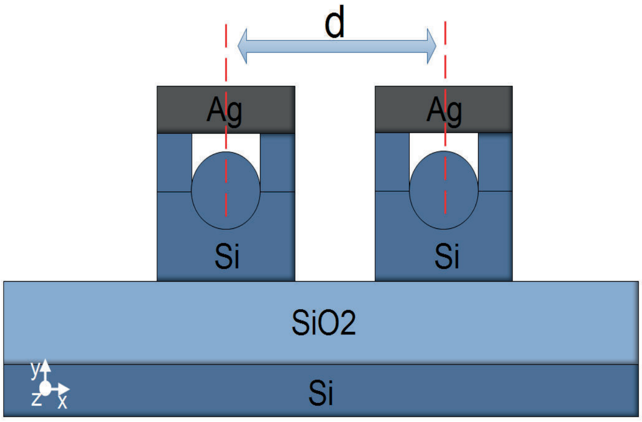

Fig. 10. The cross section of our proposed directional coupler for a coupling system with two parallel identical hybrid plasmonic waveguides. The separation distant is d.

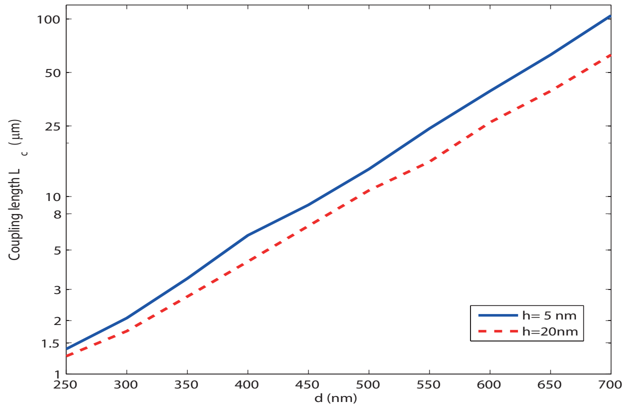

Fig. 11. coupling length L_c of two parallel hybrid plasmonic waveguides for h=5nm and h=20nm, (D=200nm, H_2=100nm, W=10nm, H=300nm).

and accurate design does not require getting a good result: (D=200nm, H=300nm,W=10nm and h=5nm)

Table I, reveals that even with inaccurate fabrication process,(inaccurate semicircle edge), the results almost does not change.

In the tables II and III, we have compared our final results for $h = 5$nm and $h = 20$nm with two other structures in [7] with parameters (D=200nm, H=350nm, W=10nm) and [12] with parameters (W=220nm, W_a=200nm). As mentioned before statistical definition is more suitable for our structure. For h=20nm it provides a large effective length and the lowest effective mode area compared to other structures.

IV. Conclusion

We have studied a Si-based hybrid plasmonic waveguide with semi-circle hole at the interface of metal and silicon layer, for Nano-scale light confinement as well as relatively long propagation distance (in the range of millimeter). The present hybrid plasmonic waveguide has been shown that, has a relatively long propagation length and Nano-scale optical confinement at the same time, by adjusting the waveguide

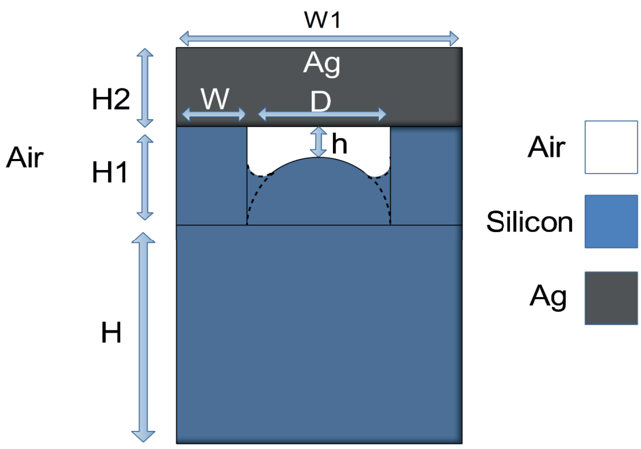

Fig. 12. The proposed hybrid plasmonic waveguide, without an accurate semi-circle on silicon rib, (H=300nm,W=10nm, D=200nm , h=5nm, W=10nm)

TABLE I
Comparison of our final result for accurate and inaccurate fabrication process, ($H = 300nm$)

Characteristic parameters	Fine structure	Normal structure (inaccurate structure)
L_{eff}	94.8582 μm	91.8429 μm
A_{eff}/A_0 (Statistical definition)	0.006067	0.006191
A_{eff}/A_0 (Energy density definition)	0.0139	0.01419

TABLE II
Comparison of our final result ($D = 200nm$, $H = 350nm$, $W = 10nm$, $h = 5nm$) with other proposed structures [7] ($D = 200nm$, $H = 350nm$, $W = 10nm$) and [12]($W = 220nm$, $W_a = 200nm$)

Characteristic parameters	Our proposed structure h=5 nm	[7]	[12]
L_{eff}	126 μm	81 μm	238 μm
A_{eff}/A_0 (Statistical definition)	0.007	0.019	0.178
A_{eff}/A_0 (Energy density definition)	0.0181	0.022	0.060

TABLE III
COMPARISON OF OUR FINAL RESULT ($D = 200nm$, $H = 350nm$, $W = 10nm$, $h = 20nm$) WITH OTHER PROPOSED STRUCTURES [7] ($D = 200nm$, $H = 350nm$, $W = 10nm$) AND [12]($W = 220nm$, $W_a = 200nm$)

Characteristic parameters	Our proposed structure h=20 nm	[7]	[12]
L_{eff}	319 μm	95 μm	288 μm
A_{eff}/A_0 (Statistical definition)	0.0558	0.125	0.210
A_{eff}/A_0 (Energy density definition)	0.091	0.090	0.085

parameters. Due to the field enhancement in the low-index region (which is air in our design) for TM polarization, an ultra-small normalized effective mode area was achieved (e.g. 0.0035 at λ=1550nm). In addition, when distant between metallic layer and semi-circle (h) decreases, the field is more confined in the low-index region. The coupling length between two adjacent waveguide also has been calculated. The simulation results show very small coupling length for small separation distant (d), (e.g. L_c= 1.30 μm) which is very helpful to realize photonic integration circuits with ultra-high integration density.

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