38. Hybrid Mode Analysis of Hybrid Dielectric Loaded Plasmonic Waveguide

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ABSTRACT

In order to analyze the optical properties of the hybrid mode, such as propagation loss, as well as the modal index of the hybrid dielectric loaded plasmonic waveguide (HDLPW), the waveguide width and thickness of dielectric regions have been varied at the working wavelength of 1550 nm under the restraint of optical power in the low-index region. The hybrid mode investigation for the propagation of hybrid fundamental and higher order modes have been done in the present work to find out the optimum dimension of the HDLPW. For applications of the sensor, multimode propagation has a vital role. Propagation length about 443 µm and confinement of light in the spacer region approximate 31 % have been achieved with the optimal waveguide dimension of 200 nm × 50 nm (width × thickness) of the spacer region of the HDLPW. Nano-scale optical devices are beneficial for development of the advanced optical communication devices that can support the efficient implementation of 5G communications and networks.

Index Terms— *Hybrid Plasmonic waveguide, Surface Plasmon polariton, Hybrid Mode, Advanced optical communication.*

INTRODUCTION

In the present scenario, technology requires the high bandwidth communication services, such as high quality-videos/images transfer, cloud computing and data collection systems. Now days, over the internet in every minute, decades of video are being viewed and uploaded [1, 2]. To handle very huge number of data or user, there is a requirement of larger bandwidth, which can be provided by the optical communication systems and networks. For the optical communications, optical waveguides, optical logic gates, optical multiplexer, optical filter, optical switch, etc. are the basic devices. In order to achieve the high optical integrations, these basic optical devices have to be improved with minimum size and smaller losses. The minimum size of optical devices can be realized through both the dielectric and plasmonic waveguides. However, the power loss in dielectric waveguides is significantly lower as compared to plasmonic waveguides, but the dielectric waveguides are suffering from diffraction limit [3, 4]. The diffraction limit of the dielectric waveguide is the major issue for the minimization of the size of the waveguides and devices. Moreover, the diffraction limit problem can be solved by using plasmonic mechanism. In the plasmonic waveguide, the structure is consists of dielectric material and metal, which is helpful to propagate the light through true nano-scale size (< 100 nm) due to surface Plasmon polaritons (SPPs). At the optical wavelength range, the metal has complex permittivity which causes more power loss. Therefore, the problem arises from both dielectric and plasmonic mechanisms can be resolved using the concept of hybrid plasmonic waveguide, which is basically the combination of these two mechanisms [5-16]. The devices based on hybrid plasmonic waveguide are very helpful to connect optics with electronics. In the hybrid plasmonic waveguide, lower refractive index material must be interfaced with metal to achieve the low propagation loss. Usually, the hybrid mode is transverse magnetic (TM) nature because plasmonic mode has only TM nature [5]. Different arrangement of the waveguide based on the hybrid plasmonic mechanism has been explained such as, hybrid metalinsulator-metal [5-11], hybrid insulator-metal-insulator [7], hybrid dielectric loaded plasmonic waveguide [12-14], hybrid plasmonic using metal cap [6, 15-17] and hybrid metal insulator [17]. Fundamental mode propagation has less propagation loss, which is beneficial for the requirement of the optical device based on large propagation length. Multimode propagation is applicable for bio-sensing applications [18-20]. For the understanding of the monolithic integration of passive optical devices, silicon-on-insulator based hybrid plasmonic waveguide is a benefit. CMOS technology is adaptable with this technology and has the potential of monolithic integration with electronic devices. PTFE-based hybrid dielectric loaded plasmonic waveguide (HDLPW) can be useful for the realization of monolithic integration with active optical devices.

In this paper, the hybrid mode investigation of the HDLPW has been done in terms of propagation loss and modal index, at the operating wavelength (λ) of 1550 nm by changing the waveguide width and thickness of low-index and high-index regions. Further, to analysis, optical properties (in terms of confinement factor and loss propagation) of fundamental hybrid mode of the HDLPW by varying in thickness of dielectric regions (both low- and high- index).

