CORPUS PUBLISHERS

Journal of Mineral and Material Science (JMMS)

Volume 3 Issue 2, 2022

Article Information

Received date :July 07, 2022

Published date: July 18, 2022

***Corresponding author**

Pasquale Cavaliere, Department of Innovation Engineering, University of Salento, Via per Arnesano 73100-Lecce, Italy

Keywords

Plasmonic; Waveguide; Gain Materials; Loss Propagation

Abbreviations

PMMA: Polymethylmethacrylate; SPP: Surface Plasmon Polaritons

Research Article

The Influence of the Different Gain Material on the Loss Compensation of Hybrid Plasmonic Waveguide

Niloofar Ebrahimzadeh[1], Behzad Sadeghi[2], Pasquale Cavaliere[3*] and Fatemeh Behdadkia[4]

[1]*Department of Photonics, Faculty of Physics University of Kashan, 87317-51167 Kashan, Iran*
[2]*New Materials Technology and Processing Research Center, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran*
[3]*Department of Innovation Engineering, University of Salento, Via per Arnesano 73100-Lecce, Italy*
[4]*Department of Physics, Isfahan University of Technology, Isfahan, Iran*

Abstract

The influence of different gain materials and waveguide parameters on propagation properties are analyzed in detail. In this paper, three materials including Al_2O_3, Si_3N_4, and Polymethylmethacrylate (PMMA) as low index materials are introduced instead of SiO_2 which is used in many experiments. The results obtained via simulations showed that by increasing the width of metal, field confinement increased and for widths larger than 450 nm the filed profile was completely confined in below the metal (zone I). In addition to, simulation results showed that Al_2O_3 and Si_3N_4 are more efficient than SiO_2 whereas PMMA is completely similar to SiO_2 in loss compensation. It was attributed to the fact that the refractive index of PMMA is close to the refractive index of SiO_2. Moreover, the effect of InGaAsP as high index gain material instead of Si is analyzed. In this case, InGaAsP also reveals a loss compensation effect similar to Si due to their close refractive indexes. Therefore, the configuration with new different gain materials potentially offers an appealing solution to provide lossless light transport via low compensation gain, hence opening venues for ultra-compact active plasmonic devices.

Introduction

Optical waveguides are of interest because of their application in optically integrated circuits [1], optical lasers [2], optical sensors [3] and optical interferometers [4]. Waveguides fall into two groups: dielectric waveguides and plasmonic waveguides [5]. The dielectric waveguides are composed of two materials with high and low indexes [6]. These waveguides have long propagation distance and low loss propagation. But the most important flaw of dielectric waveguides is their low confinement field. Therefore this type of waveguides is not appropriate for confinement in nanoscale [5]. The other type of waveguides is plasmonic waveguides which attract attention in Nano photonic [7]. Plasmonic waveguides have high confinement in nanoscale. Therefore, this waveguides in nanoscale make it possible to achieve integrated photonics circuits [8]. But the application of these waveguides is limited because of high loss propagation and low propagation distance [5]. The basis of the plasmonic waveguides is the formation of Surface Plasmon Polaritons [SPP] at the interface between metal and dielectric. Plasmonic waveguides have two common structures including Metal-Insulator-Metal (MIM) and Insulator-Metal-Insulator (IMI) [9]. There has always been a great challenge to choose the type of waveguides due to their distinct features until 2008. In this year, Alton and et al. introduced a new geometrical structure of plasmonic waveguide which show a good balance between the low loss propagation, high confinement and long propagation distance in two dimensions [10]. This new structure is a combination of a dielectric and plasmonic waveguide called the hybrid plasmonic waveguide which is made up of a high index semiconductor nanowire embedded in a low index dielectric near a metal surface. This unique feature of hybrid plasmonic waveguides encourages researchers to construct these waveguides using different geometric structures and different materials [10-13]. Both low loss propagation and high field confinement make it possible to use hybrid plasmonic waveguides for production of micron bending which has importance in the technology of photonic integrated circuit chips [10,11,14]. Also, these waveguides are useful to high-speed signal processing [12]. As well as the simulations carried out, in experimental works are shown that the hybrid plasmonic can overcome the diffraction limit with low loss propagation. Therefore, these waveguides are an ideal choice for data routing tools such as modulators and optical keys [15], and for making nanoscale lasers [13].

