ICEE 2012
20th Iranian Conference on Electrical Engineering
بیستمین کنفرانس مهندسی برق ایران

Excitation of Surface Plasmons in Metallic Thin Films Using Nanoparticle Arrays

Fahimeh Armin
Communications and Computer Research Center
Ferdowsi University of Mashhad
Mashhad,Iran
fahimeh.armin@gmail.com

Mir Mojtaba Mirsalehi
Electrical Engineering Department
Ferdowsi University of Mashhad
Mashhad,Iran
mirsalehi@um.ac.ir

***Abstract*—In this paper, a device for coupling light into symmetric and asymmetric surface plasmon modes in a metallic thin film is presented. This device consists of a two-dimensional periodic array of nanoparticles located above a silver thin film that supports surface plasmons. The nanoparticles and the metallic thin film are embedded in silica. By exciting local surface plasmons in these nanoparticles, light is coupled into the metallic thin film. The coupling process is simulated using finite integration technique. The effects of size of nanoparticles, their distance from the metallic film and the thickness of the metallic film on the coupling are investigated.**

Keywords- Surface plasmons; nanoparticle; light coupling.

I. INTRODUCTION

The history of surface plasmons (SPs) goes back to more than a hundred years ago. Although surface waves had been known to scientists since 1890's, SPs had not been discussed till 1957, when Ritchie first introduced these modes in his pioneering work [1]. Since then, SPs have received significant attention because of their unique characteristics.

The fundamentals of SPs are related to understanding and controlling the interaction between light and metal, which creates the collective oscillations of conduction electrons in metals. SPs are electron charge density waves that are bound to the surface of a conductor [2]. Concentrating and channeling light by subwavelength structures is one of the most interesting aspects of SPs. The fact that they cannot propagate away from the surface has made SPs popular in many fields, such as biosensors and photovoltaic, and also a good candidate for planar waveguides and nanowires [3-6].

The direct coupling of light into SPs is not possible because the wavevector of SPs is larger than the wavevector of the incident light. A conventional technique for exciting SPs is making use of total internal reflection (TIR) made by a prism. The wavevector of the incident light is increased when the light passes through a prism that is located near the metal surface [3]. This technique was introduced by both Kretschmann and Otto. In the geometry proposed by Otto, a prism is located near the dielectric and above the metal film. The light illuminates the interface between the dielectric and the prism with an angle greater than the critical angle of the prism and dielectric and therefore, creates SPs in metal. In Kretschmann geometry which is the most common method of coupling, the prism is interfaced with the metal. The light beam propagates in the prism and illuminates the metal/ prism interface. This illumination excites the SPs at metal/ dielectric interface.

Gratings can also be used to compensate the wavevector and couple light into SPs [5]. This method is based on the diffraction of light on a periodically modulated surface with a period Λ . When a light beam with the wavevector k is incident on this structure, the phase matching condition can be written as [3]

$$k_{sp} = k \sin\theta + m\frac{2\pi}{\Lambda}. \quad (1)$$

where k_{sp} is the wavevector of surface plasmons, $k \sin\theta$ is the in-plane component of momentum of the incident light, and m is an integer which denotes the diffraction order. Equation (1) shows that altering the angle of incident beam can change the SP resonance.

Localized surface plasmons in metallic nanoparticles have been also used for exciting surface plasmons on the surface of a metal with infinite thickness [7]. Other approaches involve using random surface roughness, grooves, and other nanostructures near or on the metal surface.

In this paper, we have studied the use of localized surface plasmons (LSPs) in a two-dimensional array of nanoparticles as a means to excide symmetric and asymmetric SPs in a silver thin film. We have also studied the effects of nanoparticles' shape, dimension and material on the amplitude of the excited SPs. A brief overview of the theory of SPs in metallic thin film is presented in section 2. This section also deals with the nanoparticles and the effect of particle shape on its resonance. Section 3 describes the simulation model and finally the results are provided section 4.

