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Research Article

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Posted Date: June 17th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1735858/v1>

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The long-range hybrid plasmonic waveguide of graded-index InGaAsP active layer based on InP

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Abstract

Indium Phosphide (InP)-based hybrid plasmonic waveguide for nanoscale optical confinement and long-range propagation at wavelength 1.55 μm has been proposed in this paper. In this structure, the InGaAsP layer is designed as a ridge with a gold cap by intervening a ridge of the InP layer between them. InGaAsP lattices are suitable for that of an InP substrate. $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ was graded in refractive index by changing the mole-fraction. Using a graded index, the confinement and the propagation length can be improved compared with the conventional one. Propagation length of 40 μm is achieved with better confinement as compared with the traditional hybrid ones. Changing only the y parameter with constant x, we get a propagation length greater than the inverse case, that is, changing only the parameter x, as well as better than the base case when the scaling is not included in the design. This is in parallel with good results in the mode effective area (A_{eff}) and Figure-of-merit (FoM) for the same condition of changing y which expresses a good confinement condition. The pioneering program COMSOL Multiphysics was used to simulate the designs proposed in this paper.

Keywords: hybrid plasmonic waveguide, $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$, graded index, propagation length, mode effective area, Figure-of-merit.

1. Introduction

The SPP as it is known is the coupling of a photon with free electrons at the interface between the metal and an insulator. Plasmonic waveguides may manipulate optical fields at the nanoscale by converting light to surface plasmon polaritons (SPPs). The hybrid surface plasmonic polariton (HSPP) waveguide in most structures of optical integrated circuits has two basic parameters that should be studied, that is, the propagation length L_p and confinement factor. By increasing the L_p in parallel with a good quantitative confinement pattern, the waveguide will operate effectively. However, there is an inverse relationship between these two properties. By manufacturing processes and offering certain models, we can overcome this barrier and raise one while preserving the other without sacrificing efficiency. There are many proposals and solutions, including the change in materials and shape. In one of the layers that make up the structure ($\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ semiconductor)[1] [2] [3], which is a quaternary material we can find out the specifications and properties of this material from Ref. [4] and [5], where doping will be applied to produce a graded refractive index. This design could serve as a potential option for many nanophotonic components, optoelectronic integrated circuit structures [6] [7] [8] [9], and Complementary Metal Oxide Semiconductors

(CMOS)[8] [10] [11]. Also, $\text{In}_x\text{Ga}_{1-x}\text{As}$ which is a Ternary Compound can be used, and its properties are viewed in Refs. [12] and [13].

In the graded refractive index, the light ray experiences refraction gradually and thus gets bent towards the center, which represents the interface between the metal and the insulator, allowing propagation of the ray in a curved path. This means that the light on traveling gets continuously refracted and bends. Therefore, the light rays do not propagate by following a straight line, rather they follow a parabolic path due to non-uniformity in the refractive index of the medium.

We have a structure consisting of a ridge waveguide of a noble metal (gold) that is above a layer of InP[1], and between the InP layer and substrate (which is of the same substance InP) there is an intermediate layer of quaternary semiconductor (InGaAsP)[14][15][16][1]. InGaAsP lattices are suitable for that of an InP substrate[17] [18] in the wavelength between 1.3-1.7 μm region, a spectral area in which low-loss, low-dispersion optical fibers are available[19][20]. This layer focuses on employing the graded index, which is x and y (mole-fractions) in the instance of the semiconductor ($\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$) quaternary, to offer a variable refractive index as a graded refractive index[21]. To reach the best structures, we will work here on the following cases: the first is taking a constant mole-fraction y with changing x , and the second is changing x for material $\text{In}_x\text{Ga}_{1-x}\text{As}$ [13][22]. The two cases are compared with the results of the conventional one that we took from the published works of literature without a graded procedure.

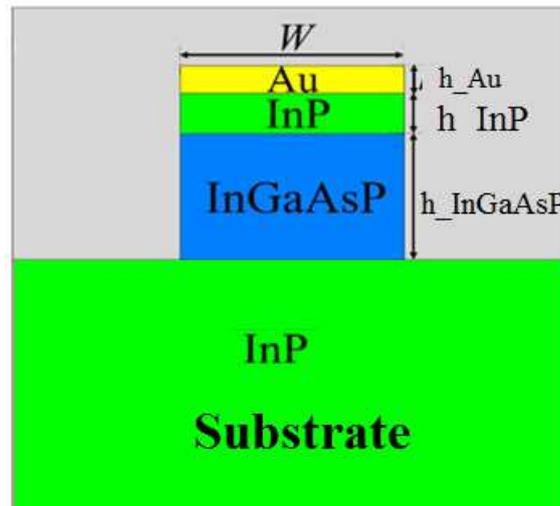


Figure 1 Structure of HSPP.

2. Analyses of the proposed HSPP

The InP-based on orthodox waveguide contains an InGaAsP core layer with a thickness of 500 nm and an InP upper cladding layer with a thickness of 160 nm on a semi-insulating InP substrate. Gold (Au) with a thickness of 110 nm caps the layer stack of the hybrid plasmonic waveguide.

2.1. The materials

There is a relation between the mole-fractions x and y in quaternary compounds, such as the structure used here, for wavelength 1.55 μm :

$$x = \frac{0.1896y}{0.4176 - 0.0125y} \quad (1)$$

The relationship between the real (n_r) and imaginary (n_i) refractive indices with composition fractions for wavelength 1.55 μm as follows[23] [24] [25] [26]

$$\left. \begin{aligned} n_r &= (12.35 + 1.62y - 0.055y^2)^{0.5} \\ n_i &= \frac{\lambda\alpha}{4\pi} \end{aligned} \right\} \quad (2)$$

Where α is the optical absorption of the InGaAsP. And the refractive index according to x mole fraction for Ternary Compound $\text{In}_x\text{Ga}_{1-x}\text{As}$ is known from Ref. [22].

