Optics Communications 343 (2015) 85–90

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Hybridization of plasmonic and photonic modes for subwavelength optical confinement with longer propagation and variable nonlinearity

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A R T I C L E I N F O

Article history:
Received 3 October 2014
Received in revised form
30 December 2014
Accepted 31 December 2014
Available online 7 January 2015

Keywords:
Hybrid Plasmonics waveguide
Nano-scale optical confinement
Optical waveguide
Integrated photonics

A B S T R A C T

Mode hybridization of photonic and plasmonic modes in hybrid plasmonic (HP) waveguide is proposed to achieve low-loss sub-wavelength (nano-scale) optical-confinement with variable optical nonlinearity. Origin and analysis of the mode hybridization is presented to come up with an efficient design of HP-waveguide. The coupled-mode-theory is used to calculate the coupling between the SPP and photonic-mode for the estimation of mode character. The mode-coupling can be modified by controlling the associated evanescent field which is responsible for the longer propagation of HP mode in the dielectric. The coupling strength (for HP mode) in $Si/SiO_2/Ag$ system is found to be 52%. The nonlinear coefficient for a 10-nm thick dielectric remains at $3.8 \times 10^7\ km^{-1}\ w^{-1}$ with propagation length of 154-μm and modal area of $0.0009/\mu m^2$. The nonlinearity of the guided mode is shown to be variable with change in waveguide width. The guiding characteristics are shown to be effectively controlled by the high-index region under the dielectric layer to provide flexible nonlinearity. The propagation loss for Si-based HP-waveguide is 0.028-dB/μm. Coupling and propagation characteristics of the HP waveguides are calculated analytically as well with Finite-Element-Method.

1. Introduction

Nanophotonics is promising for on-chip data processing and transmission in large-scale integrated photonic circuits. It is key for various applications in sensing and optical communication. Plasmonic waveguides and devices have been attracting an ever increasing interest [1,2]. For the device integration on nanoscale, the confinement and controlling the light beyond the diffraction-limit are major issues that can be addressed by plasmonics. However, such desirable features for 'nanophotonics' come at a cost, namely, high propagation losses associated with field penetration in metal regions [3–6]. Thus, significant efforts have been directed in reducing or compensating for the inherent resistive losses of plasmonic waveguides, through elaborate geometrical/material configurations [7–10]. A typical challenge for plasmonic waveguides is the trade-off between propagation loss and field confinement. In other words, they can perform either low propagation loss with a diffused field e.g., long-range surface plasmon polaritons (SPP) or compact mode size at the expense of large losses e.g., metal–insulator–metal waveguides [11,12]. Recently a novel type of plasmonic waveguide called hybrid plasmonic (HP) waveguide is proposed to attempt both low propagation loss and strong field confinement [6]. Plasmonics as major part of the emerging field of the nanophotonics [13–17] explore how electromagnetic field can be confined on the scale much smaller than the operating wavelength [9,18]. It is possible to guide and confine the light at real 'nanoscale' with the help of hybridization of the photonic mode and SPP mode; the hybridization is analytically decided by a parameter called mode character *a*, which defines the nature of the hybrid mode resulting from the coupling of the optical and SPP mode [6].

An integrated platform based on hybrid plasmonic-photonic waveguide can be promising for making photonic devices at real nanoscales. In this paper, coupling and propagation analysis of SPP and photonic modes of HP waveguide are presented with the material system – $Si/SiO_2/Ag$. Low-loss sub-wavelength (nano-scale) optical confinement with variable optical nonlinearity is proposed as result of the mode hybridization of photonic and plasmonic modes in hybrid plasmonic (HP) waveguide.

The origin and analysis of coupling, guiding and confinement of HP mode are presented analytically as well by using Finite Element Method (FEM) [16]. Our analysis reveals that the photonic mode confined in a rectangular geometry, in contrast to circular mode confined in a wire [6], can be efficiently pushed, with longer propagation, towards metal-dielectric interface. This photonic mode can be coupled with SPP mode to give us HP mode with longer (than that in circular geometry) propagation length because of the leaky nature of the modes confined in rectangular

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http://dx.doi.org/10.1016/j.optcom.2014.12.083

geometries. In addition, the evanescent nature of the field confined in the high-index region under dielectric is introduced to understand the coupling of surface plasmon and optical field. It is shown that the modification in the nature of the coupling of surface plasmon and optical field is an important requirement to push the SPP longer into the waveguide. This coupling can be modified by increasing the evanescent field into dielectric to propagate the HP mode longer in the dielectric. The coupled mode theory is used to calculate the mode character and coupling between the SPP and optical mode [19–22]. The coupling strength for Si/SiO_2/Ag system is 52% and propagation length of HP mode with silicon is 154 μm at a 10 nm thick dielectric. The propagation loss for Si based HP waveguide is 0.028 dB/μm and modal area for silicon is 0.0009/μm^2. Lower plasmonic losses in Si cause low-loss guiding of HP mode with stronger optical confinement and hence smaller mode area [23]. The thickness of high-index region and waveguide-width are shown to control the optical nonlinearity of the waveguide. It has been shown that the nonlinearity of the guided HP mode remains at par with that of photonic mode which can be considered low with nano-scale optical confinement.

