Analysis and simulations of optimal geometry shapes of the 4 and 9 nano hole arrays (NHAs) with surface plasmonics and optical properties of biosensors systems

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ABSTRACT

The possibility to limit and manipulate photons at nanometer scales attracted a lot of interest for exciting applications from subwavelength in laser, biosensors, biomedical and optoelectronics devices, the sensor optical properties, however; are complex due to two resonances through propagating and localized surface plasmons. The optical properties of surface plasmons (SPs) at the resonant wavelength is depending on the geometrical nanostructure of materials. In this article, we used different geometry of nanoholes array, 4 and 9 nanoholes array in a metallic film gold nanoparticle with different thickness (20,50,100) nm on SiO2 substrate with refractive index 1.46, we designed two different geometries; 4- holes: hole radius r1=200 nm, period p1=600 nm; and 9- holes: r2=100 nm, period p2=300 nm. Transmission and reflection spectrum have been calculated and simulated by FDTD Lumerical program. From results are observed the effect of thickness is interesting, transmission is increased at (t=20nm) for two arrays. Furthermore, the number of hole and its area has an influence on optical transmission and other parameters (E, H, Ref) which are characteristics of design of metallic nanostructure. We can see that there is a peak value of the wavelength at 519 nm approximately to 73% strong light transmission with 4-NHA in the other hand wavelength of 519 nm transmission is 45% with 9-NHA. strong light transmission is hopeful for many applications (biomedical devices, nanoantennas and laser optical fiber).

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1. INTRODUCTION

Surface Plasmons (SPs) are collective oscillations of free electrons which are excited by light or photon (from visible to IR) [1]. Firstly SPP involves on one side the coherent oscillation of the conduction electrons at the interface inside the metal, and on the other side the propagation of an electromagnetic wave along the surface, inside the dielectric as (1) and (2) as shown in Figure 1, we find the values of wave number and Surface Plasmon frequency ω_{sp} as shown in Figure 2 as [2, 3].

$$\beta = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (1)$$

$$\omega_{sp} = \frac{\omega_p}{\sqrt{1+\varepsilon_d}} \quad (2)$$

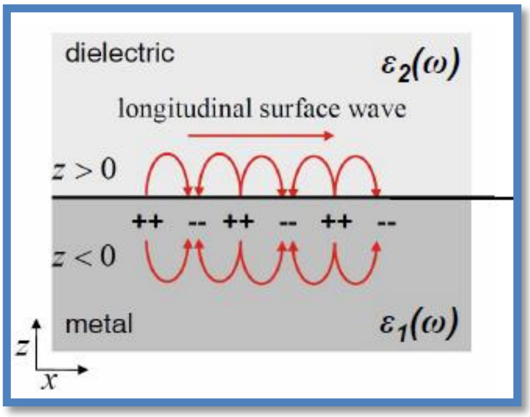


Figure 1. Schematic of a surface plasma wave (SPPs) at a metal-dielectric interface [3]

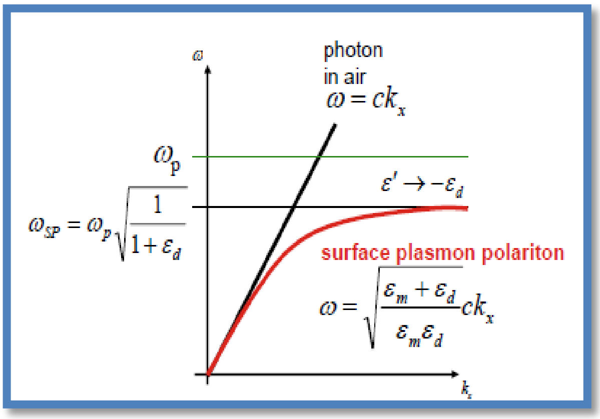


Figure 2. How to find the frequency surface plasmons at air and dielectric [2]

