Proceedings of Papers – 5th International Conference on Electrical, Electronic and Computing Engineering, IcETRAN 2018, Palić, Serbia, June 11 – 14, 2018 ISBN 978-86-7466-752-1

Customization of evanescent near fields on freestanding plasmonic nanomembranes

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***Abstract*—For a very long time optical evanescent near fields have been considered useless for practical applications and remained a theoretical curiosity. However, with advances in micro and nanotechnologies and the decreasing sizes of the photonic devices there came a need to overcome diffractive limit which sparked a practical interest in these previously overlooked field components. With the discovery of Surface Plasmon Polaritons (SPP), bound surface modes propagating along interfaces between materials with different signs of relative dielectric permittivity and being evanescent in the direction perpendicular to the interface a path was open to actively design spectral and spatial properties of near fields. Now plasmonic metamaterials and evanescent near fields are used not just for imaging beyond diffractive limit but also in transformation optics, biochemical sensing, cloaking devices, photonic integrated circuits, etc. Freestanding plasmonic nanomembranes are fairly simple and yet highly versatile structures which can be utilized in practically any of the fields of application of plasmonics, making them an ideal platform to build upon. In this paper we present a novel structural design as a means for customizing and tailoring the near field response of multilayer freestanding nanomembranes. To this purpose ellipsoidal diffractive "bumps" are built into the nanomembrane as the coupling elements between freely propagating and evanescent modes.**

***Index Terms*— Plasmonics; Nanomembranes; Optical Multilayers; Metamaterials; Nanophotonics**

I. INTRODUCTION

PLASMONICS is a field of electromagnetics that is constantly widening our understanding of light-matter interaction. Many of the effects previously considered impossible like negative index of refraction or transmission of light through subwavelength apertures were proven possible in plasmonic structures [1, 2]. This however is not limited to just exploring the phenomena, unconventional properties of these structures resulted in them being used as chemical and biological sensors [3], superabsorbers, superlenses [4], invisibility shields (cloaking devices) [5], photonic integrated circuits [6], etc. This uniqueness of plasmonic structures stems from their unparalleled ability to manipulate evanescent near fields practically enabling us to tailor light at will (transformation optics) [7].

The simplest case of a plasmonic structure is a single interface between metal and dielectric [8]. The interface acts as a waveguide for an electromagnetic wave coupled with oscillations of free electron plasma in the metal. Such a bound hybrid mode is known as the surface plasmon polariton (SPP). SPPs are evanescent in the direction perpendicular to the interface and exist outside of the light cone. This means that SPPs are waves with large wave vectors or in other words extremely short wavelengths which together with evanescence results in high field localizations on the subwavelength scale close to the interface [9].

Freestanding nanomembranes represent the next step in increasing the complexity of plasmonic structures and they can be as simple as a nanometer-thin metallic sheath surrounded by dielectric (usually air). A particularly interesting property of this type of structures due to their electromagnetic symmetry is coupling of SPPs from both sides of the sheath resulting in splitting of the resonant mode into even and odd states [8]. The odd states have much smaller field penetration depth into metal compared to SPPs resulting in even larger propagation constants, which is known as long range (LR) SPP [10]. This kind of approach can be taken further by forming a plasmonic crystal consisting of alternating thin metallic and dielectric (or another metal) layers resulting in spectral dispersive properties with some of the allowed bands exhibiting unique properties like negative group velocity [11].

Since SPPs exist outside of light cone coupling of incident light to these modes requires some form of impedance matching between the two. Utilizing diffractive gratings for this purpose allows not only for coupling between propagating modes and SPPs but also allows for tailoring of dispersive properties by changing the geometrical properties of the grating. The most common way to embed diffractive grating into a plasmonic structure is to etch an array of subwavelength openings or channels into sheet metal or plasmonic crystal. Plasmonic modes of these structures are characterized by high

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field localization within subwavelength openings [12].

In this paper we utilize COMSOL Multiphysics RF module to analyze a freestanding plasmonic nanomembrane with embedded diffractive grating complementary to those commonly used. In our case the diffractive grating is embedded within the structure via an array of subwavelength protrusions instead of apertures, with additional thin layers of metal and dielectric deposited over the membrane. Furthermore we use an asymmetric design for our structure i.e. the first and the last layer of the structure are not of the same material. The unit cell of our proposed structure is shown in Fig.1.