2.2. Numerical simulation

the structure generated by using COMSOL software simulates steps to calculate the guided eigenmodes of the hybrid plasmonic waveguide used in this work. This explains the four major steps to performing mode-solving simulations. The first step is to define the geometrical parameters of the waveguide and the refractive indices of the materials As shown in the table.1 such as the piecewise and analytic functions fig.2 and fig.3 respectively, as well as set the graded refractive index equation using eq.3 and graded profile eq.4. Designing the geometry, applying the boundary conditions, and defining the mesh fig.4 is the second step. Then, the eigenmode solver based on the finite element method is chosen to calculate the hybrid modes of the waveguide. Finally, the results such as electric field norm distribution for mode TM can be visualized 2D surface plot which results from a vertical cross-sectional slice in the waveguide, or by the applied 1D plot.

$$n_g = n_{\min} * \sqrt{1 + 2 \Delta e^{-2y/h_{\text{core}}}} \quad (3)$$

where is

$$\Delta = \frac{n_p^2 - n_{\min}^2}{2n_{\min}^2} \quad (4)$$

Where n_p , n_{\min} are peak and minimum value of the refractive index for graded material. When we use Electromagnetic Waves, Frequency Domain (emw), The major selling point node for this physics interface is the Wave Equation, Electric[27]. The governing equation looks like this:

$$\left. \begin{aligned} \nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) \mathbf{E} &= \mathbf{0} \\ \alpha = j\beta + \delta_z &= -\lambda \\ \mathbf{E}(x, y, z) &= \tilde{\mathbf{E}}(x, y)e^{-\alpha z} \end{aligned} \right\} \quad (5)$$

as well as the boundary condition Perfect Electric Conductor ($\mathbf{n} \times \mathbf{E} = \mathbf{0}$) and appropriate mesh in fig.4, we get the following results. Show us the Norm E, Poynting vector $\mathbf{p}(x, y)$, and energy density W findings.

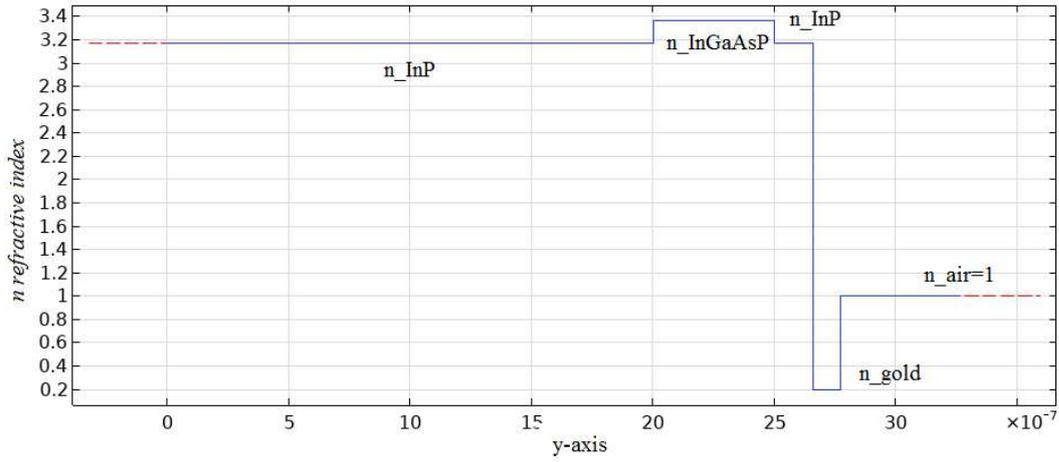


Figure 2 refractive index for all layers that are used in the structure

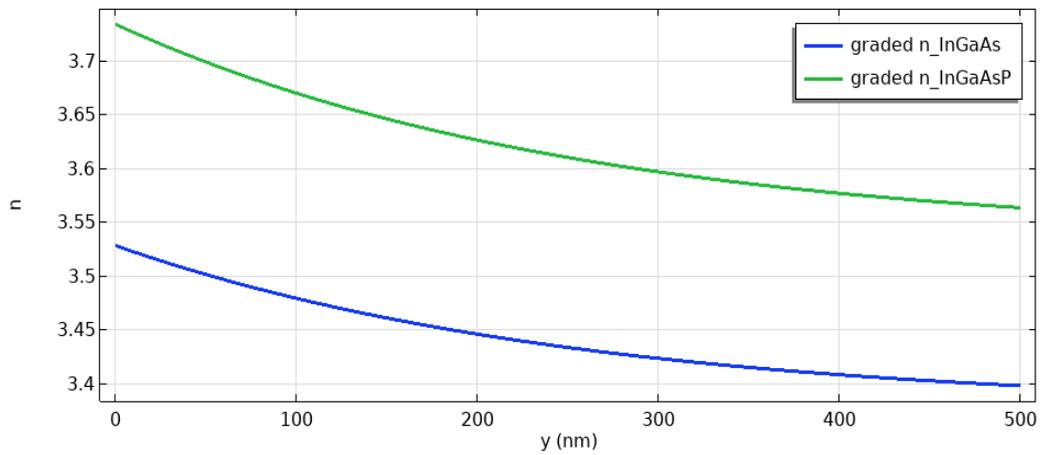


Figure 3 graded refractive index for InGaAs, InGaAsP

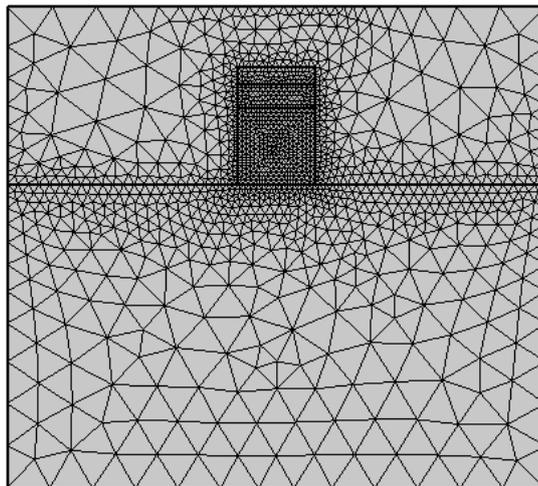


Figure 4 mesh for the structure

2.3. Propagation Length and confinement :

One property of surface plasmon is the L_p of the SPP waveguide since it has an effective refractive index (n_{eff}). Here L_p depends on the imaginary part of it according to the following relationship SPP waveguide $L_p = 1/(2k_0 n_{eff}'')$ [28], where n_{eff}'' is the imaginary part of the effective refractive index ($n_{eff} = n_{eff}' + in_{eff}''$) of the HSPP waveguide and ($k_0 = 2\pi/\lambda$) is the wavenumber in space [29] [30].