Secondly, Localized surface Plasmons (LSPs) are non-propagating excitations of the conduction electrons of metallic nanostructures coupled to the electromagnetic field. LSPs are excited at certain resonance frequencies (or resonance wavelengths, typically in the visible region), resulting in scattering and absorption at these frequencies for example optical nanoantennas as shown in Figure 3 [4]. A Plasmon is a quantized plasma oscillation, and the motion of the collective oscillation can rightly support electromagnetic (EM) waves at optical frequencies. The Lorentz-Drude model equation of motion is:

$$\vec{F} = m\vec{a} = m\frac{d^2x}{dt^2} = -qE \quad (3)$$

The dipole moment per unit volume, is:

$$P = -nqx = -\frac{nq^2}{m\omega^2}E \quad (4)$$

$$\omega_p^2 = \frac{nq^2}{\varepsilon_o m} \quad (5)$$

Nanoholes array display high transmission due to the matching between the incident light and SPRs through the holes at the surface of the metallic film [5, 6]. Thin metallic films patterned with a nanoholes array also support surface plasmons excitation due grating coupling, and the resonance condition for Plasmon excitation depends on refractive index of the surrounding medium [7]. Concerning geometrical constraints, the excitation of SPs methods depends on the design between periodicity and dielectric coefficients of the metal and dielectric. EOT (An extraordinary optical transmission) supported by a subwavelength periodic nanoholes array patterned on thin film of metal [8]. Ebbessen [9, 10] was first to originate an equation relating the dependence of the wavelength (λ max) of the SP resonances with EOTs on the procedure of 4 and 9 NHAs when the incident light is standard to the plane of the NHAs.

Some geometrical coefficients like a thickness of metal and substrate; the hole diameter also the number of periodic holes and metal properties can effect on EOT spectra because the surface plasmons that will be excited by incident light is affected by changing the size of hole and it have been confirmed that any change in the size of the holes lead to a small variations in transmission efficiency and peak positions [11-15]. Je Hong provided that the transmission characteristics is a function of film thickness of metallic hole array samples which is prepared with different hole periodicity, size and shape on a silica substrate and shows highly transmission efficiency at small thickness of gold metal [16, 17]. Plasmonic nanostructures have been extensively investigated both for scientific interest in their unique optical properties and for practical applications, such as optoelectronic devices, sensors, biomedical treatment; and so on [18, 19]. Since plasmonic sensing requires simply an optical transmission spectrum, or only the transmitted intensity at one or a few wavelengths [20, 21]. In this study we presented the differences between two holes arrays of 4 and 9 holes for different thickness (20,50,100) nm to characterize the optical properties for surface plasmons metals and to determine from these parameters the affects geometry and shape on sensors applications, biomedical and optoelectronic devices.

2. RESEARCH METHOD

Two designs of nanoholes arrays of 4 and 9 nanoholes which they patterned with periodic array of nanoholes with radius r1, r2 for 4 and 9 respectively in thin film of gold in different thickness for each design (20, 50, 100) nm which based on SiO2 substrate with refractive index (n=1.46) and thickness fixed in two cases (t=950 nm). These designs are performed as 2×2 array with P1=600nm and r1=200nm in the other hand 3×3 array with P2=300nmand r2=100nm, with consideration that these holes are patterned on the same direction of a sample Au/SiO2 as shown in Figure 3 (a-b). In this work we use FDTD method that deals with Maxwell's equations in surface plasmons, this technique is helpful to analyze the interaction of incident light with structure NHAs and by Drude model is computed the noble metals which fits the literature data from Palik [22]. From these arrays the transmission and reflection have been calculated by such program and considered magnetic field intensity (H) and electric field intensity (E) [23, 24]. In addition, there was researches about different geometry and shapes like square and hexagonal lattice, grating and grid thin film of metal to develop biological sensing performance

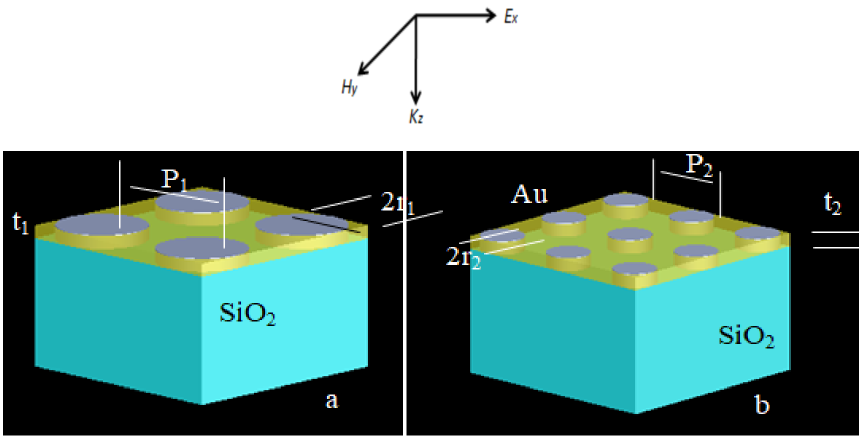


Figure 3. (a-b) schematic view of 4 and 9 NHA respectively, including the polarization & propagation direction of the incident wave and geometrical parameters: t, r, P