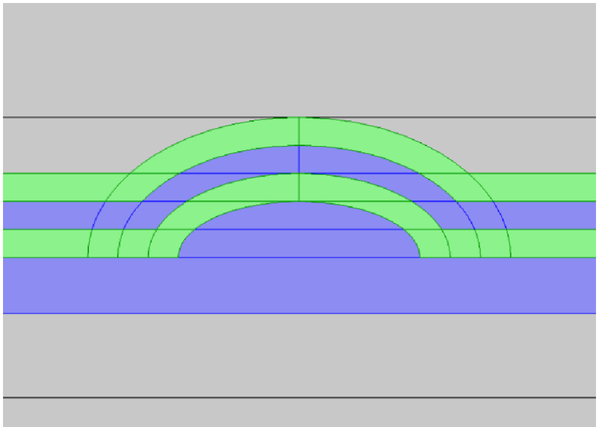

Fig. 1. Metal-dielectric multilayer freestanding nanomembrane with embedded diffractive grating. Blue layers denote metal, green layers are dielectric, surrounding medium is air (gray).

II. Theory

Electromagnetic properties of most metals in the optical range are well described by the lossy extended Drude model. The complex relative dielectric permittivity $\varepsilon(\omega)$ of metals is given by the following dispersion relation [8]:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^{\ 2}}{\omega^2 + i\gamma\omega}, \tag{1}$$

ε_∞ is the asymptotic dielectric permittivity and $\gamma=1/\tau$ is the characteristic frequency related to the damping of electron oscillations due to collisions, where τ is the relaxation time of the electron gas and plasma frequency is determined by the concentration of free carriers

$$\omega_p = \frac{ne^2}{m^*\varepsilon_0} \tag{2}$$

where n is electron concentration, e is the free electron charge ($1.6\cdot10^{-19}$ C), ε_0 is the dielectric permittivity of the vacuum ($8.854\cdot10^{-12}$ F/m), and m^* is the electron effective mass.

Dispersion relation of SPP propagating on a metal-dielectric interface is given by [1]:

$$k_{spp} = k_0\sqrt{\frac{\varepsilon_d\varepsilon_m}{(\varepsilon_d+\varepsilon_m)}} \tag{3}$$

where $k_0=2\pi/\lambda$ is the wavevector in vacuum, ε_d is the relative permittivity of dielectric and ε_m is the relative permittivity of metal described by Drude model (1).

As stated earlier, coupling between propagating waves and SPP bound on metal-dielectric interface can be achieved utilizing diffractive gratings. The difference between SPP and propagating wavevectors is matched by the diffracted modes of the grating. The wave vector of the diffracted mode is determined by the diffractive grating constant a:

$$k_d = \pm m\frac{2\pi}{a} \tag{4}$$

where m is an integer. Coupling of the propagating wave with the SPP occurs when following condition is met:

$$\vec{k}_{spp} = \vec{k}_d + \vec{k}_p \tag{5}$$

where k_p is the wavevector of the propagating wave inplane parallel to the interface

$$k_p = \frac{\omega}{c}\sin\theta \tag{6}$$

where c is the speed of light in the medium above the plasmonic surface, ω is the angular frequency and θ is the incident angle.

III. Results and Discussion

We examined optical properties of the freestanding nanomembrane described in Fig. 1. using RF module of Comsol Multiphysics software package. The width of the entire unit cell is a = 800 nm which is also equal to the embedded diffractive grating period. The central detail (protrusion) is modeled as a half of an ellipse with 100 nm and 200 nm semi axes. The bottom most metallic layer is 100 nm thick, while the additional layers of metal and dielectric (top three layers) are 50 nm thick. The structure is surrounded by air. Metal is chosen to be nickel with Drude model parameters taken from the literature [13] and dielectric is polymer with a refractive index n=1.4.

Our numerical simulation calculates spatial field distributions as well as scattering parameters for plane waves incident on the structure at various angles. Two parallel ports were added above and below the structure to introduce and collect electromagnetic radiation within the simulation domain. The active port is positioned above the structure so the light enters the domain from the top. Floquet boundary conditions are applied to the edges of the unit cell perpendicular to the layers to simulate periodicity of the structure. The parametric sweep of the wavelengths and incident angles was used to determine the dispersive properties of the scattering parameters and the spatial distributions of the electromagnetic field.