We propose a plasmonic waveguide, which fulfills both deep sub-wavelength scale confinement and relatively long propagation. The waveguide comprises a metal cap (nano tape) on top which confines light between the interface of the metal-insulator. Here developed a hybrid plasmonic waveguide architecture in which the SPP is nanoscale confined in a waveguide. In terms of the figure of merit, this structure outperforms current plasmonic waveguides, making the waveguide particularly suitable in photonic integrated circuits. We have generated a hybrid plasmonic waveguide design in which SPP is confined to a nanoscale waveguide. This structure outperforms existing plasmonic waveguides in terms of the figure of merit, making waveguides particularly useful in optical integrated circuits. The confinement is calculated using certain parameters mode area and FoM. To find a definition that will consider the true extent of the SPP field distribution to consistently quantify the mode confinement. we will provide several definitions and compare them in our study of different waveguide structures. The first definition evaluates mode confinement in the modal area A_{eff} depends on the peak energy flux density and defined as is defined as [31] [32] [10].

$$A_{eff1} = \frac{\int \mathbf{p}(x,y) dx dy}{\max[\mathbf{p}(x,y)]} \quad (6A)$$

$\mathbf{p}(x,y)$ mean energy flux density (Poynting vector), $\mathbf{p}(x,y) = [\mathbf{E}(x,y) \times \mathbf{H}(x,y)]$. The normalized modal area is defined as (A_{eff1}/AO) [33], where AO represents the diffraction-limited area in free space, $AO = \lambda^2/4$. Here λ is the vacuum wavelength. A_{eff} is based on maximum power flux density and can be used to estimate confine field enhancement that is not necessarily associated with a strong limitation of the total power. The second definition A_{eff2} is a statistic that represents the integral of the energy density W throughout the proposed design's cross-section. [34] [35]

$$A_{eff2} = \left[\int_{A_{\infty}} W(r) dA \right]^2 / \int_{A_{\infty}} W(r)^2 dA \quad (6B)$$

A better scale often considers the entire field and is more sensitive to the power distribution. Another problem comes when we try to analyze the performance of a specific waveguide structure. Although most plasmonic waveguides function using the same plasmonic phenomena, they have different diffusion and confinement characteristics. Any structure's FoM form must account for all of these factors. We must use an appropriate definition of collateral to determine the form FoM because the propagation distance is well specified. [31] [36] $FoM = \frac{L_p}{\lambda_0} \frac{A_{eff2}}{A_0}$ The ratio of the L_p to the diameter of the mode field is also known as FoM:

$$FoM = \frac{L_p}{2\sqrt{\frac{A_{eff}}{\pi}}} \quad (7)$$

the normalized mode field area ($A = A_{eff}/AO$) [31].

3. Results and Discussions:

Table 1 the parameter of the structure

Parameters	Values
width of ridge	0.5[μm]
main wire width	3000[nm]
Refractive index InGaAsP static ($y=1$)	$n=3.7336$
Refractive index InGaAs ($x=0.4$)	3.5279
Refractive index InGaAsP static ($y=0$)	3.5355
Refractive index InGaAs ($x=0$ =GaAs)	3.3767
Refractive index InGaAs ($x=0.5$)	3.1779
Refractive index InP	3.1669
Refractive index InGaAsP	3.3636
Refractive index _gold(real+image)	$0.187+10.3457*i$
Wavelength	1.55[μm]
gold thickness	110[nm]
InP thickness	160[nm]
Core thickness	0.5[μm]

Fig.5 Based on a semi-insulating InP substrate, there is a 500 nm InGaAsP core layer and a 160 nm InP top cladding layer. Gold (Au) or silver (Ag) with a thickness of 110 nm caps the layer stack of the hybrid plasmonic waveguide. During the simulation of passive devices, the thickness of the capped metal is tuned to improve power transfer from input waveguides to output waveguides. At a wavelength of 1550 nm, two refractive indexes of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ (Q(1.25)) 3.3636 (a) in case $y=0.461$ [23] and 3.2515 (b) in case $x=0.48$, $y=0.24$, the refractive index for InP, and gold (Au) is 3.1669, and $0.187+10.3457i$, respectively.

The plots of the first four TM modes, as well as the related mode profiles, for the HP-waveguide at a wavelength of 1.55 μm appear in fig.6, The fundamental TM_{00} mode in the HP-waveguide has no cutoff, and the number of modes supported by the HP-waveguide grows with the width of the ridge. As the width of the ridge grows, the real part of the effective refractive index approaches that of the InGaAsP layer. The optical power is dispersed throughout the InGaAsP core layer in a deeply etched conventional waveguide, whereas it is concentrated mostly within the InP cladding layer in an HP waveguide.