3. RESULTS AND ANALYSIS

In this work, we used FDTD by Lumerical solution Inc. to design a simulation of nanoholes array of 4 and 9-NHA in different periodic array and diameters of holes patterned on thin film of gold based on silicon dioxide, SiO2 substrate (n=1.46) by this program the interaction of incident light wavelength (λ=350-750) nm with nanoholes array structure is analyzed. From the simulation FDTD and design of NHAs, the asymmetric and anti-symmetric boundary conditions were considered for the x- and y-directions, respectively, and we study the transmission properties at normal incident of electromagnetic wave through the sub wavelength nanoholes structure. For 4-NHA, the FDTD simulations showing that transmission efficiency reached about 73% in visible.

From Figure 4 the E distributions for 4-holes array with period P1=600 nm is shown in Figure 4 (a-c), we can see that E at t=50 nm is larger than the other thickness (20,100) nm corresponding to the two modes of transmission in Figure 4c to determine the near field enhancement. In the other hand, in Figure 4 (d-f) we can see that the H distributions have a maximum value at t=50nmdepending on the two modes of reflection at t=50 nm in Figure 4e. Furthermore, these field enhancements are mainly located within the holes. This is highly desirable for biosensing devices as it rises the overlap of the analyses with the electromagnetic field (E and H) inside the hole by effective the positions of the surface plasmons.