In recent years' solutions, to overcome the inhibitory challenges are presented. Using gain material to loss compensation is one of these solutions [8,16-18]. Even though hybrid plasmonic waveguides have low loss propagation compared to plasmonic waveguides, it is also desirable to compensate loss completely by using of gain materials. For this purpose, in this paper, three different gain materials are used in a hybrid plasmonic waveguide which is most effective than gain materials that used in recent researches. Another important factor in choosing waveguides is their geometric structure [11]. Since 2008 different geometrical structures suggested for hybrid plasmonic waveguides to achieve a good balance between low loss propagation and high field confinement. In this paper, we use the introduced structure in [19], is because of the simplicity of its structure and easy manufacturing process compared to the other structures in recent researches. In this paper, we change the geometrical parameters of the waveguide and find the best parameters for high confinement. All simulation in this paper is done by using the finite element method, and the used software was COMSOL Multiphysics v4.3.

Simulation and Analysis Results

We consider waveguides with the structure which is similar to the structure in [10]. This waveguide is made of a metal strip, a narrow low index dielectric gap, a high index dielectric slab, a buffer layer, and a substrate. All layers expect metal layer along the z-axis are infinite. The schematic of this structure is depicted in Figure 1. Materials are used in each layer of this waveguide are Ag as a metal strip, SiO_2 as low index narrow gap and a buffer layer, and Si as high index slab and substrate of the waveguide. Refractive indexes of these materials at 1550 nm wavelength are $n_{SiO2}=1.445$ [19], $n_{Si}=3.455$ [19]

How to cite this article: Ebrahimzadeh N, Sadeghi B, Cavaliere P and Behdadkia F (2022) The Influence of the Different Gain Material on the Loss Compensation of Hybrid Plasmonic Waveguide. J Miner Sci Materials 3: 1039

and n_{Ag}=0.1453 +11.3587i [19].

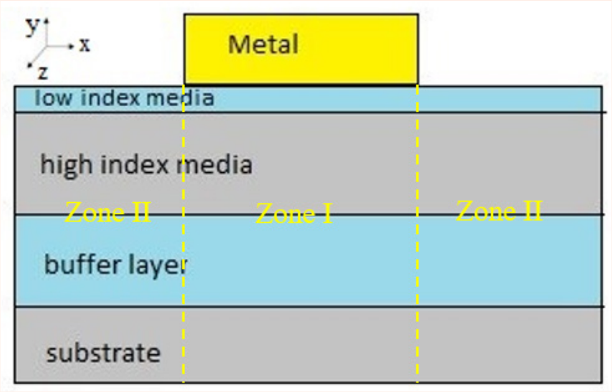

Figure 1: Structure of purposed waveguide.

Field profile

Field profile for this structure of waveguide has been simulated. The results of this simulation were shown in Figures 2 & 3. There is a strong field improvement for a narrow gap between metal and high index slab. This improvement happens because the combination of surface Plasmon wave created at the interface between metal layer, narrow gap and the discontinuity of the vertical component of dielectric mode at the interface of high index layer and low index narrow gap.

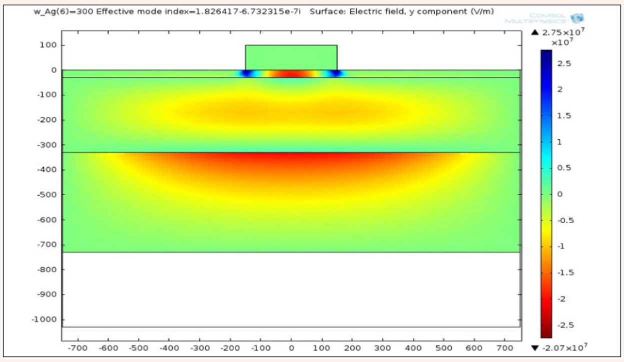

Figure 2: Field profile of TM mode in the intersection of the waveguide, the width of the metal layer is 300 nm and thickness of gap is 30 nm.