This work is organized as follows. Section II demonstrates the three dimensional view of HDLPW structure and the properties of materials. In section III, the method of numerical analysis, i.e., the finite element method has been described briefly. Section IV examines the variations of modal index and propagation loss with varying of HDLPW dimensions. The conclusion of this work has been provided in section V.

DESCRIPTION OF STRUCTURE

Figure 38-1 shows the three dimensional view of the structure of HDLPW. In the z-direction, the light is propagating and optical power is confined in the x-y plane. The HDLPW structure consists of a spacer/low-index dielectric region, sandwiched between high-index dielectric region and metal layer and dielectric is loaded with metal that means the width of the metal region is greater than the width of the dielectric region. Here, t_s is the thickness of low-index/spacer region and t_h represents high-index region thickness. The width of the hybrid dielectric loaded plasmonic waveguide is considered as W. Indium gallium arsenide phosphide (InGaAsP) is used as high refractive-index material, which has a relative permittivity of 11.32 [18], and polytetrafluoroethylene (PTFE) is used as a low refractive - index/spacer region, with relative permittivity of 1.7 [4, 10]. PTFE is useful for nonlinear applications and is of low cost. InGaAsP has nonlinear material properties with low nonlinear loss. The permittivity of silver (Ag) is calculated by Drude model, which defines the permittivity as [10],

$$\varepsilon = \varepsilon_\infty - \frac{w_p{}^2}{w^2 + jw\delta} \qquad (1)$$

where, $\varepsilon_\infty = 1$, which represents the dielectric constant at infinite angular frequency, bulk plasma frequency and damping frequency for silver are denoted as w_p $(= 1.39 \times 10^6\ rad/sec)$and δ $(= 3.08 \times 10^{13}$ per sec) respectively. Hence, at working wavelength of 1550 nm, the permittivity of silver can be obtained -129 + 3.3i. Here, the substrate material is PTFE, and air is a cladding material. All the analysis of the optical properties of the hybrid mode of the HDLPW has been done at 1550 nm..