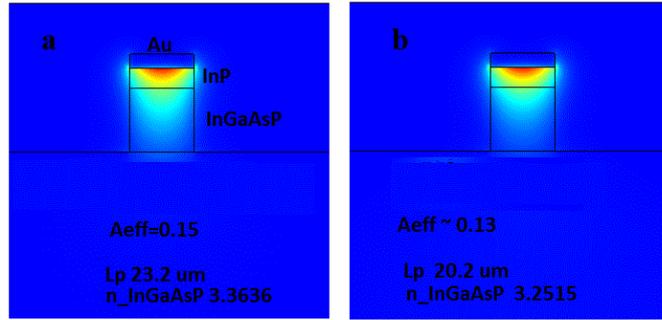


Figure 5 Electric field norm(|E|) distribution of the basic mode in an InP-based HP waveguide, $w=500$ nm $h_{\text{InGaAsP}}=500$ nm= h_{InGaAs} , the refractive index for InP, and gold (Au) is 3.1669 , and $0.187+10.3457i$ (a) $y=0.461[23]$ and 3.2515 (b) in case $x=0.48$, $y=0.24$, the refractive index for InP, and gold (Au) is 3.1669 , and $0.187+10.3457i$

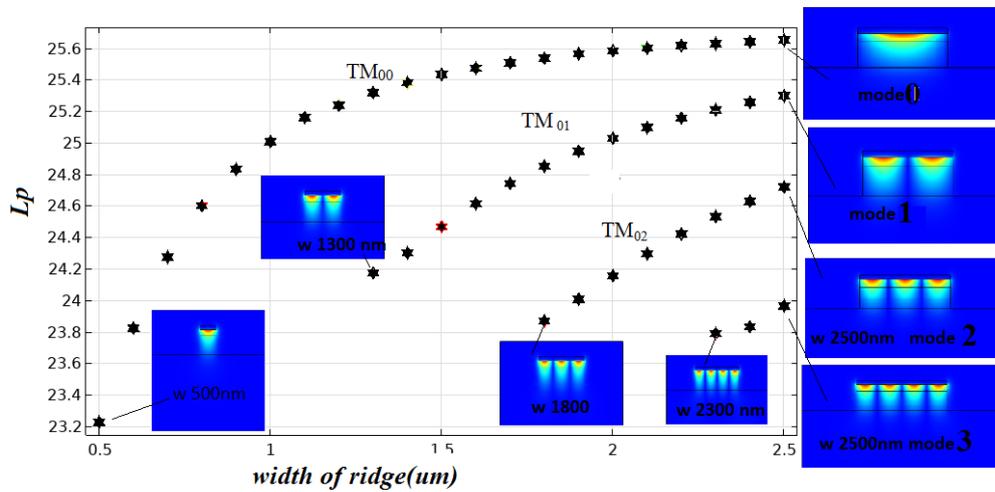


Figure 6 The L_p of the structures for the InP-based HP waveguide for the TM_{00} , TM_{01} , TM_{02} , TM_{03} , and TM_{04} patterns, dependent on the imaginary part of the refractive indexes. The norm and direction of electric field distribution TM modes for (mode0) fundamental mode (mode1) first mode (mode2) second mode and (mode3) third mode Patterns are formed when the width of the HP waveguide is increased.

Propagation length is greater than $15 \mu\text{m}$ for all ridge widths depicted in Fig. 6, The largest L_p does not exceed $26 \mu\text{m}$ for the first mode and less than it for the rest of the three modes despite the increase in the dimension widths of the ridge from 500 nm up to 2500 nm. The Comsol software was used to determine the effective refractive index and electrical field distribution of InP-based conventional and HP waveguides. By using mode analysis Fig.6 and fig.7 shows the L_p for the two InGaAsP refractive indices, so fig.8 give the Effective mode index for the two InGaAsP refractive indices in two TM mode TM_{00} and TM_{01} , with the refractive index of 3.3636 being the longer than the refractive index of 3.2515 , with the refractive index of 3.3636 being the longest but with less quantum confinement than the refractive index of 3.2515 , as indicated by the parameters A_{eff} & FoM. Figures 9 & 10 present it as well.

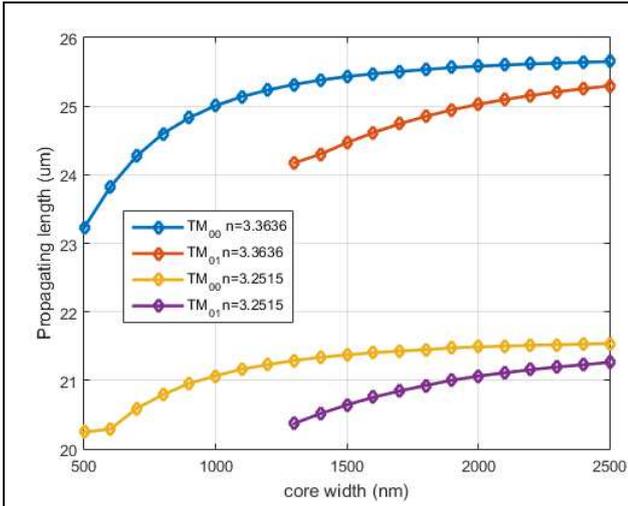


Figure 7 propagation length for the two InGaAsP refractive indices, with the refractive index of 3.3636 being the longer than the refractive index of 3.2515

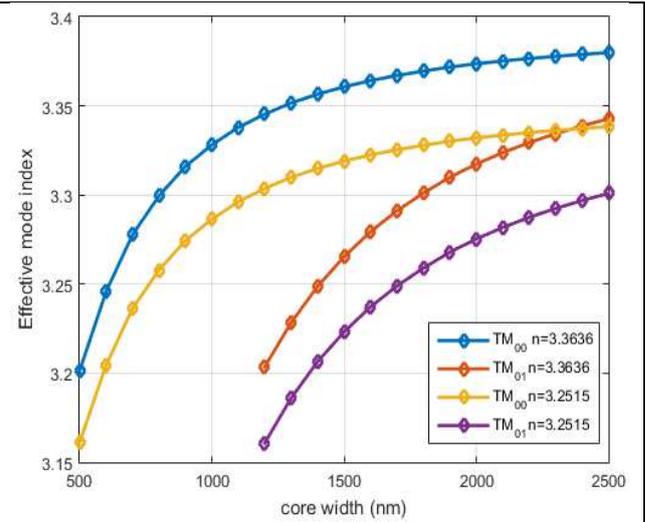


Figure 8 Effective mode index for the two InGaAsP refractive indices, with the refractive index of 3.3636 being the longer than the refractive index of 3.2515