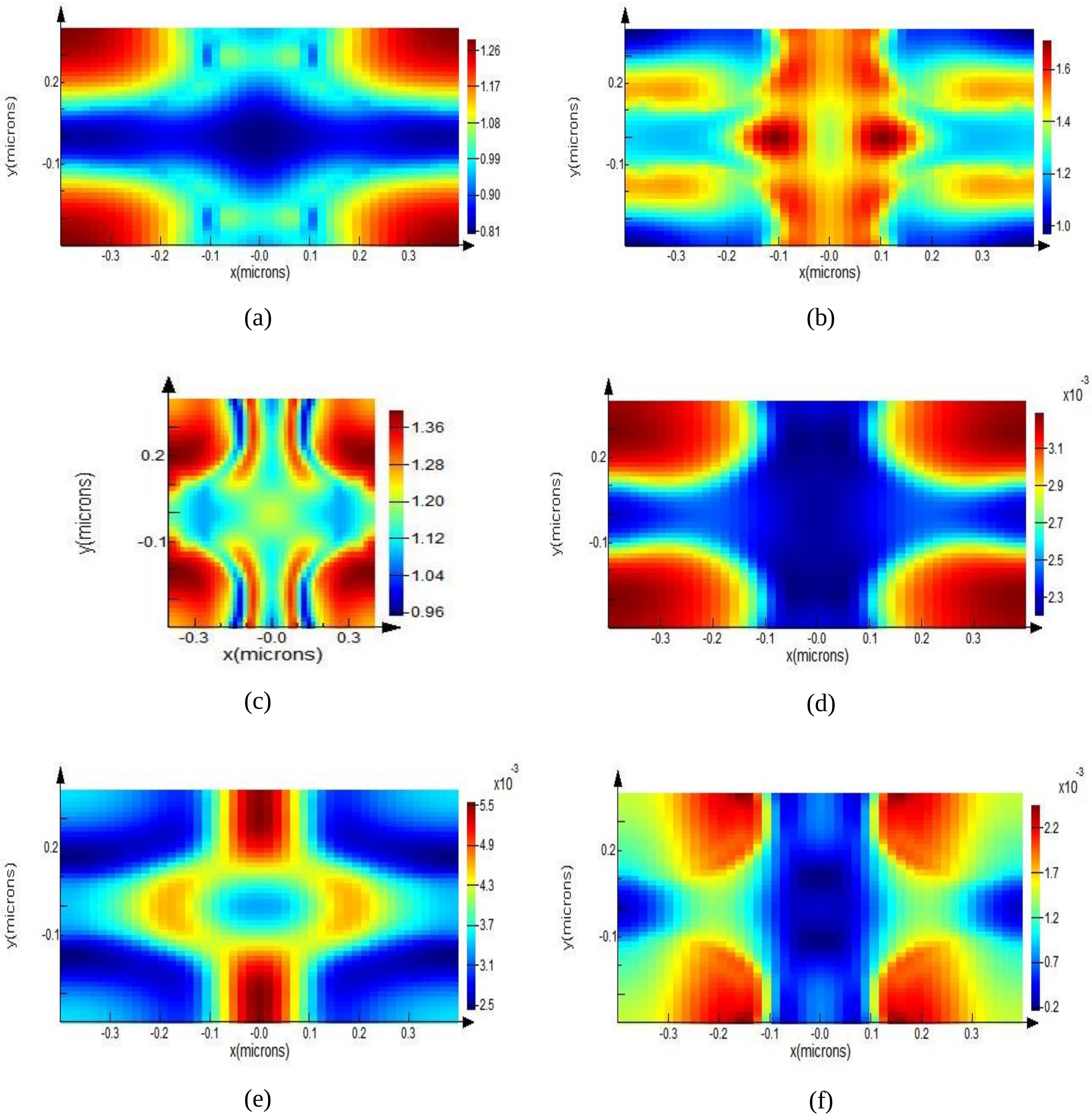


Figure 4. Field distributions for E and H of 4-NHA with varying thickness of Au: (20, 50, 100) nm

From Figure 5 the E distributions for 9-NHA with period P1=300 nm is shown in Figure 5(a-c). We can see that E at t=100 nm is larger than the other thickness (20,50) nm corresponding to the two modes of transmission in Figure 6(e) to determine the near field enhancement. In the other hand, in Figure 5(d-f) we can see that the H distributions have a maximum value at t=100 nm depending on the two modes of reflection at t=100 nm in Figure 6(d).