2. Proposed waveguide

The proposed design of the hybrid plasmonic waveguide which is to be analyzed is depicted by the Fig. 1. It consists of $SiO_{2,}$ slice sandwiched between Ag and Si to guide and confine the HP mode. The waveguide width is w and the thickness of the dielectric (SiO_2) is t_d. The optical waveguide (Si) is taken to be a square waveguide with $h=w$ where h is the thickness of the Si. The thickness of the top silver layer is taken to be 200 nm. To form an HP mode the coupling of field confined in the Si with SPP mode is controlled through the intermediate dielectric layer between metal and Si. At optimized coupling of optical and SPP modes, hybrid mode is formed for which mode character is 0.5 [6]. For the fabrication point of view we consider a rectangular geometry of the waveguide. The choice of the noble metal tells us that Ag supports longer propagation length with very low loss [20], and appropriate choice of the dielectric which enables us the induction of the gain, compensation of the loss in metal and increases the SPP signal propagation length. We choose Ag, which has highest conductivity among the metals in the wavelength range and Si, which have higher value of the relative permittivity, help to enhance more

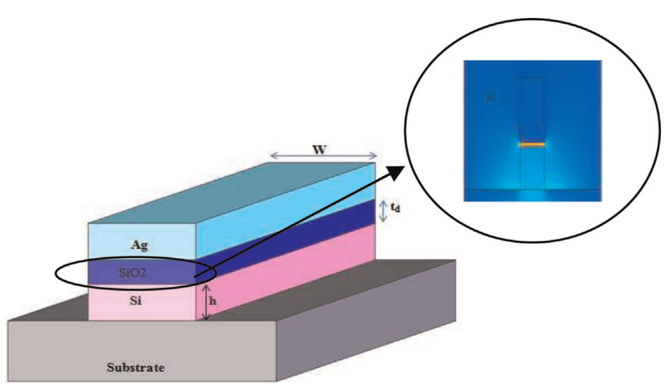

Fig. 1. Schematic of the proposed design of hybrid-plasmonic waveguide with SiO_2 of thickness t_d and waveguide width of w. Optical mode (confined in Si) can be pushed towards metal-dielectric interface surface to couple it with SPP mode. The thickness of top Ag layer is 200 nm. The thickness of Si is denoted by h. h and w are taken to be equal to form a square optical waveguide. Insect shows the field distribution E_y of the fundamental TM mode of the HPW is shown in the pictorial. The field confinement, when SiO_2 sandwiched between Ag and Si. The t_d is 10 nm and width is 200 nm. For this, mode area is 0.0009/μm^2 and modal propagation loss is 0.028 dB/μm. We have largest propagation length $L_p=154$ μm.

electric field in the dielectric region. The strong field enhancement in the SiO_2 is due to the combination of SPP at Ag and SiO_2 interface and the discontinuity in the field confinement E_y from the Si–SiO_2 interface [18].

3. Analysis of mode hybridization

With the coupled mode theory [6,20], the eigen mode Ψ supported in the coupled waveguide system can be described as the superposition of the rectangular mode $\Psi_{react.}$ and SPP mode. If t_d is the thickness of the dielectric and h and w are thickness and width of Si based optical waveguide and if $a_+(h, w, t_d)$ is the field-amplitude in the rectangular waveguide and $b_+(h, w, t_d)$ is the field-amplitude of the SPP mode, the wave function of the symmetric eigen mode Ψ_+ can be written as [6,20]:

$$\Psi_+(h, w, t_d) = a_+(h, w, t_d)\Psi_{react.waveguide}(t_d) + b_+(h, w, t_d)\Psi_{SPP} \tag{1}$$