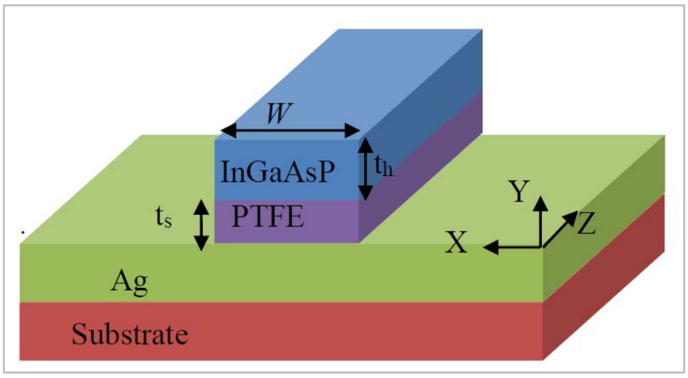
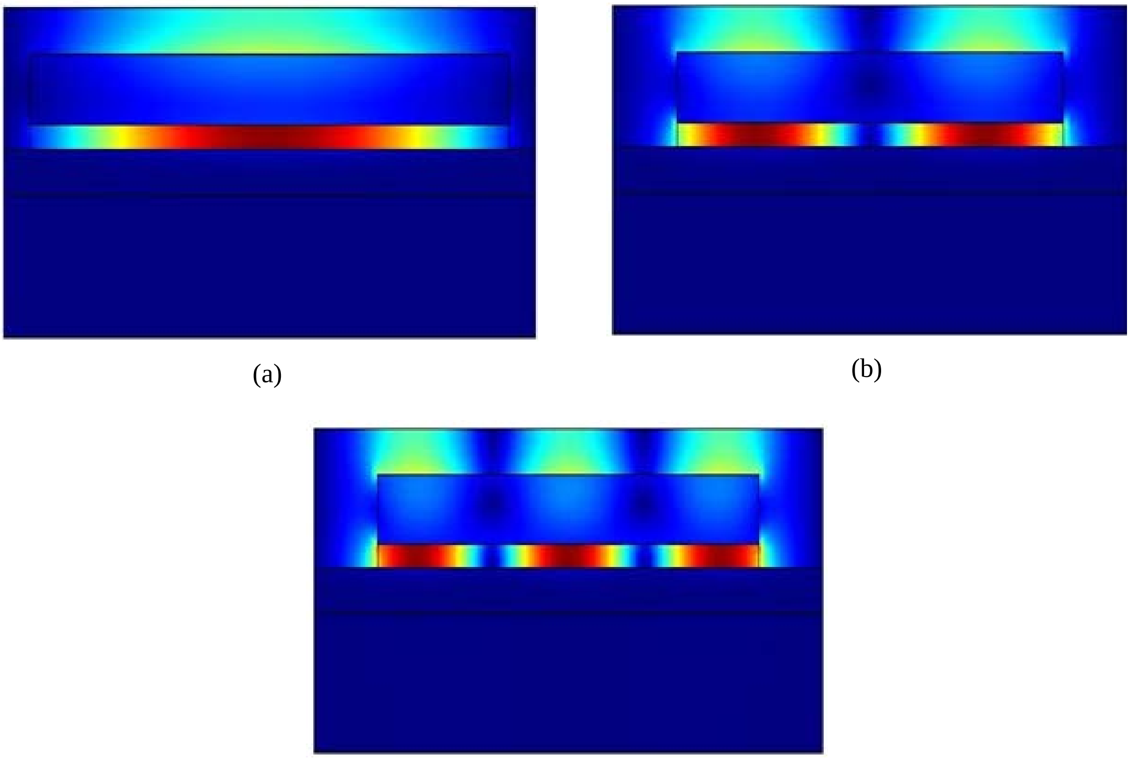


Figure 38-1 Three-dimensional view of HDLPW

METHOD OF MODE ANALYSIS

To investigate the hybrid mode characteristic of the hybrid plasmonic waveguide, different numerical methods such as, finite difference frequency domain (FDFD) method [19], finite element method (FEM) [5, 6, 8, 11] and finite difference time domain (FDTD) method [13] have been reported in literature.

In this paper, to analyze the hybrid mode characteristics of the HDLPW, COMSOL Multiphysics simulator has been used, which is basically based on FEM. In the 2-D FEM, all boundaries considered as perfect electric conductor with extra fine mesh size. The thickness of the silver layer is considered as 100 nm, to abolish the effect of metal (Ag) layer on the hybrid mode within the spacer region, whereas, the plasmonic skin depth of silver assumed constant about 20 nm at the near-infrared wavelengths. For the investigation of multimode, firstly the height (thicknesses) of spacer/low- and high-index regions are fixed along the y-axis at 50 nm and 150 nm, respectively. If the width of the waveguide is increased, then the number of propagating modes also increases. Figure 38-2 shows the mode profile of the various modes of HDLPW, where it has been observed that the optical power is restricted in the low-index region. Different possible hybrid modes for this particular dielectric loaded waveguide structure are fundamental hybrid mode(TM_{00}), first hybrid mode (TM_{01}) and second hybrid mode (TM_{02}). The hybrid mode profile analysis has also been performed by varying the thickness of the dielectric regions.


(a)

(b)

(c)

Figure 38-2 Mode profile of TM modes (a) TM00 (fundamental mode) (b) TM01 (first mode) (c) TM02 (second mode) of the HDLPW

NUMERICAL RESULTS AND DISCUSSION

Modal index and propagation length of the hybrid mode is carry out from real and imaginary part of effective index, respectively. The real part of effective index has been calculated as, $Re(N_{eff}) = \beta/k$, where β is the propagation constant and k is the wave number for the free space medium. Propagation length (p_l) of a hybrid mode is a distance at which the optical power is decreased to 36.7 % of the initial optical power and it can be measured as [8],

$$p_l = \frac{\lambda}{4\pi\, Im(n_{eff})} \quad (1)$$

where, $Im(n_{eff})$ represents an effective index of imaginary part and λ is the working wavelength.