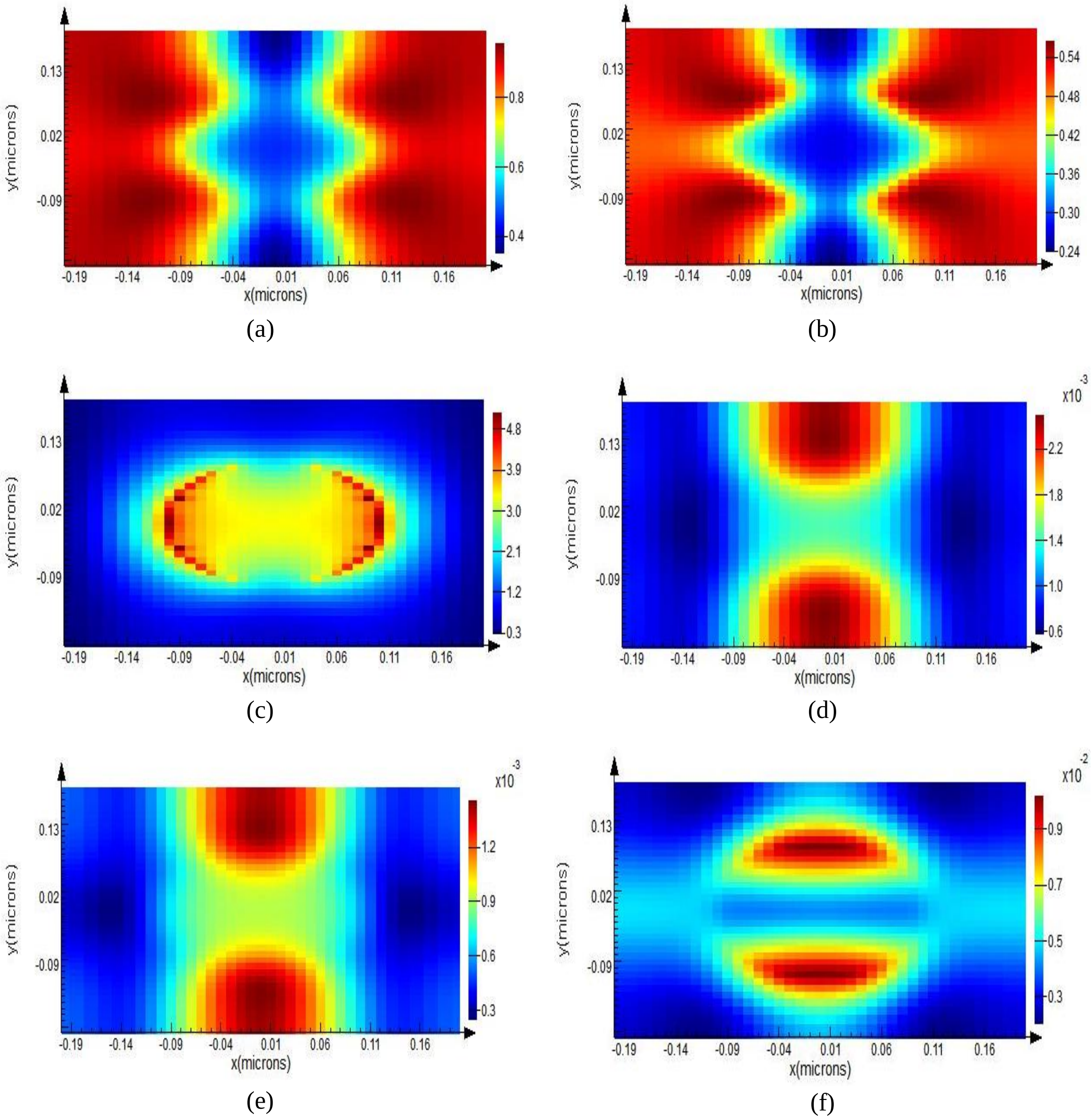


Figure 5. Field distributions for E and H of 9-NHA with varying thickness of Au: (20, 50, 100) nm

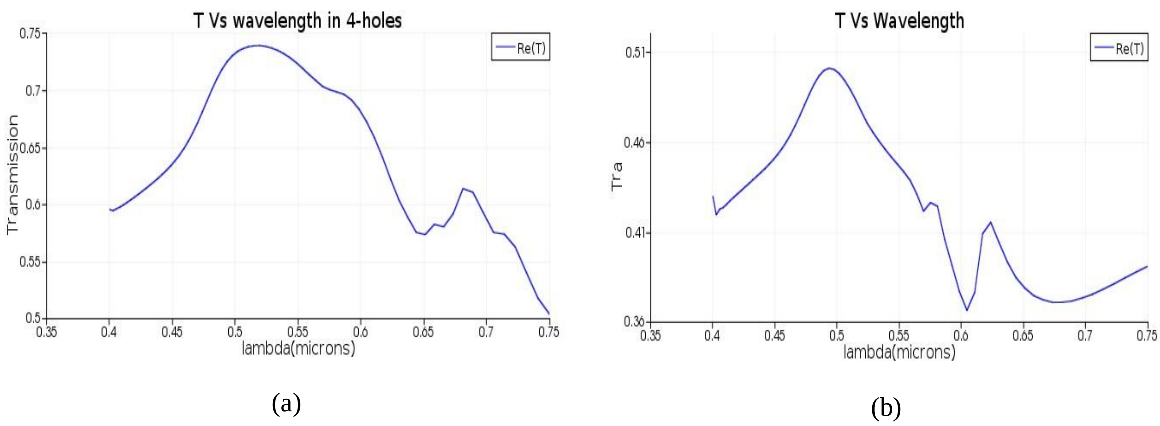
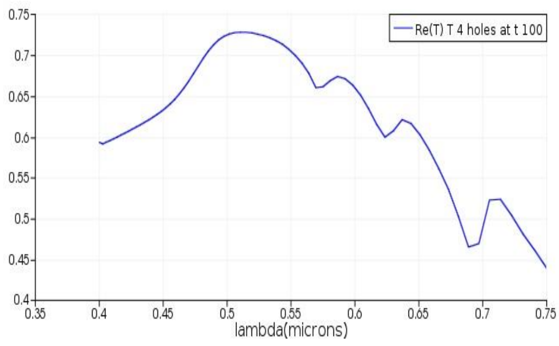
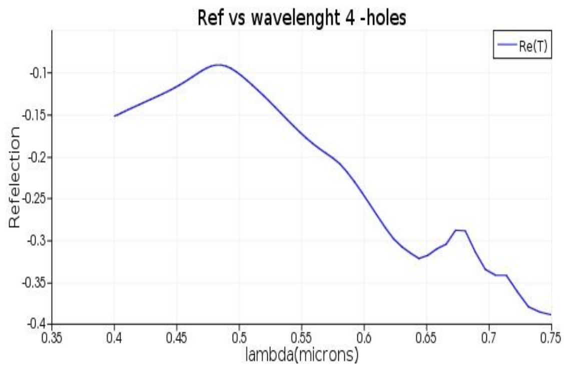