The square of the modulus of rectangular mode amplitude is the measure of the character of the hybrid mode known as *mode character* given by $|a_+(h, w, t_d)|^2$. It specifies the degree to which the guided mode is optical or SPP. A guided mode will be hybrid plasmonic if [6]

$$|a_+(h, w, t_d)|^2 = 0.5 \tag{2}$$

field-amplitude of SPP mode will then be given by

$$b_+(h, w, t_d) = \sqrt{1 - |a_+(h, w, t_d)|2} \tag{3}$$

As shown in Eqs. (2) and (3) field amplitudes are the function of h, w and t_d. The behavior of the typical coupled mode system the mode character is given as

$$|a_+(h, w, t_d)|^2 = \frac{[n_{hyb.(h,w,td\ )} - n_{SPP}]}{[n_{hyb.(h,w,td\ )} - n_{react.\,(h,w).} + n_{hyb.(h,w,td\ )} - n_{SPP}]} \tag{4}$$

Here n_{hyb} is the effective index of the hybrid mode, n_{SPP} is the effective index of the SPP mode and n_{rect} is the effective index of the optical mode in Si. The n_{hyb} is caused by the coupling of optical and SPP mode which is predicted by the real part of effective index and that is calculated by using FEM. For the prediction of mode character we calculate the effective index of the SPPs mode and that of rectangular waveguide mode as follows: The interaction of light at the metal surface leads to the confinement of the light beyond the reach of the dielectric photonic structure [21]. The interaction between the metal and the dielectric interface supports SPPs, these are the evanescent electromagnetic wave bound to the interface that are strongly coupled to the coherent oscillation of free electron charge at metal surface. The eigen mode of an interface between a dielectric and a metal are SPPs. We refer to them as the eigen modes in the sense that they are solution of Maxwell's equations that can be formulated in the absence of an incident field. In general, coupling of the hybrid mode can be either TE or TM type but since the SP mode supports in metal dielectric interface are TM in nature, the permittivity ε only varies in one spatial coordinates $\varepsilon=\varepsilon(z)$. The interface is set to coincide with $z=0$ and the wave propagation is taken in the x direction, showing the spatial variation in the plane y-direction. The propagating wave can be written as

$$E(r,\ t) = E(z)e^{i(\beta x - \omega t)} \tag{5}$$

where β is the propagation constant of the traveling waves. It is given as

$$\beta = n_{eff}\frac{2\pi}{\lambda_0} \tag{6}$$

The Helmholtz equation for the propagation wave is written as

$$\frac{\partial^2 E(z)}{\partial z^2} + \left(\omega^2\, k_0^2 - \beta^2\right)E(z) = 0 \quad (7)$$

The two Maxwell's equations for this are

$$\Delta \times E = i\omega B \quad (8)$$

$$\Delta \times B = -\, i\omega\mu\varepsilon E \quad (9)$$

The wave vector is perpendicular to the interface in this medium for $Z > 0$:

$$\kappa_1^2 = \beta^2 - k_0^2 \varepsilon_m \quad (10)$$

for $Z < 0$,

$$\kappa_2^2 = \beta^2 - k_0^2 \varepsilon_d \quad (11)$$

In order to confine the surface wave on the interface, the real part of κ_1 and κ_2 must be positive, which in turn requires that the real part of the complex permittivity ε_m and ε_d are of opposite in sign.

$$\frac{\kappa_1}{\kappa_2} = \frac{-\varepsilon_m}{\varepsilon_d} \quad (12)$$

The interface between dielectric and metal satisfies the conditions. A confined surface wave propagating along such an interface is called SPP, which arises by coupling of the electromagnetic field to the surface plasmon. The dispersion relation for the SPP is given as

$$\beta = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (13)$$

where $(2\pi/\lambda_0) = \kappa_0$

$$\beta = k_0\sqrt{\frac{\varepsilon_m .\, \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (14)$$

and

$$n_{eff} = \frac{\beta .2\pi}{\lambda_0} = \sqrt{\frac{\varepsilon_m .\, \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (15)$$

This relation gives the effective index of the SPP mode as

$$n_{SPP} = \frac{\beta .2\pi}{\lambda_0}\sqrt{\frac{\varepsilon_m .\, \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (16)$$

and similarly the wave vector for the SiO_2/Si is given as [22]:

$$\kappa_3^2 = k_0^2 \varepsilon_{Si} - \beta^2 \quad (17)$$

$$\kappa_4^2 = k_0^2 \varepsilon_d - \beta^2 \quad (18)$$

and after solving that we obtained it as

$$\beta = \kappa_0\sqrt{\frac{\varepsilon_{Si} .\, \varepsilon_d}{\varepsilon_{Si} + \varepsilon_d}} \quad (19)$$

$$n_{eff} = \frac{\beta .2\pi}{\lambda_0} = \sqrt{\frac{\varepsilon_{Si} .\, \varepsilon_d}{\varepsilon_{Si} + \varepsilon_d}} \quad (20)$$