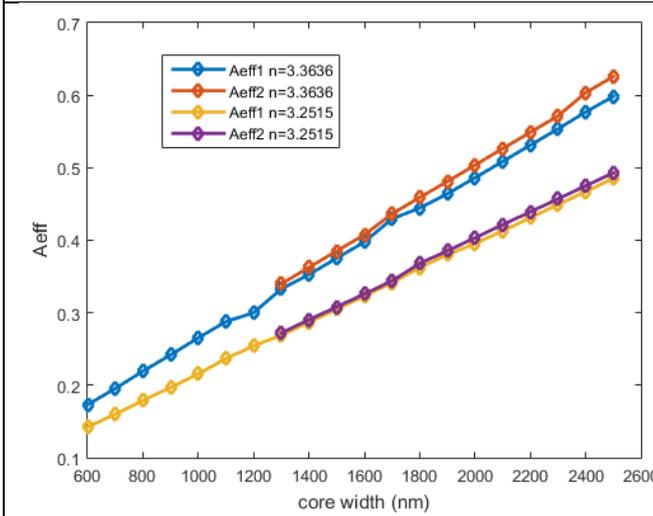


Figure 9 A_{eff1} and A_{eff2} for n_{InGaAsP} 3.3636 and 3.2515 to increase the width in x-axes, used in two equations (3 and 4)

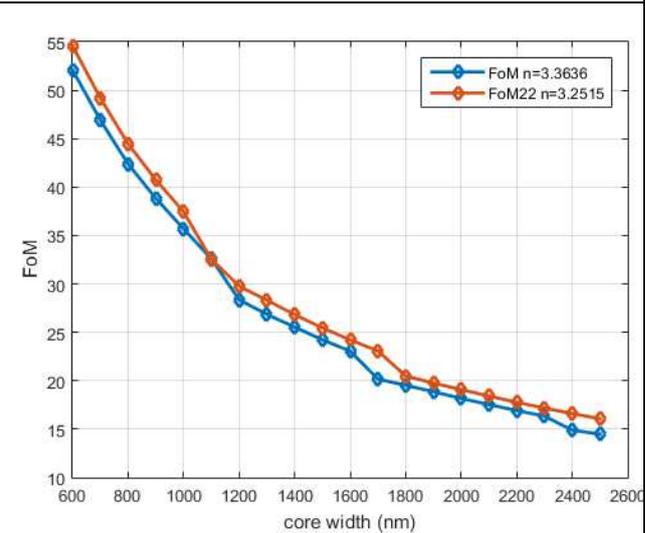


Figure 10 Figure of merit for n_{InGaAsP} 3.3636 and 3.2515 to increase the width in x-axes

The Graded-index GRIN configuration is analyzed in the radio frequency (RF) section of COMSOL, which is the latest version of the software. A two-dimensional model is created and simulated at the telecom wavelength of 1.55 μm . L_p of SPP wavelength propagating along the surface of the metal and the mode width of it is calculated and drafted below.

Fig.11 shows the modes versus width of ridge dimensions $w=500$ nm to $w=2500$ nm. Fig.11 corresponds to the structure with a GRIN square ridge, and Fig.6 corresponds to the structure with a constant-index square ridge.

Introducing the graded into the refractive indices of InGaAs, InGaASP by changing the doping ratios of the mole fractions (X and Y), will be done in two ways: stabilizing the X ratio and changing the doping ratio y mole fraction, and changing the X ratio and then conducting analysis and simulation of the resulting field using the Comsol Multiphysics program. It determines the L_p and the amount of quantitative confinement, as well as whether these parameters have improved or not. The L_p as well as the parameters used to measure confinement, namely the area mode and the figure of merit, are seen in the next three figures (11,12and 13). By fixing X and scaling with the mole fraction $1 > Y > 0$, we get a graded refractive index (3.5355 - 3.7336) which is better in values than the second case, which uses the tertiary material InGaAs $1 > X > 0$ and gives us The refractive index ranges from 3.5279 to 3.3767, as seen in the simulations and calculations In the underneath figures. In the first structure, the L_p varies between 32 μm at 400 nm ridge width and 40.18 μm at 2500 nm ridge width. In terms of enumeration parameters, as in fig.12, the mode area is better in the first case than the second, and fig.13 shows the parameter FoM is similar in both situations. As a result, the limitation in the hybrid plasmonic waveguide maintains its quality without waste.

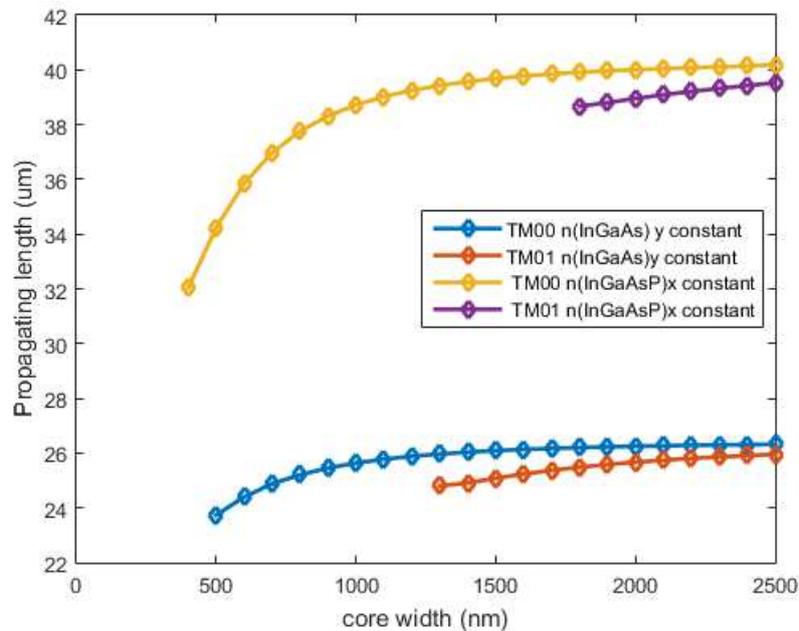


Figure 11 The L_p in the first case using the quaternary material InGaAsP was by fixing X and scaling with the mole fraction $1 > Y > 0$, and we get a grade in the refractive index (3.5355 - 3.7336) that was better in values than the second case when using the tertiary material InGaAs $1 > X > 0$ in which we get It is included in the refractive index from (3.5279- 3.3767).