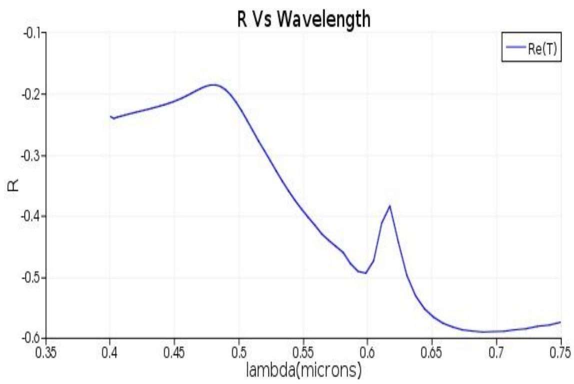
Figure 6. (a, b and c) transmission; d and e reflection resonance for 4-NHA at t(Au)= (20, 50, 100) nm



(c)



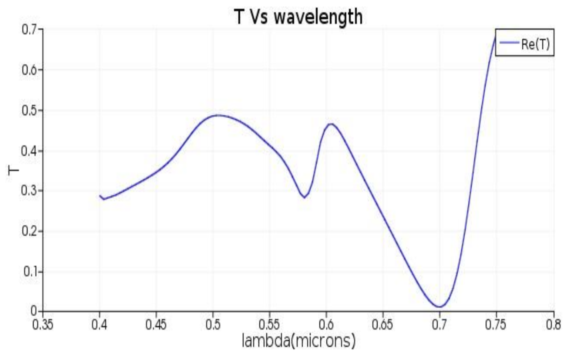
(d)



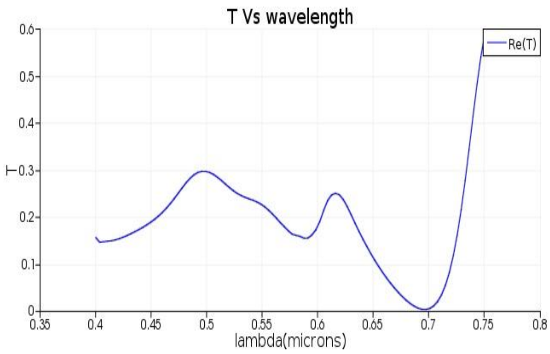
(e)

Figure 6. (a, b and c) transmission, d and e reflection resonance for 4-NHA at t(Au)= (20, 50, 100) nm (*continue*)

We can see that there is a peak value of the wavelength at 519 nm approximately to 73% strong light transmission with 4-NHA in Figure 7(a), in the other hand wavelength of 519 nm transmission is 45% with 9-NHA in Figure 6(a). Strong light transmission is hopeful for using in biological devices with Au/SiO2 interface. In the future, supplementary studies will want to be focused at enlightening the optical frequency modes of transmission and reflection efficiency of NHAs and decreasing BW if NHAs are to be utilized as spectral of filters for biosensors and medical applications.

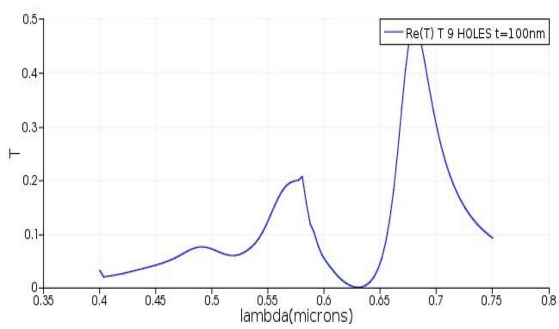


(a)

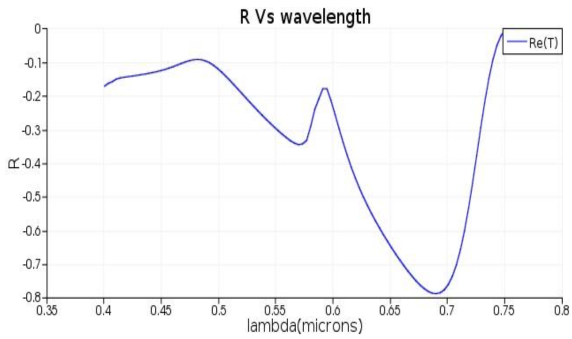


(b)