This relation gives the effective index of the rectangular (optical) waveguide mode as

$$n_{rect.} = \frac{\beta .2\pi}{\lambda_0} = \sqrt{\frac{\varepsilon_{Si} .\, \varepsilon_d}{\varepsilon_{Si} + \varepsilon_d}} \quad (21)$$

Plasmonic mode (SPP) confined at the interface between metal-dielectric does not propagate longer because of the high ohmic losses associated with the metal. The coupling of the SPP with the field confined in the dielectric is determined by the nature of the field in the dielectric which is controlled by the total internal reflection in the dielectric. To push the plasmonic mode longer in the waveguides, the coupling of the surface plasmon in the metal surface should be modified by introducing an enhanced evanescent field in the dielectric. It is a well known situation in leaky waveguides where leaky modes propagate longer in cladding regions [21]. In case of conventional metal-dielectric plasmonic waveguides, the vertical coupling is a measure of coupling between surface plasmon and optical field, is proportional to skin depth z. Enhanced evanescent field in the dielectric causes longer propagation length into the waveguide [21]. In a high refractive index region given below, dielectric should be added to enhance evanescent field in the dielectric by modifying the coupling between surface plasmon and optical field. The waveguide structure thus becomes hybrid plasmonic waveguide [6]. The skin depth quantifies the confinement of the surface wave and is defined as the distance from the interface where the magnitude of the field has dropped to $1/e$:

$$z = \frac{1}{|\kappa_i|} \quad (22)$$

For the larger decay length, the weaker confinement, L is the intensity of the propagating wave has dropped to $1/e$:

$$\text{so} \quad L_{SPP} = \frac{1}{2\mathrm{Img}(\beta)} \quad (23)$$

img.(β) deals with the loss of the waveguide.

The coupling strength plays most important role in dragging the optical mode to metal dielectric interface, and the coupling strength (κ) between SPP and optical mode can be written as [19]:

$$\kappa(h, w, t_d) = \sqrt{(n_{eff} - n_{SPP})(n_{eff} - n_{rect.})} \quad (24)$$

Using Eq. (24), we obtained the coupling strength between the SPP and optical mode for the two material systems. The values for the n_{spp} and $n_{rect.}$ are, respectively, obtained from Eqs. (16) and (21). Our analysis indicates permittivity has a significant effect on the propagation length and mode area; the coupling strength for the Si/Ag is 0.52. Fig. 2(a) depicts the results. The SPP mode shows a larger coupling with Si. Higher the coupling strength, stronger will be the mode confinement with longer propagation length. For single mode operation of the waveguide, the width of the SiO_2 should remain below 240 nm. At an operating wavelength of 1550 nm for low loss and strong field confinement, with good coupling strength and larger propagation length, the minimum value of t_d=10 nm below which the rectangular geometry of the HP mode and the mode will become the pure SPP [6]. Thus the Subwavelength optical confinement with strong mode confinement and lesser modal propagation loss is achieved at t_d=10 nm. Now the reduced equation according to Eq. (4), is given as to predict the mode character of the hybrid mode and SPP mode as

$$|a_+(h, w, t_d)|^2 = \frac{\kappa(h, w, t_d)^2}{[n_+(h, w, t_d) - n_{react(h,w)}] + \kappa(h,w,t_d)^2.} \quad (25)$$

The reduced form of the equation from coupled mode theory is given by

$$n_+ = n(h, w, t_d) + \Delta(h, w, t_d) \quad (26)$$

$$n(h, w) = \frac{n_{react.}(h, w) + n_{SPP}}{2} \quad (27)$$

$$\Delta(h, w, t_d) = \sqrt{\frac{(n_{react.}(h, w) - n_{PP})^2}{4} + \kappa(h, w, t_d)^2} \quad (28)$$