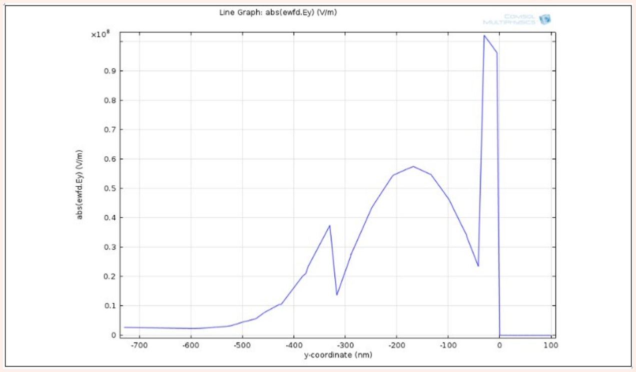

Figure 3: Vertical line scan of the E_y field profile across the center of the metal strip. The width of the metal layer is 300 nm and thickness of gap is 30 nm.

Effect of change geometric parameter

The geometrical parameter is one of the most important factors for waveguide performance. In Figure 4, the effect of metal width on field confinement is demonstrated. It is evident that by increasing the width of the metal strip field confinement increases and it is constant for the width further than 400 nm. In another word it can be said that due to metals always cause a high confinement of field, when the width of the metal slab increases, metal slap can confine more than lower width. As it is reported in [19], if this waveguide considers to be two parts, including one section can be zone under the metal (zone I) and other is the sideways (zone II). As shown in Figure 4 when the width of the metal increases the section under the metal (zone I) extend and more area is limited to the zone. While for more width than 400 nm due to the fact that nearly all of the field is confined and subsequently variation of the field profile stays fixed.

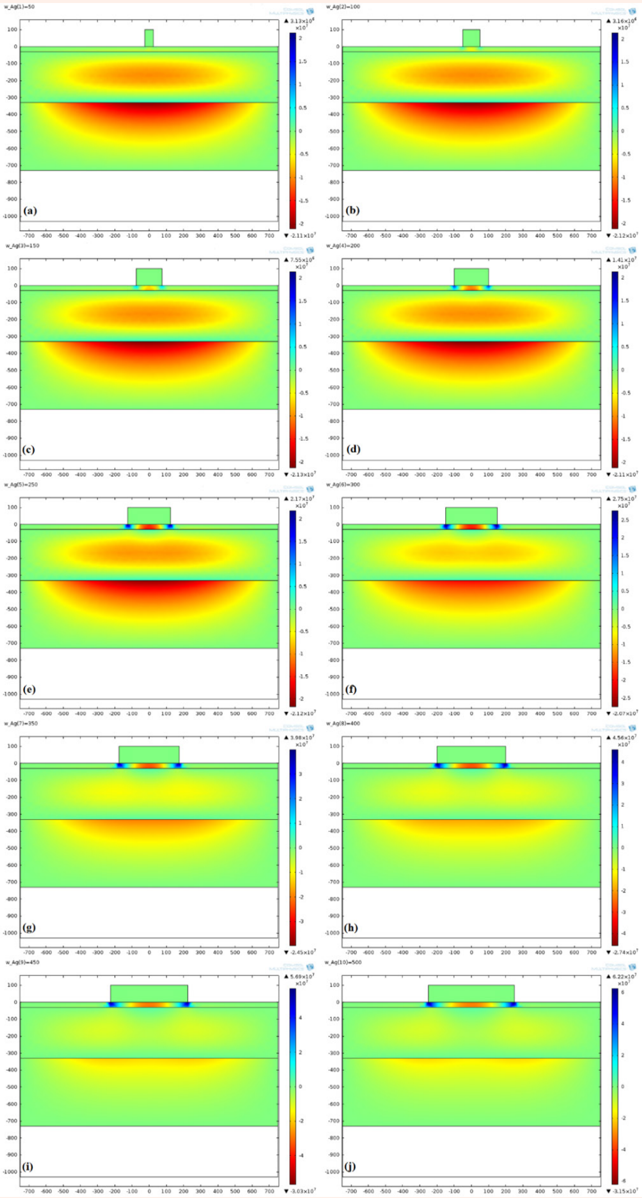

Figure 4: The variation of E_y field profile as function of metal strip from 50 nm to 500 nm; w=(a) 50nm, (b)100nm, (c)150nm, (d)200nm, (e)250nm, (f)300nm, (g)350nm, (h)400nm, (i)450nm, (j)500nm.