The dispersive properties of the structure are shown in Fig. 2. Since there is practically no transmission through the

ISBN 978-86-7466-752-1

structure resonant dips in the reflection are associated with coupling of the incident light to the surface modes. For normal incidence the structure supports the least number of surface modes in an observed spectral range as shown in Fig. 2.a with two significant resonant dips at 450 nm and 610 nm. For oblique incidence shown in Fig.2.b and Fig.2.c for 30º and 60º incidence angles respectively structure exhibits rich modal behavior.

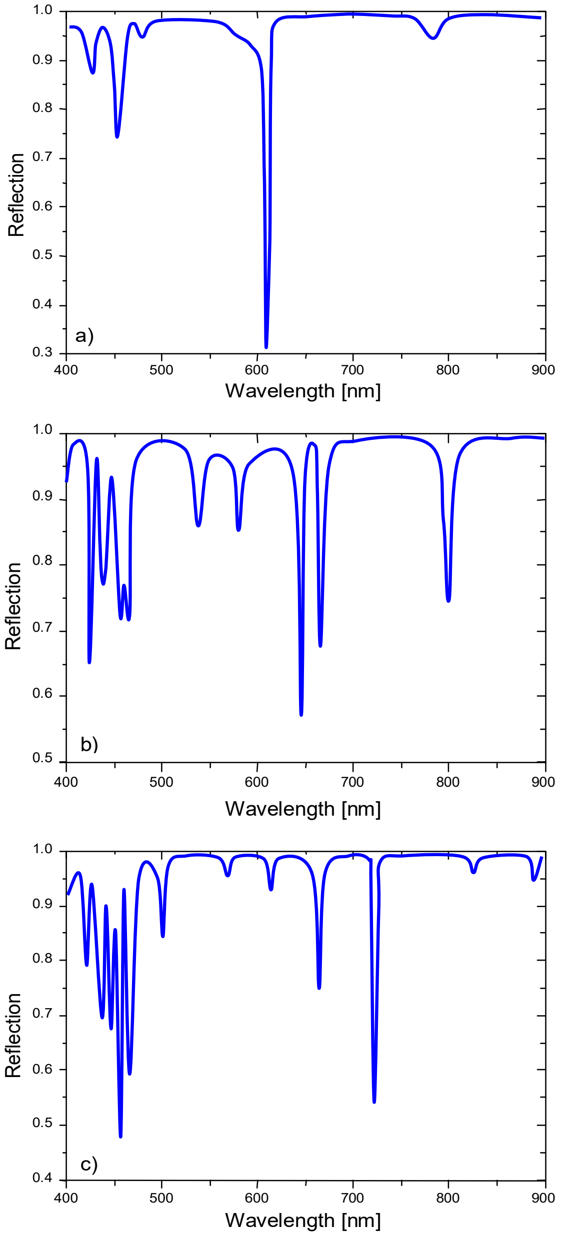

Fig. 2. Dispersive properties of nickel-polymer multilayer freestanding nanomembrane for different incident angles: a) normal incidence; b) 30º incident angle; c) 60º incident angle

Spatial field distributions for some of the resonant peaks are shown in Fig.3-6. Additionally, Figs. 3-6. show power flow (Pointing vector) through the structure. What is most interesting is that the evanescent near fields on the surface of the structure are primarily localized on the air-dielectric interface or in other words dielectric-dielectric (D-D) interface instead on the metal-dielectric (M-D) interface. What we have is that the light "sees" everything below the first interface as a single material with metallic properties. This of course is the very definition of metamaterials and effective parameters and is nothing new in itself, but in terms of plasmonic excitations and evanescent near fields it has been primarily observed for static plasmonic modes i.e. localized surface plasmon resonance (LSPR) on core-shell particles. Considering that the design of the structure mimics core-shell particles, its optical response follows the same suite but for propagating modes. A further examination of the power flow also supports this notion, Fig. 4 being a particularly good example, where power flow follows both M-D and D-D interfaces but both evanescent fields and power flow are predominantly bound to D-D interface.