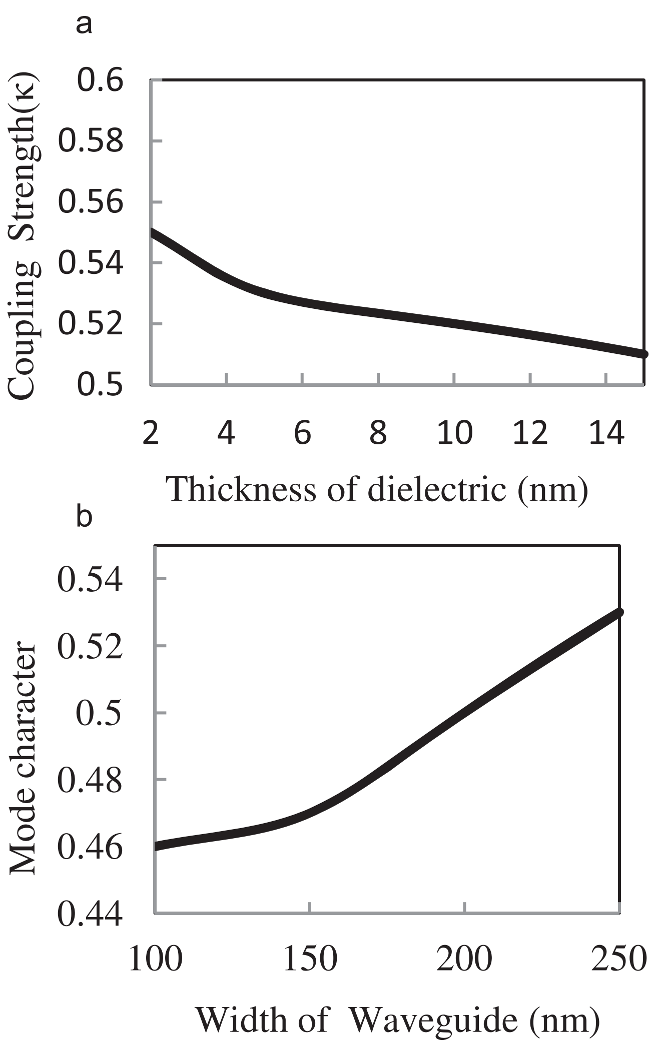

Fig. 2. (a) Effect of dielectric thickness on the coupling of optical and SPP mode at width=200 nm, h=200 nm. At t_d=10 nm with the L_p=154 μm, loss=0.028 dB/μm, and coupling strength=0.52; (b) variation of the mode character with the width of waveguide at constant t_d=10 nm. As mode character approaches to HP mode at t_d =10 nm and at width=200 nm for Si, we have largest propagation length L_p =154 μm and mode area is 0.0009/μm^2 and modal propagation loss is 0.028 dB/μm.

From Eqs. (24) and (4) we found following equation:

$$[n_+(h, w, t_d)] = [n_{hyb.}(h, w, t_d)] \tag{29}$$

Therefore for the calculation of the mode character Eq. (4) can be written as given above and it gives us the mode character of the hybrid mode, SPPs mode and optical mode. Therefore by using Eq. (25), we are able to calculate the mode character. These results match with our analytical and simulation, we obtained mode character which is approximately equal to the HPM i.e. $|a_+(h, w, t_d)|^2$=0.50 at t_d=10 nm for Si/Ag with very low modal propagation loss, larger propagation length and tight field confinement.

From the above numerical analysis we have come to the conclusion that n_{eff} can be obtained for the hybridization of the optical mode and SPP mode. Fig. 2(b) tells us about the mode character hybrid plasmonic waveguide, and we observed that for width <200 nm, it is SPP mode and at width=200 nm, it is hybrid plasmonic mode and for width >200 nm, it is optical mode. The similar behavior is shown upto t_d=15 nm, after reaching this level mode indicates the optical behavior, here we shows only for t_d =10 nm. In Fig. 2(b), we found that mode character is 0.5 at width 200 nm for Si which shows the hybrid plasmonic waveguide nature.

4. Propagation characteristics

Geometrical parameters of the proposed waveguide design can be significantly control the guiding performance of the HPW by observing the effect of the thickness and width of the SiO_2. The effective index n_{eff} of the guided mode rises as width increases or t_d decreases. The simulation of the guiding characteristic is done using the Finite Element Method (FEM). The Propagation length for the guided HP mode is given by [15] L_{prop} (μm)=$\lambda/4\pi(n_{eff})$imaginary, and modal propagation loss is given by [16], L_m (dB/μm)=$(2K_0(\text{img.})n_{eff})4.34$. The nature of the guided mode can be be evidenced by modal area of the field confinement [6]. The effective mode area of the guided fundamental mode will be a measure of the nature whether the localized field is optical, pure plasmonic or hybrid plasmonic [13] and it would be the merit for confinement ability which is given by [16] A_m (/μm^2) $=\int_{-\infty}^{\infty} p(x, y)dxdy/\max[p(x, y)]$. By varying the waveguide-width and dielectric thickness t_d we obtained the tradeoff between the modal propagation loss and mode area. We observed that strong mode confinement with lesser modal propagation loss and larger propagation length is obtained at $w<240$ nm at t_d=10 nm. The high-index region, silicon here, also plays a significant role in controlling the mode hybridization across the dielectric layer. Fig. 3 shows the effect of variation in silicon thickness on the propagation length (via coupling of SPP and photonic modes) with w=200 nm and t_d=10 nm. As we increases the thickness of the silicon, firstly upto 150 nm there is increase in the propagation length and from 150 nm onward upto 300 nm remains constant and for 300 onwards upto 500 nm it increases. We observed that upto 100 nm of Si-thickness plasmonic (SPP) mode dominates which typically shows very high losses and hence short propagation length, from Si-thickness of 100–300 nm SPP and photonic modes got hybridized providing a mode character of 0.5 which shows long range propagation with subwavelength optical confinement. Beyond Si-thickness of 300 nm evanescent filed into dielectric begins to lose its coupling with SPP mode which disable the mode hybridization; the guided mode now becomes leaky photonic mode with larger field in the silicon. Thus the presence of high-index region under the dielectric is crucial and can be used to mold the coupling of the free electrons of metal with the optical fields. At value of the 200 nm for width and thickness of the Si waveguide we obtained proper tradeoff between modal propagation loss and mode area and in terms of the nonlinearity. As we know that, with raising the width of waveguide and with decreasing the thickness of the dielectric, the propagation decreases.