Loss compensation by using gain material

Hybrid plasmonic waveguides can be a solution for obtaining low loss propagation and high confinement. Also, it is beneficial to use a gain material for loss compensation completely [16,17]. In this paper, the low index narrow gap and high index materials slab are separately used as gain materials. Three new materials are introduced as the low index narrow gap and one new material offered as high index material layer. Using of these materials as gain material and their effect on loss compensation are simulated by finite element method and COMSOL Multiphysics v4.3. Hybrid plasmonic waveguides by coupling the dielectric mode and Surface Plasmon Polaritons (SPP) produces the hybrid mode [9]. Effective index (n_{eff}=k/k_0) is the most important parameter for describing hybrid mode. k and k0 are specified as the propagation constant of hybrid mode and the free space wave number, respectively [19]. On the other hand, n_{eff} is a complex number which is written as follows.

$$n_{eff} = n'_{eff} + in''_{eff}$$

When n_{eff}'' is positive, waveguide has loss propagation and when the gain material is used, by pumping the gain material gain bulk (n_b'') increases, and n_{eff}'' becomes smaller and smaller until it reaches to zero [16]. In this point loss propagation is completely compensated and gain bulk in this point called critical gain.

Loss compensation by using low index gain material: In the previous research, SiO_2 with a refractive index of 1.445 was used as an interested material in the narrow gap layer [12]. In this paper, the effect of using SiO_2 as gain material is re-simulated for the comparison of loss compensation with other materials which are suggested.

As shown in Figure 5, by increasing the gain bulk for SiO_2, -Im [n_{eff}] approaches zero. In Other words, by increasing the gain bulk loss propagation of waveguide become small and smaller and in one point loss can be compensated completely. After that increasing the gain bulk cause to strong field improvement. The previous studied have shown that other materials could be more efficient as a gain material in comparison with SiO_2 [12]. When a material is more efficient, full loss compensation happens for less critical gain bulk. In this paper, three low index material including Al_2O_3, Si_3N_4 and PMMA are introduced as gain material instead of SiO_2. Their refractive indexes for 1550 nm wavelength are n_{Al2O3}=1.7 [20], n_{Si3N4}=1.98 [21], and n_{PMMA}=1.5 [17]. In Figure 6 loss compensation of waveguide by using offered materials and SiO_2 as gain media is demonstrated. This comparison shows that Al_2O_3 and Si_3N_4 are more efficient as gain material. Al_2O_3 is the most efficient material as gain material. Another point according to Figure 6 is that when PMMA use as low index gain material, It has similar behavior to SiO_2. This happens because the refractive indexes of SiO_2 and PMMA are very close together. Note that for all of the above cases, Si is the high index slab.

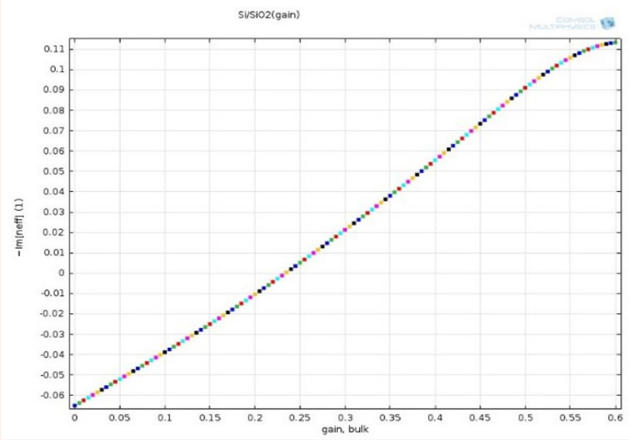

Figure 5: The curve of the imaginary part of the effective index as a function of gain bulk material, when SiO2 used as low index gain material.