A. EFFECT OF WIDTH OF THE HDLPW ON HYBRID MODE PROFILE

In this part, thickness of the dielectric region is fixed as $t_s = 50\ nm$, $t_h = 150$ nm and only the waveguide width of the HDLPW is varying from 100 nm to 1800 nm. The purpose of analysis of the hybrid mode to achieved smaller size of the optical devices and low propagation loss. Hybrid mode is only those modes whose optical power is mostly confined in the low - index region. However, the propagation of the higher order hybrid model has been useful for sensing applications. When the width of the waveguide is increases, it causes the propagation of higher order hybrid modes in the hybrid plasmonic waveguide. Figure 38-3 shows the real part of the effective index of the hybrid modes at 1550 nm for the HDLPW. The figure clearly indicates that, the number of hybrid modes increases with the increase in the waveguide width. At minimum width of the waveguide, where the light is propagating through the spacer/low-index region is known as cutoff width of the hybrid mode. Here, TM_{00} (fundamental mode) does not show cutoff width, but the cutoff widths for TM_{01} and TM_{02} are 700 nm and 1200 nm, respectively for the current hybrid plasmonic waveguide structures.

The propagation length of all three hybrid modes of the hybrid plasmonic waveguide is almost constant after a certain increase in waveguide width, which is illustrated in Fig. 38-4. The figure shows that $TM_{00,}$ TM_{01} and TM_{02} have a uniform propagation length after 500 nm, 1400 nm and 1600 nm, respectively. Moreover, the propagation loss is increasing with the higher order modes of the waveguide. So, propagation length is greater in the fundamental mode in comparison to higher mode.

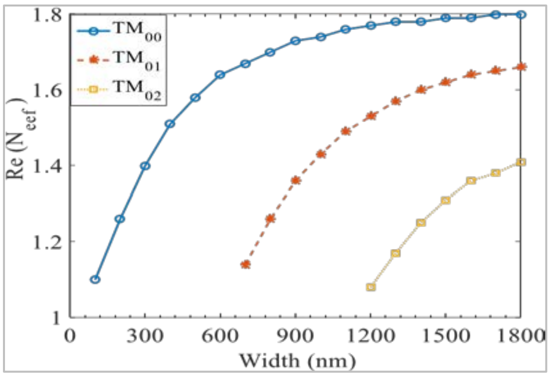


Figure 38-3 Effective index for fundamental (TM00), first (TM01) and second (TM02) hybrid modes with waveguide width of the HDLPW.

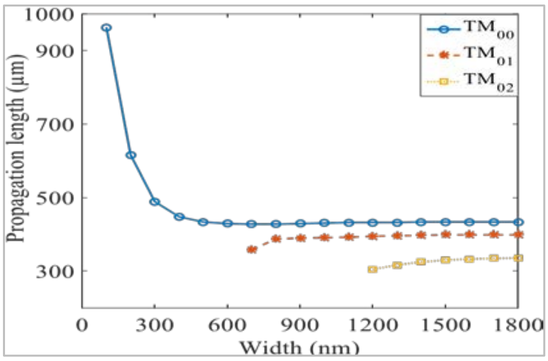


Figure 38-4 Propagation length for fundamental (TM00), first (TM01) and second (TM02) modes with waveguide width of the HDLPW