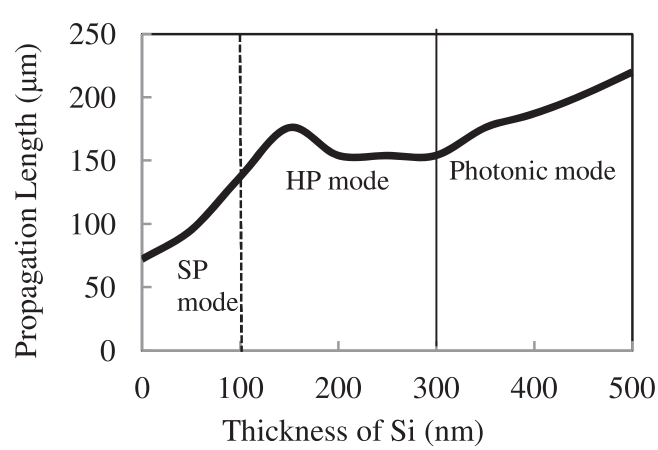

Fig. 3. The effect of thickness of high-index region (silicon here) on the propagation length showing the journey of the guided mode from pure plasmonic to leaky photonic mode through hybrid plasmonic mode; the thickness of the Si at constant w=200 nm and t_d=10 nm of the waveguide.

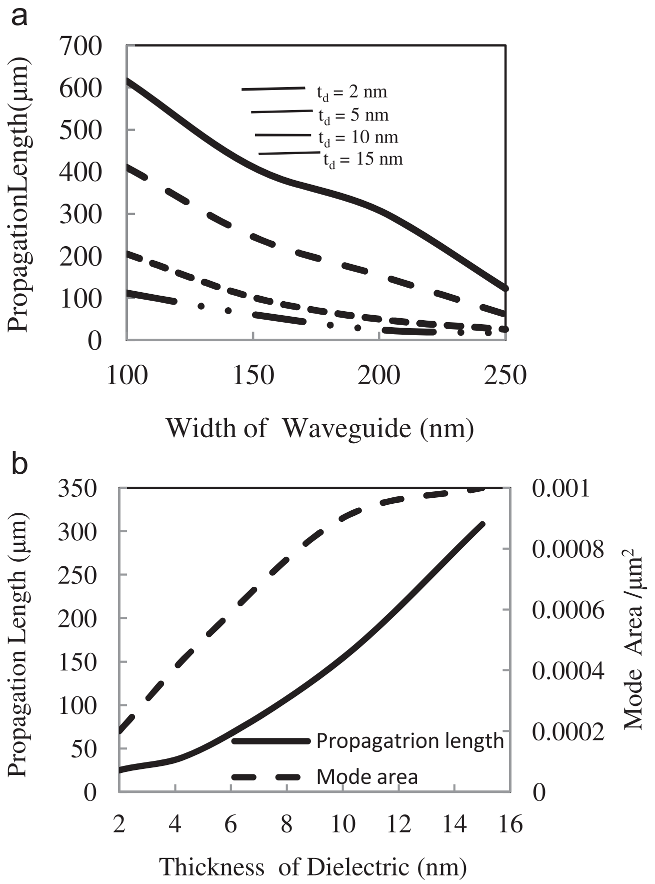

Fig. 4. (a) Variation of the propagation length with w at different thickness. The mode area at t_d=10 nm and at width W=200 nm, A_m=0.0009/μm^2 and modal propagation loss is 0.028 dB/μm. And coupling strength is 0.52. (b) Variation of the propagation length and mode area with different t_d at constant width w=200 nm. At t_d=10 nm we have L_p=154 μm and mode area is A_m=0.0009/μm^2 and the modal propagation loss is L_m=0.028 dB/μm.