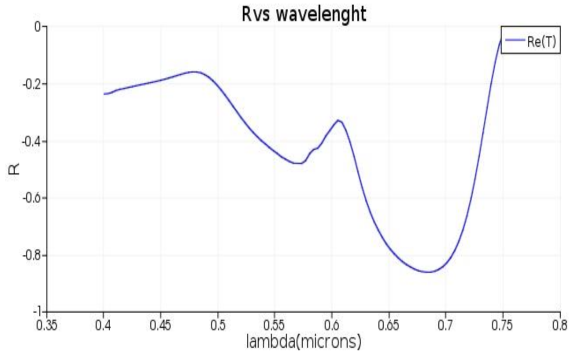
Figure 7. (a, b and c) transmission, d and e reflection resonance for 9-NHA at t(Au)= (20, 50, 100) nm



(c)



(d)



(e)

Figure 7. (a, b and c) transmission, d and e reflection resonance
for 9-NHA at t(Au)= (20, 50, 100) nm (*continue*)

4. CONCLUSION

In this article, we studied the important parameters that effect on the performance optical properties in NHA and surface plasmons like, the noble metals with dielectric layers, different geometrical of NHA with varying thickness and methods of excitation SPs. From the results are observed the effect of holes depth, with consideration the number of holes and P have an influence on SPs interface, transmission is increased at (t=20nm) for two arrays but at 4-holes is greater than 9-holes array, that leads to which one is suitable for biosensors, nanoantennas and biomedical detection systems. With each thickness it is challenging to fabricate the nanoholes NHAs structure because the metal film is too thick for a clean liftoff (typically≥100 nm for Au and ≥300 nm for Ag to make the film "optically thick") [25]. The hole dimensions were known as a chief reason in the attendance of the optical resonance points in the transmission and reflection ranges. There were important modifications between optical transmission fields of NHAs with 4- and 9-hole forms.

REFERENCES

[1] J.N. Anker, W.P. Hall, O. Lyandres, N.C. Shah, J. Zhao, and R.P. Van Duyne, "Biosensing with Plasmonic Nano Sensors," *Nature Materials*, vol. 7(6), pp. 442–453, 2008.
[2] Maier, S., *Plasmonics*, New York: Springer, Ch. 2, pp. 45, 2007.
[3] Alexander G. Bro, Reuven Gordon, Brian Leathem, Karen L. K., "Surface Plasmon Sensor Based on the Enhanced Light Transmission Through Arrays of Nanoholes in Gold Films," *Langmuir*, vol. 20, pp. 4813-4815, 2004.
[4] J.M. McMahon, *et al*., "Tailoring the Sensing Capabilities of Nanoholes Arrays in Gold Films with Rayleigh Anomaly-Surface Plasmon Polariton," *Opt. Express*, vol. 15(26), pp. 18, 2007.
[5] R.B.M. Schasfoort and Anna J., *Handbook of Surface Plasmon Resonance*, ch1, pp. 38, 2008.
[6] Antoine Lesueur, Nathan C. Lindquist, Kwan Seop Lim, and Sang-Hyun Oh, "Plasmonic nanoholes arrays for real-time multiplex biosensing," pp. 703504-10, 2008.
[7] Andreas B. Dahlin., "Sensing Applications Based on Plasmonic Nonporous," *The whole story. Analyst*, vol. 140, pp. 4748–4759, 2015.
[8] L. Wu, P. Bai, X. Zhou, and E. P. Li, "Reflection and Transmission Modes in Nanoholes-Array-Based Plasmonic Sensors," *IEEE Photonics Journal*, vol. 4, no. 1, pp. 26-33, Feb. 2012.

[9] Liz Y. Wu, Benjamin M. Ross and Luke P. Lee, "Optical Properties of the Crescent-Shaped Nanohole Antenna," *Nano Lett, 2009*, vol. 9(5), pp. 1956–1961, 2009.

[10] T. Thio, H. F. Ghaemi, H. J. Lezec, P. A. Wolff, and T. W. Ebbesen, "Surface-Plasmon-Enhanced Transmission Through Hole Arrays in Cr films," *J. Opt. Soc. Am. B*, vol. 16(10), pp. 1743–1748, 1999.

[11] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical Transmission Through Sub-Wavelength Hole Arrays," *Nature*, vol. 391(6668), pp. 667–669, 2018.