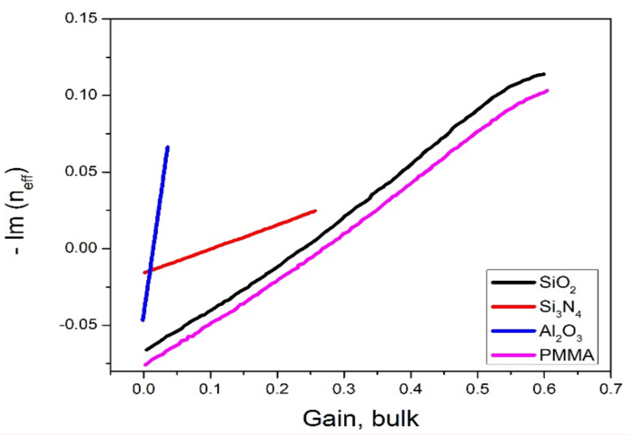

Figure 6: The comparison of the effect of different materials as low index gain materials on the imaginary part of the effective index.

Loss compensation by using high index gain material: Previous studies have shown that the use of high indexes materials can be more effective than using low indexes to compensate loss propagation. One of the reasons for using a high index material as a gain media is that in this layer the overlap factor is larger than other layers and the interaction between the electric field and the gain material is stronger. In [19], silicon is used as a high index gain media. In this paper, the use of another material such as InGaAsP with refractive index 3.37 [18] is suggested and is simulated. In Figure 7, the result of simulation for loss compensation when InGaAsP use as high index gain material is shown. In this case, PMMA is used as the low index material in narrow band gap. Also, the behavior Si is re-simulated and shown when using as a high index gain material. It should be noted that in this case SiO_2 use as low index material. The cause of this similar behavior is that these material have similarity in their refractive index. By a closer inspection at Figure 7, it can be understood that by increasing the gain bulk, the difference between the two curves is reduced. In the critical gain, which completely compensates for the loss, it will be at its lowest value compared to less gain bulk., Therefore, it can be said that the conventional composition of PMMA/ InGaAsP as low/high index materials in this case greatly resembles the SiO_2/Si composition. Therefore, it can be suggested that the combination of PMMA/InGaAsP is a good alternative to SiO_2/Si composition.

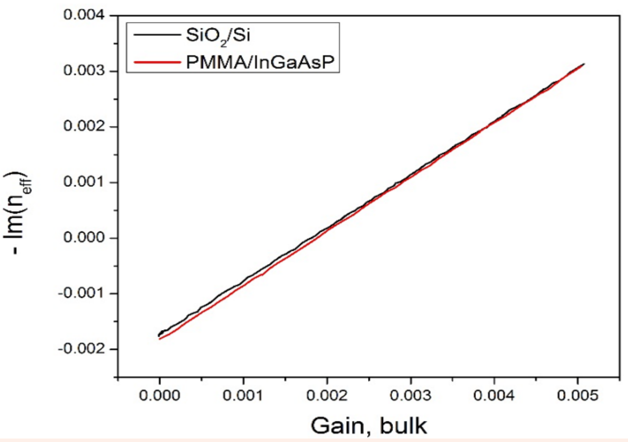

Figure 7: The comparison of the effect of InGaAsP and Si as high index gain materials on the imaginary part of effective index.

Citation: Ebrahimzadeh N, Sadeghi B, Cavaliere P and Behdadkia F (2022) The Influence of the Different Gain Material on the Loss Compensation of Hybrid Plasmonic Waveguide. J Miner Sci Materials 3: 1039

Conclusion

In this paper, an active plasmonic waveguide with a simple structure includes a metal strip is assumed to be used to compensate for waveguide loss. The effects of waveguide geometric dimensions and material constant on loss propagation, have also been studied. Gain materials are presented in both layers with high and low refractive index. In recent research, SiO_2 and Si have been used, respectively, as useful materials with low and high indexes. Si_3N_4 and Al_2O_3 are suggested as a low-refractive index have been introduced instead of using SiO_2. Simulation results showed that these two materials act more efficiently than SiO_2 in the loss compensation. Also, simulations show that PMMA can have similar behavior to SiO_2 in compensating the loss. Additionally, the two materials including InGaAsP and Si act similarly to compensate the loss of waveguide as high index material. Therefore, it can be concluded that the performance of the composition of PMMA/InGaAsP on the loss compensation is similar to the common SiO_2/Si composition.