Fig. 4(a) depicts that with increasing the width, the propagation length is decreased. As the thickness of the dielectric is reduced, the propagation length is also reduced, we have highest propagation length at 15 nm and lowest propagation length at 2 nm, but there is tradeoff between modal propagation loss and mode confinement thus with t_d=10 nm and at w=200 nm, we have proper tradeoff between modal propagation loss, with increase in the width and decreases in the thickness, the modal propagation loss increases. We observed that at the small value of dielectric thickness we have higher modal propagation loss.

The modal propagation loss is 0.028 dB/μm and mode area is 0.0009/μm^2 for Si. But we found a different type of the behavior in case of mode area.

On observing theses results closely we found that at W=200 nm and t_d=10 nm, we have proper tradeoff between the modal propagation loss, mode area and propagation length. In Fig. 4(b) we have a plot for the propagation length and mode area with thickness of the dielectric at W=200 nm. The solid black line shows the propagation length and dotted lines show the mode area for Si at W=200 nm at different thickness. At t_d=10 nm we have larger propagation length and lesser modal propagation loss and smaller mode area. The third order material plays a crucial role in many applications of nonlinear optics. The third order response leads to process such as third harmonic generation and two photon absorption, but more importantly leads to intensity dependent refractive index, which is the basis of most nonlinear optical switching devices. The intensity dependence of refractive index is described as [20,24] $n=n_0+n_2I$, where 'I' is the laser intensity and n_2 is the coefficient of the intensity dependent refractive index. This quantity can related to the nonlinear susceptibility by means of $n_2=12\pi^2\aleph^3/n_0^2$, where n_0 is the refractive index of the medium. The value of the refractive index for Si is 3.4 and for SiO_2 is 1.45 and third order susceptibility for Si is 2.0×10^{-10} and 1.8×10^{-14} for SiO_2 by putting these values, we obtained the value for the n_2. The value of third order nonlinear optical coefficient for Si is 2.7×10^{-16} m^2/W and 3.2×10^{-18} m^2/W for SiO_2. We obtained the nonlinearity as [26,27], $\gamma=n_2\beta/A_{eff}$, where n_2 the nonlinear index β is the propagation constant, and A_{eff} is the effective mode area. Fig. (5) shows the nonlinear effect on the proposed design.The nonlinear index β is the propagation constant, and A_{eff} is the effective mode area.

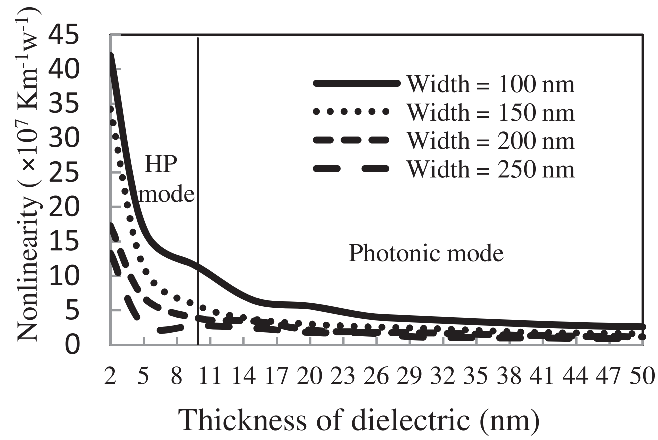

Fig. 5. Variation of the nonlinear coefficient with the thickness of the dielectric. At t_d=10 nm, nonlinear coefficient $\gamma=3.8\times10^7$ km^{-1} w^{-1} with lesser modal propagation loss L_m=0.028 dB/μm, larger propagation length L_p=154 μm and mode area is A_m=0.0009/μm^2 is obtained, where w is the width of the waveguide.