II. SURFACE PLASMONS IN METALLIC THIN FILMS

The Drude model is a simple conceptual and analytical model for explaining general electron transport in metals. In this theory the relative permittivity is calculated by [7]

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\Gamma\omega}. \quad (2)$$

where ω_p is the plasma frequency and Γ is the scattering rate. Refractive index of silver (Ag) can be found in the data set of Jonson and Christy [8] or in the hand book of Palik [9].

By solving Maxwell's equations in a three-layer structure made of a metallic thin film of thickness 2*a,* sandwiched between two identical semi-infinite layers of dielectric as shown in Fig. 1, and exploiting (2), the following equations are obtained [1]

$$\tanh k_m a = -\frac{k_d \varepsilon_m}{k_m \varepsilon_d} \quad (3)$$

$$\tanh k_m a = -\frac{k_m \varepsilon_d}{k_d \varepsilon_m}. \quad (4)$$

where ε_m and ε_d are the permittivities of metal and dielectric, respectively. The parameters k_m and k_d are wavevectors in metal and dielectric and satisfy the following equation:

$$k_{m,d}^2 = \varepsilon_{m,d} (\frac{\omega}{c})^2 - k_{sp}^2. \quad (5)$$

in this equation k_{sp} denotes the SP wavevector:

$$k_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}. \quad (6)$$

equations (3) and (4) describe odd and even modes, respectively.

It can be shown that the odd modes have higher energy and are asymmetric, in contrast with the even modes that are symmetric with lower energy. Theses symmetric and asymmetric modes have interesting characteristics. For example, the propagation length for the symmetric modes will increase as the film thickness is decreased but in contradictory this length will decrease for the asymmetric modes [10]. The same is true for the penetration depth of the SPs in the dielectric. By decreasing the film thickness, asymmetric modes penetrate further in the dielectric, while for the symmetric modes this length is decreased [14].

As it was mentioned above, one way to couple light to SPs is to use nanoparticles. Resonance condition can occur in a nanoparticle when it has dimensions much smaller than the wavelength of incident light. In this situation, the local

Figure 1. Geometry of a three layer structure, the dielectric layers are assumed to be semi infinite

electromagnetic fields in nanoparticle are dramatically enhanced and as a result, the elastic scattering cross section of nanoparticle exceeds its physical cross section. This resonance condition leads to the excitation of localized surface plasmons (LSPs) in a nanoparticle. From this point of view, nanoparticles can act as a resonator for the SPs [12]. Nanoparticls made of noble metals, like silver, gold, and copper can support LSPs. For these noble metals the SP resonance occurs in the visible range of the spectrum.

In contrast to SPs, the incident of light can directly excite LSPs in a nanoparticle. This incident light would be strongly scattered by the particle which can generate a broad range of wavevectors including the wavevector of the desired SP.

For small particles compared to the wavelength of the external field, and under the assumption of homogeneous fields the polarizability of an ellipsoidal nanoparticle α_i can be obtain [13]

$$\alpha_i = \frac{4\pi}{3} abc \frac{\varepsilon_m - \varepsilon_d}{\varepsilon_d + A_i[\varepsilon_m - \varepsilon_d]}. \quad (7)$$

where the subscript i denotes the ellipsoidal axis. The parameters *a*, *b* and *c* are the ellipsoidal radiuses and A_i is a shape dependant constant which depends on the aspect ratio of the particle and the polarization of the incident field. For a nanosphere this constant is equal to 1/3. According to this equation, a resonance occurs when the polarizability is maximized, i.e., when the denominator in (7) is equal to zero. For a nanosphere, this means that the magnitude of the real part of metal's permittivity should be equal to $-2\varepsilon_d$.

As can be concluded from (7) resonance for an ellipsoidal particle depends on more factors, the dielectric function of the surrounding medium, the dielectric function of the metal, and most important of all on particles aspect ratio. In comparison to spherical nanoparticles, the resonance of an ellipsoidal nanoparticle is shifted to red if the polarization of the incident light is parallel to the long axis and it is shifted to blue if the polarization is parallel to the short axis of the ellipsoid. Equation (7) shows that LSPs like SPs are strongly dependent on shape, dimension, composition of metal and the type of dielectric that surrounds the metal.