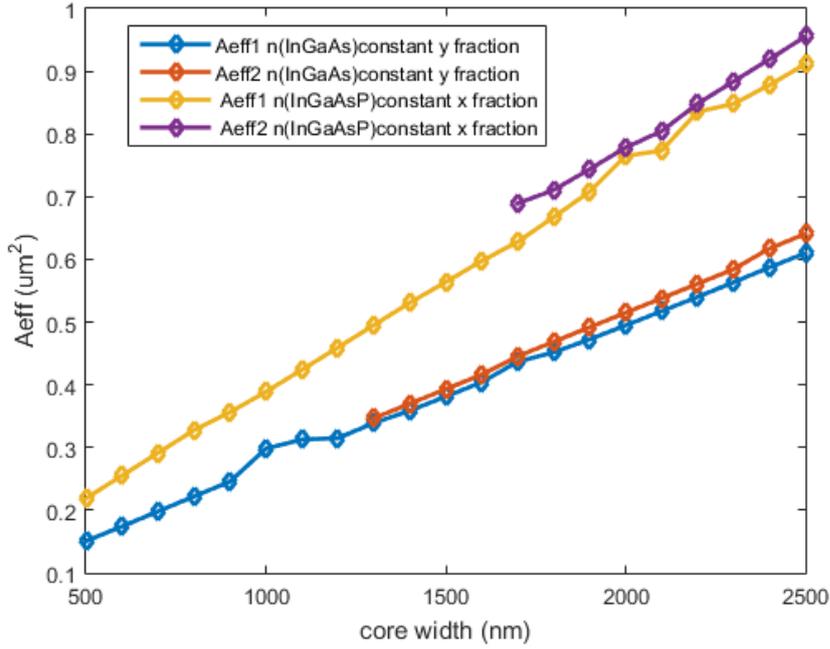


Figure 12 shows the A_{eff} mode area parameters used in two equations (3 and 4) that were used in the confinement measurement. By setting X and scaling with the mole fraction $1 > Y > 0$, the first case using the quaternary material InGaAsP yielded a refractive index gradient that was better in values than the second case using the tertiary material InGaAs $1 > X > 0$.

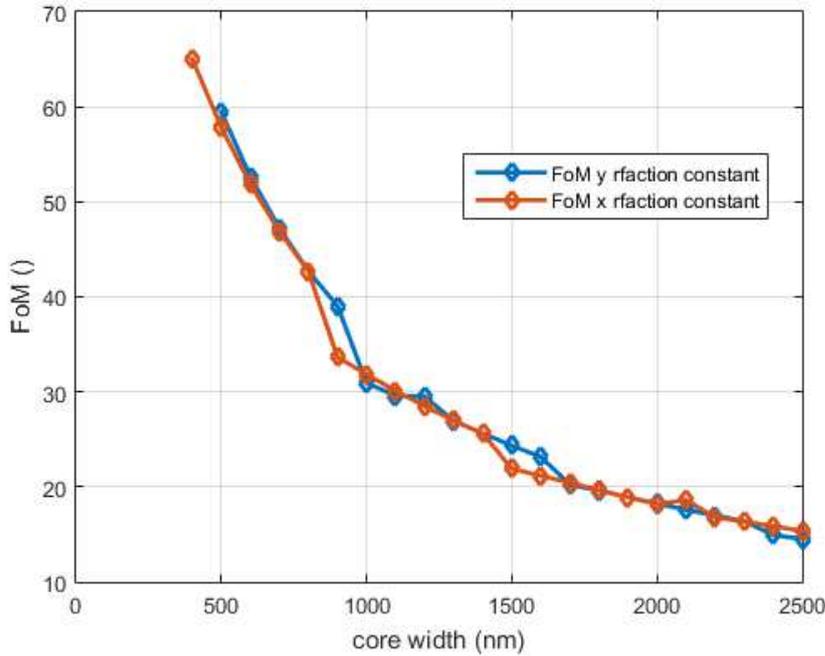


Figure 13 shows the FoM number of the merit parameter used in confinement measurement, first case InGaAsP Gradad in refractive index which was very close in values to the second case when using the tertiary material InGaAs.

When replacing the aforementioned wavelength $1.550 \mu\text{m}$ to $0.633 \mu\text{m}$ wavelength and applying the same previous parameters, we found that there is a jump in L_p $10 \mu\text{m}$ to reach more than $70 \mu\text{m}$ for the quaternary

compound InGaAsP while retaining the quantitative confinement value in width=500 nm with indices Figures 16, 15, 14 indicate that $A_{eff} = 0.1 \text{ m}^2$, FoM = 88 is also better than the prior case: $A_{eff} = 0.15 \text{ m}^2$, FoM = 60.

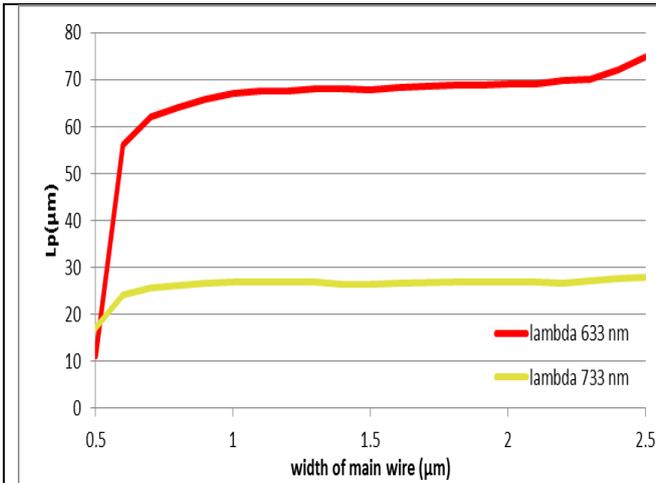


Figure 14 L_p for graded index HSPP at wavelengths 633 nm and 733 nm.