B. EFFECT OF THICKNESS OF HIGH-INDEX REGION

In this section, the waveguide width of HDLPW is fixed to 1500 nm to investigate the higher order hybrid mode profiles. The thickness of the low-index region is considered as 50 nm. To observe the variations in the hybrid mode profile of the HDLPW with the variations of thickness of the high - index region, Fig. 38-5 illustrates the relation between the thickness of the high - index region and real part of the effective index. The figure clearly indicates that the real part of the effective index increases with increasing thickness of the high - index region, which shows that for the significantly larger thickness of the high - index region, the hybrid mode of the hybrid plasmonic waveguide turns toward the dielectric waveguide. The fundamental mode propagates for all the assumed values of thickness of the high - index region, whereas, the first and second modes are propagating in the waveguide, if $t_h \geq 75$ nm and 100 nm, respectively. Figure 5 shows that the effective index of the fundament hybrid mode is more than other higher order modes, which indicates the strength of the electric field, along the y-axis is more, so it is confined large power in the low-index region. The cutoff thickness of the high - index region is defined as the minimum thickness of the waveguide from which optical power starts to propagate in the spacer region. Here, fundamental hybrid mode is no cutoff thickness, while for the first and second hybrid modes it is around 75 nm and 100 nm, respectively. Figure 38-6. shows that propagation length variations by changing of the thickness of the high-index region. The propagation length of the fundamental hybrid mode is firstly decreases, after certain value its get saturated and then increases with thickness of the high - index region, but the higher order hybrid mode is only saturated and increases with the thickness of InGaAsP. The figure shows that the propagation length of the fundamental mode is quite larger than higher order mode.

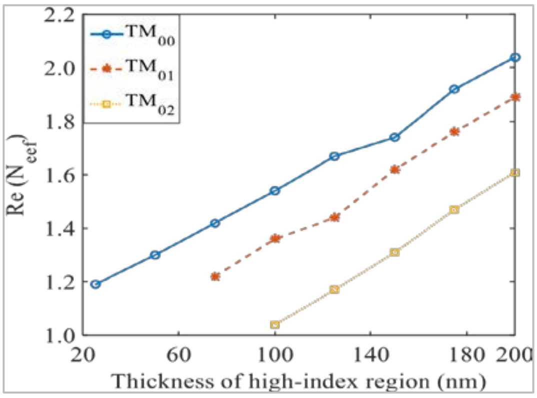


Figure 38-5 Effective index for fundamental (TM00) and first (TM01) modes with the thickness of InGaAsP of the HDLPW

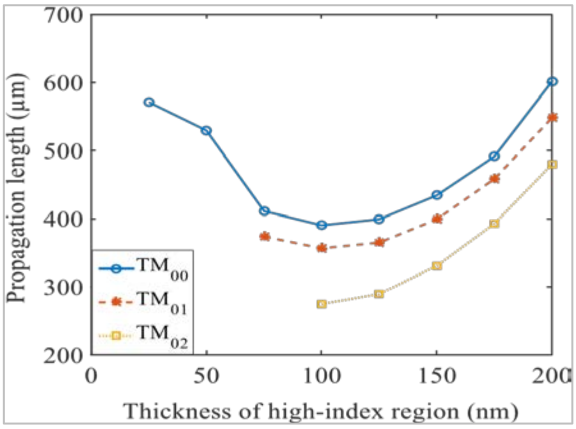


Figure 38-6 Propagation length for fundamental (TM00) and first (TM01), modes with thickness of InGaAsP of the HDLPW

C. EFFECT OF THICKNESS OF LOW-INDEX REGION

In this section, the waveguide width of the HDLPW is fixed at 1500 nm for the analysis of hybrid mode profiles of fundamental and higher order modes. The thickness of highindex region (t_h) is assumed as 150 nm. The investigation of the hybrid mode profile has been observed by varying the thickness of the low - index region of the hybrid plasmonic waveguide. Figure 38-7. indicates that modal index decreases with increasing value of the thickness of the low-index region. With the significant increase in the thickness of spacer region, the nature of hybrid mode turns towards the plasmonic mode. Fig. 38-8 illustrate that the thickness of the spacer region is increasing, propagation length increases. Figure clearly shows that fundamental mode is low propagation loss as compared to higher order mode.