III. SIMULATION MODEL

Figure 2 shows a schematic diagram of the structure that is studied here. It consists of a two-dimensional array of nanoparticles located above a silver thin film. Both sides of this thin film are covered by SiO_2 which acts as the dielectric for this plasmonic structure. The nanoparticles are arranged in a two-dimensional array. This array is also embedded in SiO_2 and is located above the metallic film. The thickness of the film is chosen to support symmetric or asymmetric modes

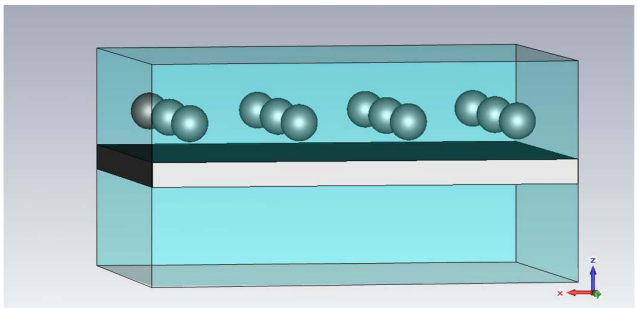

Figure. 2. A schematic diagram of a three layer structure with a two-dimensional array of nanoparticles

along the film. The spacing between the nanoparticles is also important because these particles scatter light in all directions and therefore, the spacing should be chosen properly to prevent near field coupling between nanoparticles. Otherwise, coupling between the particles makes them to behave like a waveguide which obviously does not lead to the expected results. However, this near field coupling may be beneficial for channeling light or making optical switches [14].

The technique used to simulate the structure was finite integration technique (FIT) applied in CST Microwave Studio [13]. Figure 3 shows a schematic of the volume used in this simulation. Along the *x-y* plane, the silver film and the metallic nanoparticle array are assumed to be extended infinitely. Because of the symmetry of the structure only ¼ of the nanoparticle along with the metallic film is considered for simulation. The boundary conditions are chosen to model such infinite structure. In the *x-z* plane, the magnetic boundary conditions at $y=0$ and at $y=ly$, and in the *y-z* plane, the electric boundary condition at $x=0$ and at $x=lx$ were applied, while in the *x-y* plane, the open boundary conditions were used at $z=lz$ and $z=-lz$. Considering these boundary conditions, we can simulate a finite 3D structure instead of an infinite structure and get the same result.

A value of 2.21 was chosen for the dielectric constant of SiO_2 while the dielectric constant of silver film cannot be set to a constant value and should be described by Drude model.

IV. Simulation Results

In the first set of simulations, the film thickness was changed from 10 to 50 nm while the radius of particles was set to 30 nm. The electric field, E_z was found as a function of time at a location where the electric field is maximum. The electric field, E_z is shown in Fig. 4 for a spherical particle near the metal surface. The excitation signal ends before 0.02 ps but E_z extends for more than 0.2 ps. This indicates the electromagnetic resonance of the system. Using Fourier transform of this time domain signal, the resonance frequency of each thickness is obtained and plotted in Figs. 5 and 6. These results show that film thickness is an important factor in both resonance frequency and amplitude of electric field. The results demonstrated in Fig.5 suggest that resonance frequency increases with the increasing film thickness. The amplitude of electric field in Fig. 6 has been normalized to the amplitude of incident wave.