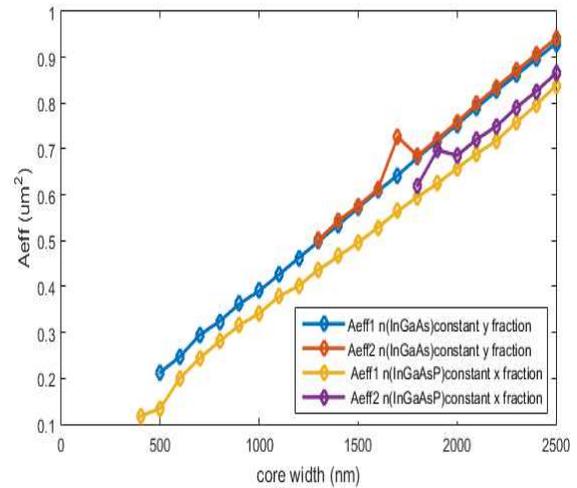


Figure 15 A_{eff1} and A_{eff2} for graded index HSPP at wavelengths 633 nm and 733 nm.

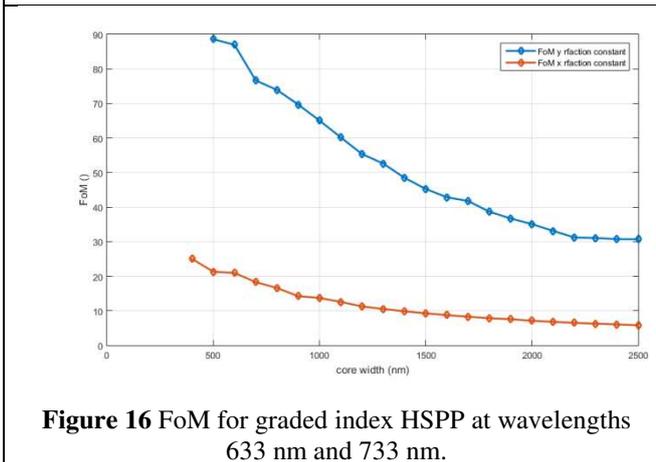


Figure 16 FoM for graded index HSPP at wavelengths 633 nm and 733 nm.

4. Conclusion :

A graded-index waveguide for SPP was suggested, enabling light focus and longer distance propagation. The graded-index design has been developed using the effective index method and numerically analyzed with the COMSOL Multiphysics program. In contrast to prior approaches for HP plasmonic waveguides, L_p was twice as much in case graded refractive index for InGaAsP more than InGaAs and conservative confinement. Because our method is scalable to telecom wavelengths, it is expected to spur more research into plasmonic multimode-interference devices based on traditional waveguide optics design techniques. The best results were in the case of the gradient in the refractive index of the quaternary compound InGaAsP, in which the value of $L_p = 40.18 \text{ } \mu\text{m}$ reached, which is twice its value in the base case. All of the above was at wavelength 1550 nm, but at frequencies, with wavelengths 633 nm there was a big jump in L_p to reach more than 71 nm, and the confinement remains good and the amount of FoM is greater and better clear in figs 14,15and 16.

References

- [1] J. Wen *et al.*, “Numerical investigation of on-chip wavelength conversion based on InP/In_{1-x}Ga_xAs_yP_{1-y} semiconductor waveguide platforms,” *Opt. Commun.*, vol. 473, no. April, pp. 1–6, 2020, doi: 10.1016/j.optcom.2020.125921.
- [2] J. Wen, K. Li, Y. Gong, B. Hughes, and M. A. Campbell, “Performance evaluation of on-chip wavelength conversion based on InP / In_{1-x}Ga_xAs_yP_{1-y} semiconductor waveguide platforms.”
- [3] A. Bernard *et al.*, “Mid-infrared optical characterization of InGaAsP,” *J. Opt. Soc. Am. B*, vol. 35, no. 12, p. C25, 2018, doi: 10.1364/josab.35.000c25.
- [4] B. Jensen and A. Torabi, “Refractive index of quaternary In_{1-x}Ga_xAs_yP_{1-y} lattice matched to InP,” *J. Appl. Phys.*, vol. 54, no. 6, pp. 3623–3625, 1983, doi: 10.1063/1.332402.
- [5] M. P. C. Krijn, “Heterojunction band offsets and effective masses in III-V quaternary alloys,” *Semicond. Sci. Technol.*, vol. 6, no. 1, pp. 27–31, 1991, doi: 10.1088/0268-1242/6/1/005.
- [6] M. Smit *et al.*, “An introduction to InP-based generic integration technology,” *Semicond. Sci. Technol.*, vol. 29, no. 8, p. 083001, Jun. 2014, doi: 10.1088/0268-1242/29/8/083001.
- [7] X. Zhang *et al.*, “Heterogeneous 2.5D integration on through silicon interposer,” *Appl. Phys. Rev.*, vol. 2, no. 2, 2015, doi: 10.1063/1.4921463.
- [8] J. and D. P. Capmany, “Programmable integrated photonics,” in *Emerging Applications in Silicon Photonics*, Oct. 2020, p. 344, doi: 10.1117/12.2584904.
- [9] V. J. Sorger, R. F. Oulton, R. M. Ma, and X. Zhang, “Toward integrated plasmonic circuits,” *MRS Bull.*, vol. 37, no. 8, pp. 728–738, 2012, doi: 10.1557/mrs.2012.170.
- [10] J. Xiao *et al.*, “A CMOS-compatible hybrid plasmonic slot waveguide with enhanced field confinement,” *IEEE Electron Device Lett.*, vol. 37, no. 4, pp. 456–458, 2016, doi: 10.1109/LED.2016.2531990.
- [11] I. A. Pshenichnyuk, S. S. Kosolobov, and V. P. Drachev, “Towards deep integration of electronics and photonics,” *Appl. Sci.*, vol. 9, no. 22, pp. 1–16, 2019, doi: 10.3390/app9224834.
- [12] S. Lien and C. Ng, *physics of Optoelectronic Devices*. John Wiley, 1995.
- [13] J. A. A. Engelbrecht, “An assessment of some theoretical models used for the calculation of the refractive index of In_xGa_{1-x}As,” *Phys. B Condens. Matter*, vol. 535, no. May, pp. 8–12, 2018, doi: 10.1016/j.physb.2017.05.047.
- [14] M. Nikoufard, M. K. Alamouti, and S. Pourgholi, “Multimode Interference Power-Splitter Using InP-Based Deeply Etched Hybrid Plasmonic Waveguide,” *IEEE Trans. Nanotechnol.*, vol. 16, no. 3, pp. 477–483, 2017, doi: 10.1109/TNANO.2017.2688397.
- [15] M. A. Mahdian, M. Nikoufard, and F. Soleimannezhad, “Effect of etching depth on the performance of InP-based hybrid plasmonic waveguides,” *AEU - Int. J. Electron. Commun.*, vol. 126, no. August, 2020, doi: 10.1016/j.aeue.2020.153403.
- [16] M. A. Mahdian, M. Nikoufard, and F. Soleimannezhad, “Effect of etching depth on the performance of InP-based hybrid plasmonic waveguides,” *AEU - Int. J. Electron. Commun.*, vol. 126, no. August, p. 153403, 2020, doi: 10.1016/j.aeue.2020.153403.
- [17] M. Sotoodeh, A. H. Khalid, and A. A. Reza zadeh, “Empirical low-field mobility model for III-V compounds applicable in device simulation codes,” *J. Appl. Phys.*, vol. 87, no. 6, pp. 2890–2900, 2000,