References

1. Nishihara H, Haruna M, Suhara T (1989) Optical integrated circuits. McGraw-Hill, New York, US.
2. Degnan JJ (1976) The waveguide laser: A review. Applied Physics 11: 1-33.
3. Horváth R, Pedersen HC, Skivesen N, Selmeczi D, Larsen NB (2003) Optical waveguide sensor for on-line monitoring of bacteria. Optics Letters 28(14): 1233-1235.
4. Treyz G, May P, Halbout JM(1991) Silicon Mach–Zehnder waveguide interferometers based on the plasma dispersion effect. Applied Physics Letters 59(7): 771-773.
5. Dai D, He S (2010) Low-loss hybrid plasmonic waveguide with double low-index nano-slots. Optics Express 18(17): 17958-17966.
6. Okamoto K (2006) Fundamentals of optical waveguides. Academic Press, US.
7. Wei H, Xu H (2012) Nanowire-based plasmonic waveguides and devices for integrated nanophotonic circuits. Nanophotonics 1: 155-169.
8. Babicheva VE, Kulkova IV, Malureanu R, Yvind K, Lavrinenko AV (2012) Plasmonic modulator based on gain-assisted metal–semiconductor–metal waveguide. Photonics and Nanostructures-Fundamentals and Applications 10(4): 389-399.
9. Maier SA (2007) Plasmonics: fundamentals and applications. Springer Science & Business Media, Germany.
10. Oulton RF, Sorger VJ, Genov D, Pile D, Zhang X (2008) A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation. Nature Photonics 2 496-500.
11. Dai D, He S (2009) A silicon-based hybrid plasmonic waveguide with a metal cap for a nano-scale light confinement. Optics Express 17(19): 16646-16653.
12. Dai D, Shi Y, He S, Wosinski L, Thylen L (2011) Gain enhancement in a hybrid plasmonic nano-waveguide with a low-index or high-index gain medium. Optics Express 19(14): 12925-12936.
13. Oulton RF, Sorger VJ, Zentgraf T, Ma RM, Gladden C, et al. (2009) Plasmon lasers at deep subwavelength scale. Nature 461(7264): 629-632.
14. Kim JT(2011) CMOS-compatible hybrid plasmonic waveguide for subwavelength light confinement and on-chip integration. IEEE Photonics Technology Letters 23(4): 206.
15. Sun X, Zhou L, Li X, Hong Z, Chen J (2011) Design and analysis of a phase modulator based on a metal–polymer–silicon hybrid plasmonic waveguide. Applied Optics 50(20): 3428-3434.
16. Alam MZ, Meier J, Aitchison J, Mojahedi M (2007) Gain assisted surface plasmon polariton in quantum wells structures. Optics Express 15(1): 176-182.
17. Bian Y, Zheng Z, Zhao X, Xiao J, Liu H, et al. (2013) Gain-assisted light guiding at the subwavelength scale in a hybrid dielectric-loaded surface plasmon polariton waveguide based on a metal nanorod. Journal of Physics D: Applied Physics 46: 335102.
18. Nezhad MP, Tetz K, Fainman Y(2004) Gain assisted propagation of surface plasmon polaritons on planar metallic waveguides. Optics Express 12(17): 4072-4079.
19. Gao L, Tang L, Hu F, Guo R, Wang X, et al. (2012) Active metal strip hybrid plasmonic waveguide with low critical material gain. Optics Express 20(10): 11487-11495.
20. Song Y, Wang J, Li Q, Yan M, Qiu M (2010) Broadband coupler between silicon waveguide and hybrid plasmonic waveguide. Optics Express 18(12): 13173-13179.
21. Philipp HR (1973) Optical properties of silicon nitride. Journal of the Electrochemical Society 120: 295-300.

Citation: Ebrahimzadeh N, Sadeghi B, Cavaliere P and Behdadkia F (2022) The Influence of the Different Gain Material on the Loss Compensation of Hybrid Plasmonic Waveguide. J Miner Sci Materials 3: 1039