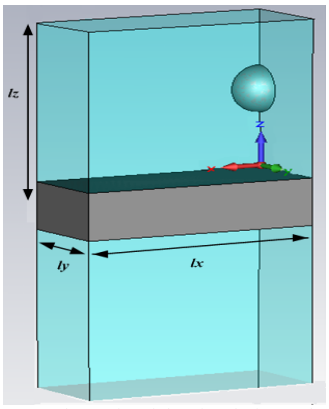

Figure 3. A schematic of the simulation volume

In the next set of simulations, the effect of the nanoparticles distance from the metallic film was investigated. The results for an array with nanoparticles with radii of 30 nm have been shown in Figures 7 and 8. Figure 7 shows that distance of the nanoparticle from the metallic film has a direct effect on the amplitude of electric field, E_z. The amplitude of electric field decreases as the nanoparticle array moves away from the metallic film. The same is true for the resonance frequency of SPs. The resonance frequency decreases as the nanoparticle array moves away from the metallic film. However the change in the resonance frequency related to the distance of the array from the metallic film is not significant.

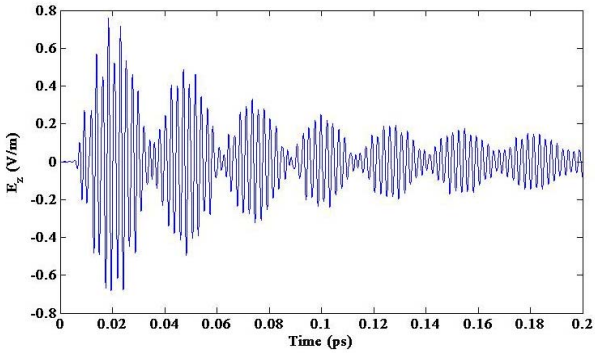

Figure 4. Electric field, E_z for spherical nanoparticles with radii 30 nm, Note that the excitation signal ends before 0.02 ps.

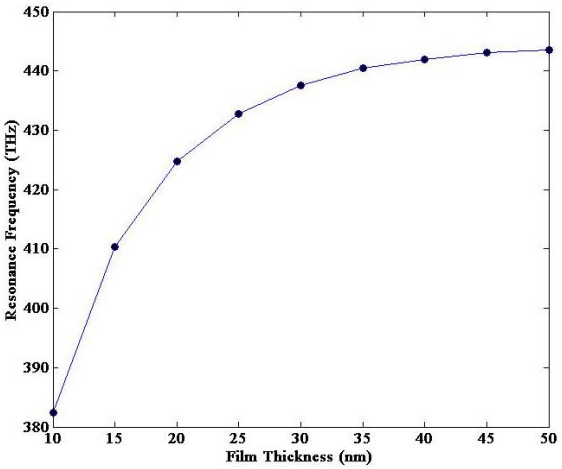

Figure 5. Resonance frequency versus film thickness for nanoshperes with radii of 30 nm located 80 nm above the metal film

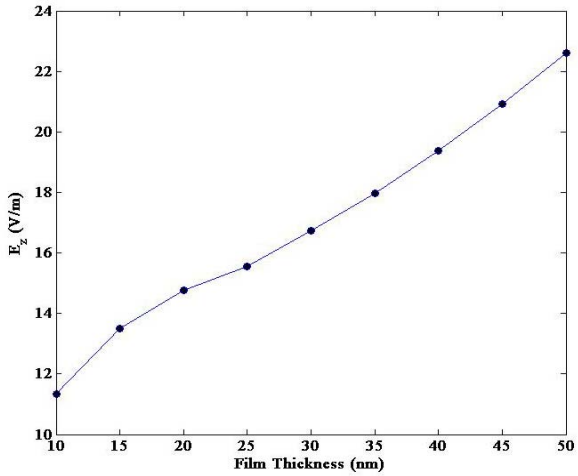

Figure 6. Normalized amplitude of E_z signal versus film thickness for nanoshperes with radii of 30 nm located 80 nm above the metal film