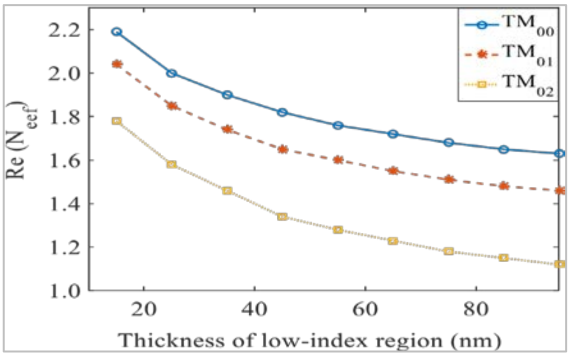


Figure 38-7 Effective index for fundamental (TM00) and first (TM01) modes with the thickness of PTFE of the HDLPW

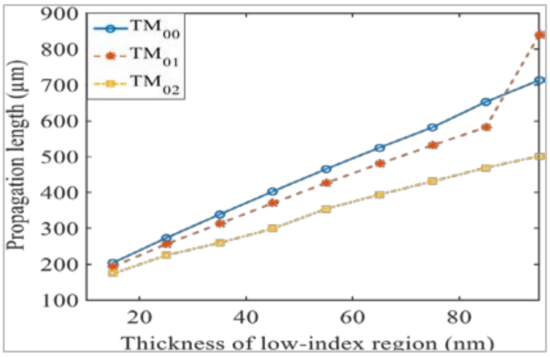


Figure 38-8 Propagation length for fundamental (TM00) and first (TM01), modes with thickness of PTFE of the HDLPW

D. EFFECT OF THICKNESS DIELECTRIC REGION OF FUNDAMENTAL MODE OF THE HDLPW

In this section, To investigate the optical properties of the fundamental hybrid mode of the HDLPW, the width of the waveguide is fixed at 200 nm. From the above section analysis, conclude that fundamental mode is less propagation loss. Figure 38-9(a). indicates that real part of the effective index is decreasing as thickness of low-index increases and highindex decreases. Which indicates that smaller values of the high - index region is plasmonic nature and also higher value of the low - index region is plasmonic nature. If increasing the value of thickness in spacer region is plasmonic because hybrid mode turns toward pure plasmonic as Ag-PTFE. At a constant spacer thickness, if thickness of the high - index region is increasing then hybrid modes again turn toward plasmonic nature but due to Ag-InGaAsP. For the hybrid mode, choose between them according to the requirement of propagation length and confinement of light. Figure 38-9(b). illustrated that propagation length is increasing as increases thickness of low-index region.

To optimize the dimension of the hybrid plasmonic waveguide by using of the confinement factor of light. However, confinement factor is associated with the power (energy) confined in the low-index region of the hybrid mode in the hybrid plasmonic waveguides. It is defined as the ratio of the optical power propagating through spacer region (P_{spacer}) to the total optical power (P_{total}) propagating through the hybrid plasmonic waveguide and in percent, it is expressed as [21],

$$CF(\%) = \frac{\iint |\langle P_{zi}(x,y)dxdy\rangle|}{\iint_{-\infty}^{\infty} |\langle P_{z}(x,y)dxdy\rangle|} \times 100 \qquad (2)$$

Here, the optical power of time-averaged Pointing vector along the z-axis in the spacer region represents as $P_{zi}(x,y)$ and $P_{z}(x,y)$ indicates the total optical power of the timeaveraged Pointing vector along the z-axis of the whole waveguide structure. confinement factor in the terms of percentage is shown in fig. 38-9(c). figure clearly indicate that confinement of light is firstly increases, then saturated with the thickness of the dielectric region. If $t_h > 170\ nm$ and $t_s > 40\ nm$, confinement of light, almost maximum at lower dimension. So optimal dimension for HDLPW are W = 200 nm, $t_h = 170\ nm$ and $t_s = 40\ nm$, at which propagation length and confinement factor 443μm and 0.3 respectively.