[12] N. M. Ridzuan, M. F. L. Abdullah, M. B. Othman, M. B. Jaafar, "A Carrier less Amplitude Phase (CAP) Modulation Format: Perspective and Prospect in Optical Transmission System," *International Journal of Electrical & Computer Engineering(IJECE)*, vol. 8, no. 1 pp. 585-595, Feb. 2018.

[13] Kazi Shahiduzzaman, Majumder F. Haider, Bijoy K. Karmaker, "Terrestrial Free Space Optical Communications in Bangladesh: Transmission Channel Characterization," *International Journal of Electrical & Computer Engineering (IJECE)*, vol. 9, no. 4 part II, pp. 3130-3138, Aug. 2019.

[14] Van der Molen KL, Koerkamp KJK, Enoch S, Segerink FB, van Hulst NF, Kuipers L, "Role of Shape and Localized Resonances in Extraordinary Transmission Through Periodic Arrays of Subwavelength Holes: Experiment And Theory," *Phys Rev B*, vol. 72, pp. 045421, 2018.

[15] Rodrigo SG, García Vidal FJ, Martín-Moreno L, "Influence of Material Properties on Extraordinary Optical Transmission Through Hole Arrays," *Phys Rev B*, vol. 77, pp. 075401, 2008.

[16] Cetin AE, Etezadi D, Galarreta BC, Busson MP, Eksioglu Y, Altug H, "Plasmonic Nanoholes Arrays on a Robust Hybrid Substrate for Highly Sensitive Label-Free Biosensing," *ACS Photon*, vol. 2, pp. 1167–1174, 2015.

[17] N. A. B. Ahmad, S. H. Dahlan, N. A. Cholan, "Theoretical Analysis of a Two-Stage Sagnac Loop Filter using Jones Matrices," *International Journal of Electrical & Computer Engineering (IJECE)*, vol. 7, no. 6, pp. 2950-2957, Dec. 2017.

[18] M. Aljanabi, "Resonance Frequency Analysis of Laser Optical Fiber Based on Microcantilever," *International Journal of Electrical & Computer Engineering (IJECE)*, vol. 9, no. 4, pp. 3090-3099, 2019.

[19] Kunli Xiong and Andreas B, "Biosensing Using Plasmonic Nano Hole Arrays With Small, Homogenous And Tunable Aperture Diameters," *Royal Society of Chemistry*, 2017.

[20] Nadjat Benadla, Kheireddine Ghaffour, "Optimizing The Performance Of Photovoltaic Cells IBC (Contact Back Interdigitated) By Numerical Simulation," *International Journal of Electrical & Computer Engineering (IJECE)*, vol. 9, no. 6, (Part I), pp. 4566-4572, Dec. 2019.

[21] Uzairue Stanley, Victor Matthews Olu, Charles Ochonogor, Amaize Peter, Anyasi Francis, "Experimental Analysis of Cable Distance Effect on Signal Attenuation in Single and Multimode Fiber Optics," *International Journal of Electrical & Computer Engineering(IJECE)*, vol. 8, no. 3, pp, 1577-1582, Jun. 2018.

[22] Hamid Bouyghf, Bachir Benhala, Abdelhadi Raihani, "Analysis of the Impact of Metal Thickness and Geometric Parameters on the Quality Factor-Q in Integrated Spiral Inductors by Means of Artificial Bee Colony Technique," *International Journal of Electrical & Computer Engineering (IJECE)*, vol. 3, no. 1, pp. 2918-2931, 2019.

[23] L. Wu, P. Bai, and E. P. Li, "Designing Surface Plasmon Resonance of Subwavelength Hole Arrays by Studying Absorption," *J. Opt. Soc. Amer. B, Opt. Phys*, 2016.

[24] Andre-Pierre Blanchard-Dionne and Michel Meunier, "Sensing with Periodic Nanohole Arrays," *Advances in Optics and Photonics*, vol. 9, no. 4, pp. 891-940, 2017.

[25] Ali Shaban Hassooni, Murad Obaid Abed, Ehab Abdul Razzaq Hussein, H. J. Abd, "A Mitigation of Channel Crosstalk Effect in Dispersion Shifted Fiber Based on Durability of Modulation Technique," *International Journal of Electrical & Computer Engineering (IJECE)*, vol. 10, no. 1 part II, pp. 891-899, Feb. 2020.