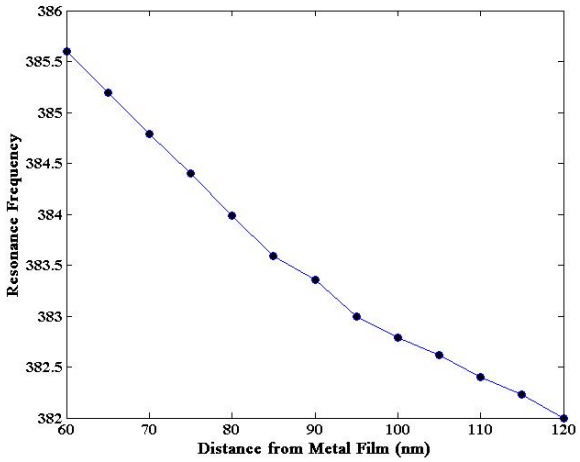

Figure 7. Resonance frequency versus distance of an array of nanoparticles with radii of 30 from the metallic film with a thickness of 10nm

Figure 9 shows the simulation result for the different size of the nanoparticles in the array. These results suggest that that the size of the particles can also affect the on the amplitude of electric field, E_z. the amplitude of electric field has increased whit the increasing of the radii of the particles in the array.

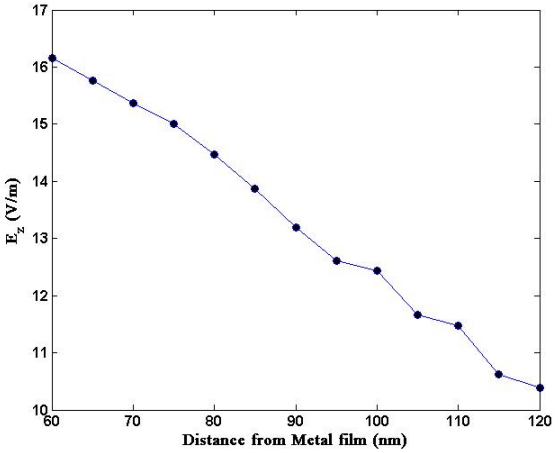

Figure 8. Normalized amplitude of E_z signal versus distance of an array of nanoparticles with radii of 30 from the metallic film with a thickness of 10nm

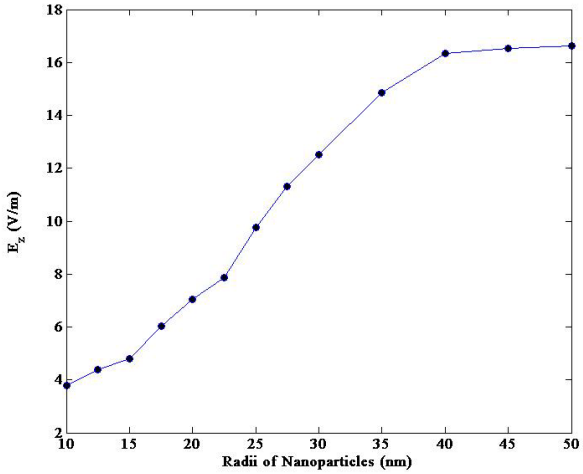

Figure 9. Normalized amplitude of E_z signal versus radii of the particles in the array located 80 nm above the metal film with a thickness of 10 nm

These simulations show that the amplitude and frequency of the coupled wave in metal dielectric interface depends on film thickness, distance of nanoparticles from metallic film and the size of the nanoparticle.

Another parameter which can affects the coupling, as mentioned before, is the spacing between nanoparticles. Figure 10 shows the simulation results for this parameter which indicates that as the spacing between the nanoparticles increases the resonance frequency uniformly decrease.

V. CONCLUSIONS

A two-dimensional array of silver nanoparticles embedded in silica for coupling light in symmetric and asymmetric surface plasmons in a thin silver film was studied. Numerical simulations indicate that this two-dimensional array can be used as a coupling device for surface plasmons in metallic thin films. It has been shown that different parameters such as nanoparticles size, film thickness and distance of the particles from the film, affect the amplitude and frequency of the surface plasmons. These observations suggest that the amplitude and frequency of the surface plasmons on metallic thin films can be tuned by using these parameters.