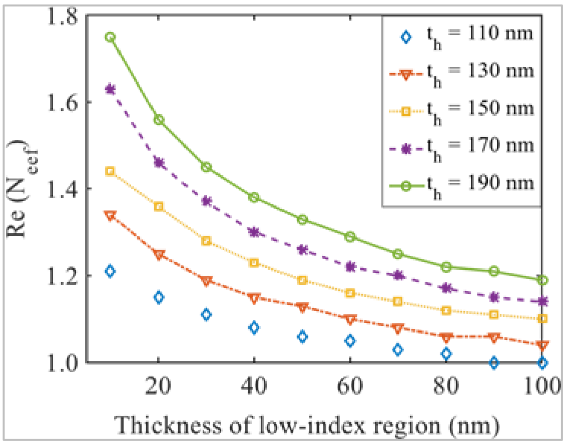


Figure 38-9(a) Effective index for fundamental mode with thickness of dielectric region of the HDLPW

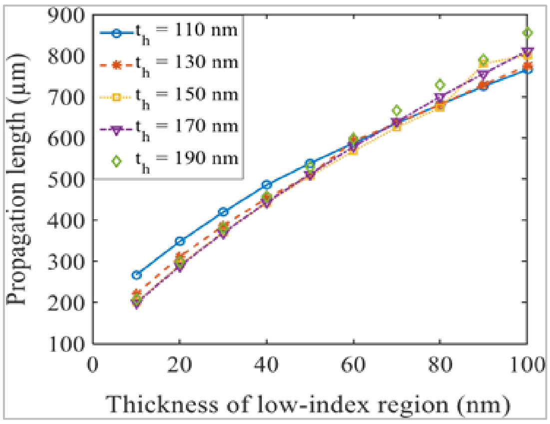


Figure 38-9 (b) Propagation length for fundamental mode with thickness of dielectric region of the HDLPW

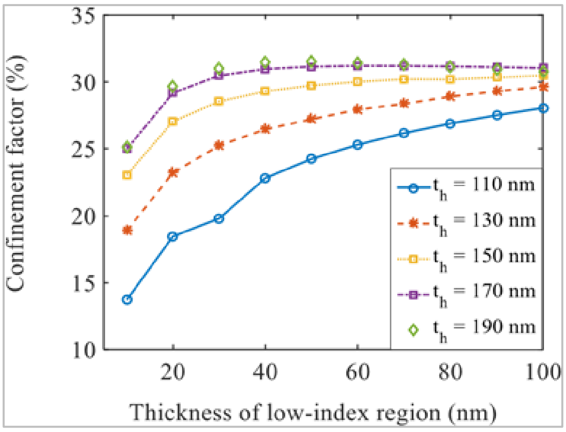


Figure 38-9 (c) confinement factor for fundamental mode with thickness of dielectric region of the HDLPW

CONCLUSION

In the current work, the optical properties of the hybrid modes have been investigated for the hybrid dielectric loaded plasmonic waveguide. The analysis of the modal index and propagation loss of HDLPW structure has been done by changing the waveguide dimensions. The hybrid mode investigation has been achieved for both fundamental and higher order hybrid modes. The propagation of multimode is a key factor for the bio-sensor devices. For the multimode propagations, propagation length of the hybrid mode is better than higher order modes. Further, we investigated the optical properties (such as propagation loss and confinement factor) of the hybrid fundamental mode of the HDLPW by variants of the thickness of dielectric region (both low- and high-index regions). Propagation length about 443 μm and confinement of light in the spacer region approximate 31 % have been achieved with the optimal waveguide dimension of 200 nm × 50 nm (width × thickness) of the spacer region of the HDLPW. This analysis is beneficial for the nano-scale optical devices such as power splitter, sensors, directional coupler, all-logic gates, etc. based on hybrid plasmonic mechanism. For future purposes, optical devices are solving the problem of interconnecting between electronics and optics technology. Nano-scale optical devices are beneficial for development of the advanced optical communication devices that can support the efficient implementation of 5G communications and networks.

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