- doi: 10.1063/1.372274.
- [18] S. J. Sweeney and J. Mukherjee, "Optoelectronic Devices and Materials," in *Springer Handbook of Electronic and Photonic Materials*, no. January 2017, S. Kasap and P. Capper, Eds. Boston, MA: Springer US, 2017, pp. 1–1.
- [19] C. Chan, S. L. Ng, and L. Lam, "InGaAsInGaAsP quantum well infrared photodetector array operating at 1.5J. m wavelength," pp. 141–144, 2000.
- [20] S. Adachi and C. W. Tu, "Physical Properties of III-V Semiconductor Compounds: InP, InAs, GaAs, GaP, InGaAs and InGaAsP," *Phys. Today*, vol. 47, no. 2, pp. 99–100, 1994, doi: 10.1063/1.2808406.
- [21] S. Seifert and P. Runge, "Revised refractive index and absorption of In_{1-x}Ga_xAs_yP_{1-y} lattice-matched to InP in transparent and absorption IR-region," *Opt. Mater. Express*, vol. 6, no. 2, p. 629, 2016, doi: 10.1364/ome.6.000629.
- [22] B. Optoelectronics, "Refractive index n of InGaAs." batop.com/information/n_InGaAs.html.
- [23] M. Nikoufard, "Integrated wavelength division multiplexing," Technische Universiteit Eindhoven, 2008.
- [24] F. Fiedler and A. Schlachetzki, "Optical parameters of InP-based waveguides," *Solid State Electron.*, vol. 30, no. 1, pp. 73–83, 1987, doi: 10.1016/0038-1101(87)90032-3.
- [25] A. Snyder and J. Love, *Optical waveguide theory.-London: Chapman & Hall*. Springer Science & Business Media, 1983.
- [26] S. Irmscher, *Design , Fabrication and Analysis of InP-InGaAsP Traveling-Wave Electro-Absorption Modulators*. 2003.
- [27] COMSOL Inc., "RF module user guide v5.3a," 2017. [Online]. Available: http://localhost:8090/docserver/#!/com.comsol.help.rf/html_RFModuleManual.html.
- [28] Y. Chowdhury, "Plasmonic Waveguides : Design and Comparative Study," *Thesis, MS*, 2011.
- [29] R. Tamaki, Y. Shoji, L. Lombez, J.-F. Guillemoles, and Y. Okada, "Quasi-Fermi level splitting in InAs quantum-dot solar cells from photoluminescence measurements," *Opt. Express*, vol. 16, no. 1, p. 32, Jan. 2020, doi: 10.1117/12.2545657.
- [30] C. Y. Chunwei Ye, Y. L. Yumin Liu, J. W. Jie Wang, H. L. Hongbo Lv, and Z. Y. Zhongyuan Yu, "Graded-index ridge surface plasmon polaritons waveguide," *Chinese Optics Letters*, vol. 12, no. 9. pp. 092402–092405, 2014, doi: 10.3788/col201412.092402.
- [31] T. Ma *et al.*, "Graphene-Coated Two-Layer Dielectric Loaded Surface Plasmon Polariton Rib Waveguide with Ultra-Long Propagation Length and Ultra-High Electro-Optic Wavelength Tuning," *IEEE Access*, vol. 8, pp. 103433–103442, 2020, doi: 10.1109/ACCESS.2020.2999395.
- [32] J. Wang, Y. X. Guo, B. H. Huang, S. P. Gao, and Y. S. Xia, "A Silicon-Based Hybrid Plasmonic Waveguide for Nano-Scale Optical Confinement and Long Range Propagation," *IEEE Trans. Nanotechnol.*, vol. 18, pp. 437–444, 2019, doi: 10.1109/TNANO.2019.2911333.
- [33] Z. Zhang and J. Wang, "Long-range hybrid wedge plasmonic waveguide," *Sci. Rep.*, vol. 4, pp. 1–9, 2014, doi: 10.1038/srep06870.
- [34] Y. CHOWDHURY, "plasmonic waveguide design and Comparative Study," 2011.
- [35] Y. Bian *et al.*, "Highly confined hybrid plasmonic modes guided by nanowire-embedded-metal grooves for low-loss propagation at 1550 nm," *IEEE J. Sel. Top. Quantum Electron.*, vol. 19, no. 3, 2013, doi:

10.1109/JSTQE.2012.2212002.

- [36] N. T. Huong, N. D. Vy, M. T. Trinh, and C. M. Hoang, "Tuning SPP propagation length of hybrid plasmonic waveguide by manipulating evanescent field," *Opt. Commun.*, vol. 462, no. December 2019, p. 125335, 2020, doi: 10.1016/j.optcom.2020.125335.