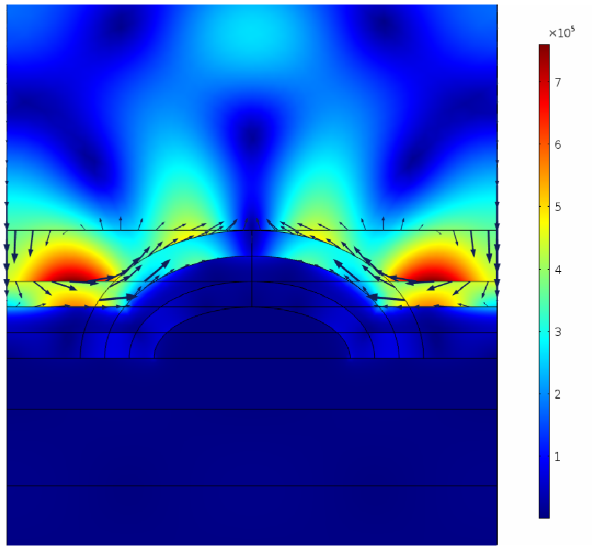

Fig. 3 Electric field spatial distribution for normal incidence at 610 nm. Arrows denote power flow through the structure.

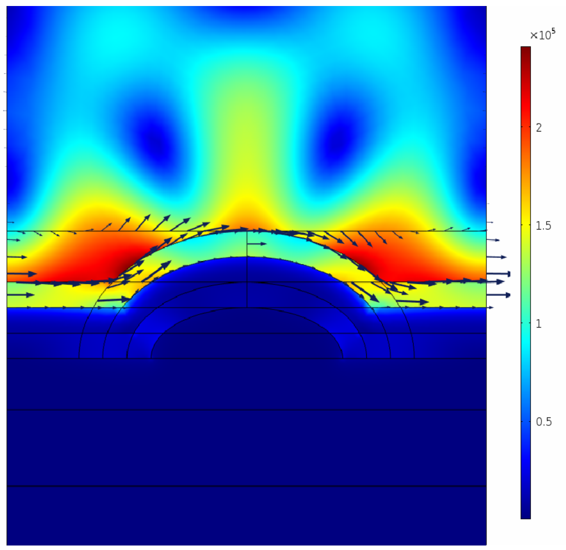

Fig. 4 Electric field spatial distribution for 30º incident angle at 670 nm. Arrows denote power flow through the structure.

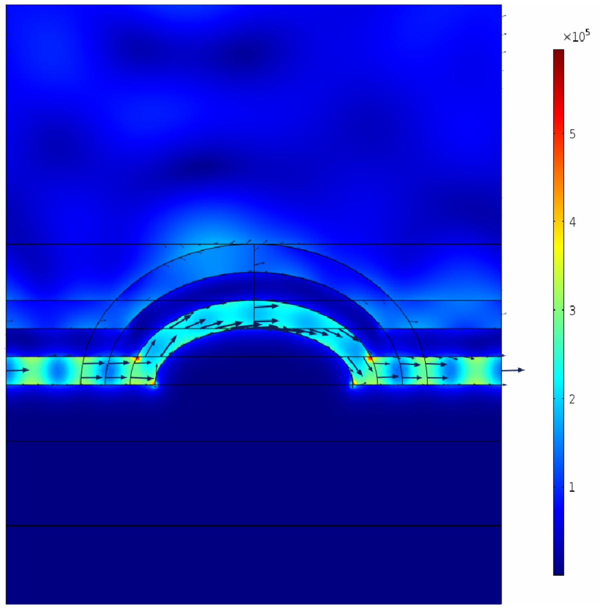

Fig. 5. Electric field spatial distribution for 30º incident angle at 425 nm. Arrows denote power flow through the structure.

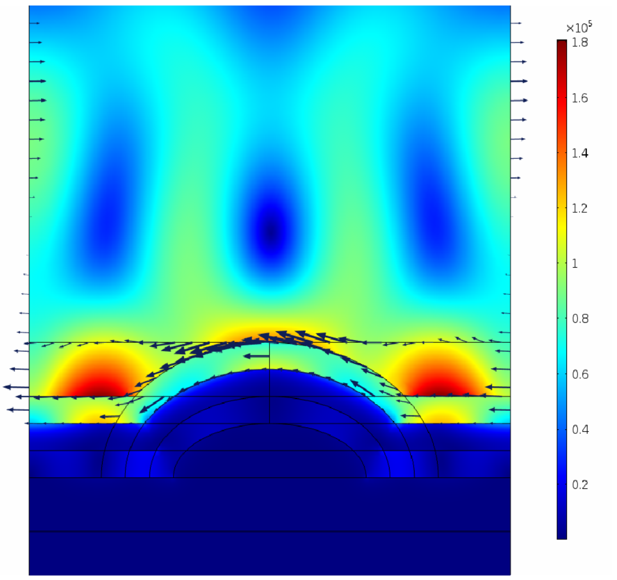

Fig. 6. Electric field spatial distribution for 60º incident angle at 660 nm. Arrows denote power flow through the structure.