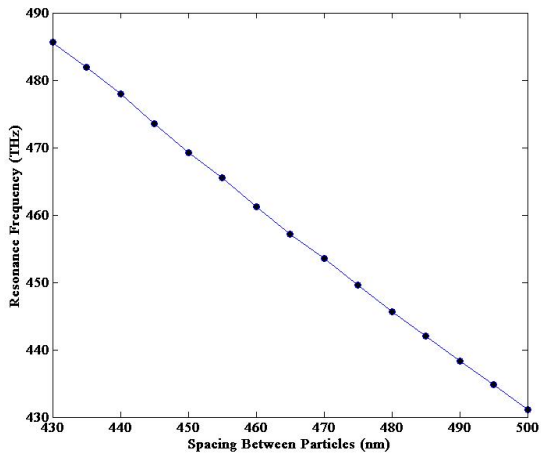

Figure 10. Resonance frequency versus spaces between the nanoparticles, located 80 nm above a metal film with a thickness of 10 nm

REFERENCES

[1] R. H. Ritchie, "Plasma losses by fast electrons in thin films," *Phys. Rev.*, vol. 106, no. 5, pp. 874–881, 1957.

[2] S.A. Maier, *Plasmonics: Fundamentals and Application*, London, United Kingdom: Springer, 2007.

[3] J. Homola, "Electromagnetic theory of surface plasmons," in *Springer Series on Chemical Sensors & Biosensors*, O. S. Wolfbeis, vol.4, Berlin, Heidenberg: Springer, 2006, pp.1-19.

[4] K. R. Catchpole, A. Polman, "Plasmonic solar cells," *Optics Express,* vol. 16, no. 26, pp. 21793-21800, 2008.

[5] L. S. Mukina, M. M. Nazarov and A. P. Shkurinov. "Propagation of THz plasmon pulse on corrugated and flat metal surface," *Surface Science*, vol. 600, no. 20, pp.4771-4776, Oct. 2006.

[6] J. Dorfmuller, R. Vgelgesang, W. Khunsin, C. Rockstulh, C. Etrich and K. Kern, "Plasmonic nanowire antennas: Experiment, simulation, and theory," Nano Lettes, DOI: 10.1021/nl101921y.

[7] A. Ghoshal and P. Kik, "Theory and simulation of surface plasmon excitation using resonant metal nanoparticle arrays," *Journal of Applied Physics*, vol. 103, pp. 113111-113119, 2008.

[8] P. B. Johnson and R.W. Christy, "Optical constants of the noble metals," *Phys. Rev. B*, vol. 6, pp. 4370-4379, 1972.

[9] E. D. Palik, *Handbook of Optical Constants of Solids,*Washington DC: Academia Press Inc., 1985.

[10] W. Barnes, "Surface plasmon-polariton length scale: a route to sub-wavelength optics," *Journal of Optics A*, vol. 8, no.4, pp. 87-93, 2006.

[11] J. Dionne, L. Sweatlock and H. Atwater, "planar metal Plasmon waveguides: frequency- dependent dispersion, localization, and loss beyond the free electron model," *Physical Review B*, vol. 72, pp. 405-415, 2005.

[12] J. Mock et al,"Distance-dependant plasmon resonant coupling between a gold nanoparticle and gold film," *Nano Letters*, vol. 8, no. 8, pp. 2245-2252, 2008.

[13] A. Hohenau, A. Leitner and F. Aussenegg, "Near-field and far-field properties of nanoparticle arrays," in *Surface Plasmon nanophotonics*, 1ed., M. Brongersma, P. Kik and Ed. Dordretch, Netherland: Springer, 2007, pp 11-25.

[14] S. A. Maier, M. L. Brongersma, P. G. Kik, S. M. Meltzer, A. G. Requicha and H.A. Atwater, "Plasmonics- a rout to nanoscale optical devices," *Adv. Matter*, vol. 13, pp. 1501-1505, 2001.

[15] http://www.cst.com/