Fig. 5 shows the nonlinear effect on the proposed design. The nonlinearity in hybrid plasmonic waveguide used in application such as nonlinear directional coupler, low power, all optical switching and in the nonlinear signal processing. Here we start with the t_d=2 nm and vary it upto 50 nm. At t_d=2 nm, 5 nm, 10 nm and w_{Si} and h_{Si}=200 nm, we have nonlinear coefficient $\gamma=17.3\times10^7$ km^{-1} w^{-1}, 6.9×10^7 km^{-1} w^{-1}, and 3.8×10^7 km^{-1} w^{-1} .At w=100 nm, 150 nm, 200 nm, 250 nm, at constant t_d=10 nm we have nonlinearity varing from 11.2×10^7 km^{-1} w^{-1}, 5.6×10^7 km^{-1} w^{-1}, 3.8×10^7 km^{-1} w^{-1}, 2.8×10^7. At t_d=10 nm and w=200 nm it slow down the light with lesser modal propagation loss L_m=0.028 dB/μm, larger propagation length L_p=154 μm with mode area A_m=0.0009/μm^2, as compared to other, reported in the literature [25–28] with nonlinearity 3.8×10^7 km^{-1} w^{-1}. From [25] at t_d=20 nm and at w_{Si} =100 nm, nonlinearity is 4.7×10^8 km^{-1} w^{-1}, at this width of silicon and thickness of dielectric we have nonlinearity 5.6×10^7 km^{-1} w^{-1}. From [28] the obtained value for the nanoshell plasmonic waveguide at the aspect ratio near to 1.33 is 4.1×10^7 km^{-1} w^{-1} and for the hybrid plasmonic waveguide the value obtained is 3.8×10^7 km^{-1} w^{-1}, at unity aspect ratio. From [27], the nonlinearity for the slot hybrid plasmonic waveguide is 7.82×10^6 km^{-1} w^{-1}. We obtained the variable value of the nonlinearity for SiO_2. As we increases the thickness of the dielectric, nonlinearity decreases and at these values the mode area increases The thickness of high-index region and waveguide-width can control the optical nonlinearity of the waveguide. The nonlinearity of the guided HP mode remains at par with that of photonic mode which can be considered low with nano-scale optical confinement.

5. Conclusion

The origin and design analysis of nano-scale optical confinement and long range propagation in a hybrid plasmonic (HP) waveguide are discussed in this paper. Material systems Si/SiO_2/Ag are presented to analyze hybrid mode character and to realize an efficient design of the HP waveguide. The *mode character* predicts whether it is HP mode, pure-plasmonic (SPP) or optical mode. The coupled mode theory is used to calculate the mode character and coupling between the SPP and optical mode. The coupling strength, to achieve *mode character* $a=0.5$ (for HP mode), for Si/SiO_2/Ag system is found 52%. It is shown that the modification in the nature of the coupling of surface Plasmon's and optical field is an important requirement to push the SPP longer into the waveguide. This coupling can be modified by increasing the evanescent field into dielectric for to push HP mode longer in the dielectric. It is also found that the HP mode originated from the optical mode confined in a rectangular geometry can have longer propagation length. Propagation length of HP mode with silicon is 154 μm at a 10 nm thick dielectric. The calculated modal area of the proposed HP waveguide is 0.0009/μm^2 and the modal propagation loss is 0.028 dB/μm. The coupling and propagation characteristics of the HP waveguides are calculated analytically as well by using FEM. Our analysis shows that the optical mode confined in a rectangular geometry, in contrast to circular mode confined in a wire can be efficiently pushed towards metal-dielectric interface. This optical mode can be coupled with SPP be modified by increasing the evanescent field into dielectric for to push HP mode longer in the dielectric. It is also found that the HP mode originated from the optical mode confined in a rectangular geometry can have longer propagation length. Propagation length of HP mode with silicon is 154 μm at a 10 nm thick dielectric. The calculated modal area of the proposed HP waveguide is 0.0009/μm^2 and the modal propagation loss is 0.028 dB/μm. The coupling and propagation characteristics of the HP waveguides are calculated analytically as well by using FEM. Our analysis shows that the optical mode confined in a rectangular geometry, in contrast to circular mode confined in a wire can be efficiently pushed towards metal-dielectric interface. This optical mode can be coupled with SPP mode to give us HP mode with longer (than that in circular geometry) propagation length because of the leaky nature of the modes confined in the rectangular geometries. The high-index region under the (confinement) dielectric layer also plays a significant role in controlling the mode hybridization across the dielectric layer. It is found that beyond a certain thickness of high-index region evanescent filed into dielectric begins to lose its coupling with SPP mode which disables the mode hybridization; the guided mode now becomes leaky photonic mode with larger field in the high-index region. Thus the presence of high-index region under the dielectric is crucial and can be used to mold the coupling of the free electrons of metal with the optical fields. Lower plasmonic losses in Si cause low-loss guiding of HP mode with stronger optical confinement and hence smaller mode area. The thickness of high-index region and waveguide-width are shown to control the optical nonlinearity of the waveguide. It has been shown that the nonlinearity of the guided HP mode remains at par with that of photonic mode which can be considered low with nano-scale optical confinement. The proposed work can be useful to enable an integrated platform based on hybrid plasmonic-photonic waveguide which can be promising for making photonic devices at real nanoscales with flexible and variable nonlinearity.

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