An additional advantage of our design is that the bound plasmonic modes of the structure are not limited to the surface of the structure, as shown in Fig. 5 where light is localized within a dielectric channel sandwiched between two nickel layers offering an additional degree of freedom in customizing evanescent near fields.

Another interesting observation can be made from Fig. 6. The light enters the simulation domain from top to bottom and with an increase of the incident angle in the plane parallel to the layers light flows from left to right and when light couples to propagating surface modes they follow the surface but also flow from left to right Fig. 4-5. The light flows from left to right in Fig. 6 away from the surface but the surface bound modes flow from right to left exponentially decaying with distance from the surface. This is of course because coupling is achieved by the backwards scattered wave on the protrusion due to a steep incident angle but provides for a very interesting situation which closely resembles negative refraction.

IV. Conclusion

We analyzed optical properties of a nickel-polymer multilayer freestanding nanomembrane. We have shown that our structure exhibits similar properties of evanescent near fields as core-shell nanoparticles only associated with propagating surface modes allowing us to further customize the near field response. By utilizing asymmetric design with the first layer of the structure being dielectric and the last layer metal we have shown that it is possible to further push light localization from the metal into the purely dielectric part of the structure. The main focus of our further research will be utilization of our results as a possible solution in minimizing high material losses in plasmonic structures associated with metals.

Acknowledgment

This work was supported by the Serbian Ministry of Education, Science and Technological Development under Project TR32008.

References

[1] 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, no. 6668, pp. 667-669, 1998.

[2] V. M. Shalaev, W. Cai, U. K. Chettiar, H.-K. Yuan, A. K. Sarychev, V. P. Drachev, and A. V. Kildishev, “Negative index of refraction in optical metamaterials,” *Opt. Lett.*, vol. 30, no. 24, pp. 3356-3358, 2005.

[3] X. Zhang, Z. Li, S. Ye, S. Wu, J. Zhang, L. Cui, A. Li, T. Wang, S. Li, and B. Yang, “Elevated Ag nanohole arrays for high performance plasmonic sensors based on extraordinary optical transmission,” *J. Mat. Chem.*, vol. 22, no. 18, pp. 8903-8910, 2012.

[4] K. Aydin, V. E. Ferry, R. M. Briggs, and H. A. Atwater, “Broadband polarization-independent resonant light absorption using ultrathin plasmonic super absorbers,” *Nature Comm.*, vol. 2, pp. 517, 2011.

[5] M. Kadic, S. Guenneau, and S. Enoch, “Transformational plasmonics: Cloak, concentrator and rotator for SPPs,” *Opt. Express*, vol. 18, no. 11, pp. 12027-12032, 2010.

[6] E. Ozbay, “Plasmonics: Merging Photonics and Electronics at Nanoscale Dimensions,” *Science*, vol. 311, no. 5758, pp. 189-193, 2006.

[7] J. B. Pendry, D. Schurig, and D. R. Smith, “Controlling electromagnetic fields,” *Science*, vol. 312, no. 5781, pp. 1780-1782, 2006.

[8] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer Science+Business Media, New York, NY, 2007.

[9] W. L. Barnes, A. Dereux, and T. W. Ebbesen, “Surface plasmon subwavelength optics,” *Nature*, vol. 424, no. 6950, pp. 824-830, 2003.

[10] P. Berini, “Long-range surface plasmon polaritons,” *Adv. Opt. Photon.*, vol. 1, no. 3, pp. 484-588, 2009.

[11] S. M. Vuković, Z. Jakšić, I. V. Shadrivov, and Y. S. Kivshar, “Plasmonic crystal waveguides ” *Appl. Phys. A*, vol. 103, no. 3, pp. 615-617, 2011.

[12] F. J. Garcia-Vidal, L. Martin-Moreno, and J. B. Pendry, “Surfaces with holes in them: new plasmonic metamaterials,” *J. Opt. A-Pure Appl. Opt.*, vol. 7, no. 2, pp. S97-S101, 2005.

[13] A. D. Rakić, A. B. Djurišić, J. M. Elazar, and M. L. Majewski, “Optical properties of metallic films for vertical-cavity optoelectronic devices,” *Appl. Opt.*, vol. 37, no. 22, pp. 5271-5283, 1998.