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There were 247 submissions. Each submission was reviewed by at least 1, and on the average 2, reviewers. The committee decided to accept papers as follows. Invited papers are included and presented as papers in Sessions.

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- **Special Session dedicated to academician Rajko Tomović**

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- **Special Session: New Materials**

Moderators:
Corresponding member SASA Velimir Radmilović: **Decoupling of Electrical and Thermal Properties in Nanostructured Materials;**

Prof. Vladimir Srdić: **Ultrafast Spin Dynamics in Multiferroic Oxides;**

Prof. Petar Uskoković: **Synthesis and Supercapacitive performances of Electrospun Carbon Nanofibers Decorated with Spinel $Co_{1.5}Mn_{1.5}O_4$ Nanocrystals**

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August 27, 2019

Belgrade

Boris Loncar

Reversed ellipsoidal troughs sculpted in plasmonic multilayer nanomembranes

Marko Obradov, Zoran Jakšić, *Senior Member, IEEE* , Ivana Mladenović, Dragan Tanasković, Dana Vasiljević Radović

***Abstract*—Nanomembranes represent a versatile novel building block in micro- and nanoelectromechanical systems, inspired by biological cell membranes. If built as quasi-2D multilayer metal-dielectric nanocomposites, they represent a natural choice for the use in plasmonics and optical metamaterials, ensuring a new degree of design freedom and thus a number of new applications.**

In this contribution we consider surface sculpting of two types of three-layer nanomembranes – metal-insulator-metal (MIM) and insulator-metal-insulator (IMI) structures. The geometry we analyze represents troughs with ellipsoidal profiles sculpted in the multilayer nanomembranes, simultaneously acting as plasmonic waveguides and ensuring tailoring of frequency dispersion of the plasmonic nanomembranes.

We determine frequency dispersions of the scattering parameters for the simulated nanomembranes, as well as the spatial ditribution of the optical near fields in and around them, both evanescent (plasmon-polariton based) and propagating. To this purpose we utilize finite element method simulations.

The obtained results show that our IMI structures exhibit a behavior similar to that of the EOT arrays, resulting in optical transparency of the structure for resonant plasmonic modes. On the other hand, MIM structures offer an excellent confinement of electromagnetic radiation within the dielectric layer. We conclude that both MIM and IMI channels allow for additional degrees of freedom in customization the nanomembrane evanescent fields, making a way to numerous potential applications.

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

Marko Obradov is with Centre of Microel. Technologies, Institute of Chemistry, Technology and Metallurgy, University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia (e-mail: marko.obradov@nanosys.ihtm.bg.ac.rs).

Zoran Jakšić is with Centre of Microelectronic Technologies, Institute of Chemistry, Technology and Metallurgy, University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia (e-mail: jaksa@nanosys.ihtm.bg.ac.rs).

Ivana Mladenović is with Centre of Microelectronic Technologies, Institute of Chemistry, Technology and Metallurgy, University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia (e-mail: ivana@nanosys.ihtm.bg.ac.rs).

Dragan Tanasković is with Centre of Microelectronic Technologies, Institute of Chemistry, Technology and Metallurgy, University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia (e-mail: dragant@nanosys.ihtm.bg.ac.rs).

Dana Vasiljević Radović is with Centre of Microelectronic Technologies, Institute of Chemistry, Technology and Metallurgy, University of Belgrade, Njegoševa 12, 11000 Belgrade, Serbia (e-mail: dana@nanosys.ihtm.bg.ac.rs).

I. INTRODUCTION

SYNTHETIC NANOMEMBRANES are artificial, biologically inspired, freestanding, self-supported structures resembling bilipid cell membranes but offering a much wider choice of materials, surface patterns and profiles [1]. They are quasi-2D structures, meaning that their aspect ratios can be huge – their widths and lengths can be even six to seven orders of magnitude larger than their thickness [2]. The possibility to functionalize nanomembranes [3] opens a pathway towards myriads of pratical applications. One of the possible approaches to such functionalization is 3D surface sculpting of nanomembranes, as proposed in [4] and described in more details in [3].

Plasmonic nanomembranes represent mono- or multilayer structures that can be described as 1D plasmonic crystals [5]. They consist of one or more of conductive materials whose electron dynamics is described by Drude model, with possible incorporation of dielectric(s). Freestanding plasmonic nanomembranes represent a new building block in photonics, subwavelength optics and plasmonics and they can be as simple as a nanometer-thin metallic sheath surrounded by dielectric (air). The subwavelength thickness of nanomembranes together with their electromagnetic symmetry ensures coupling of surface plasmons polaritons (SPP) from their both sides, resulting in the appearance of the SPP with extremely large propagation paths. Such SPPs are known as long range (LR) SPPs [6].

Similarly to metamaterials and nanoplasmonic structures, plasmonic nanomembranes exhibit peculiar phenomena, many of which are not met in natural materials, including extremely high values of refractive index, very low and zero values, as well as negative refractive index. It may be safely said that plasmonic nanomembranes enable one to manipulate evanescent near fields, practically making it possible to tailor light at will. A whole new field of electromagnetic optics developed from these properties – the transformation optics [7, 8]. This on the other hand ensures various applications like ultrasensitive chemical and biological sensors with single-molecule sensitivity, superlenses and hyperlenses, superabsorbers, superconcentrators, invisibility shields (cloaking devices), all-optical integrated circuits, and many more [9].

Since SPPs exist outside of light cone coupling of incident light to these modes requires some form of impedance matching between the two. The use of diffractive gratings for this purpose ensures not only coupling between propagating modes and SPPs but also allows tailoring of dispersive properties by changing the geometrical properties of the grating. Plasmonic modes of these structures are characterized by high field localization within subwavelength openings.

The analysis of plasmonic nanomembranes integrated with diffractive couplers is of large practical interest since it gives us data on the optimum ways of coupling between evanescent modes of LR SPP and propagating light. More generally, it ensures tailoring of frequency dispersion including the determination of modes that simultaneously exist within the light cone an outside of it.

Fig. 1. General presentation of a sculpted nanomembrane with a diffractive grating formed by an array of reversed troughs with ellipsoidal profiles.

In this contribution we analyze a specific geometry of plasmonic nanomembrane integrated with a diffractive grating. The case we analyze is represented in Fig. 1. It shows troughs with ellipsoidal cross-section sculpted in the surface of a nanomembrane. Contrary to [10], here we analyze both IMI and MIM multilayer nanomembranes. To this purpose we utilize COMSOL Multiphysics RF module. We analyze a freestanding plasmonic nanomembrane with embedded diffractive grating. The unit cell of our proposed structure is shown in Fig. 2.

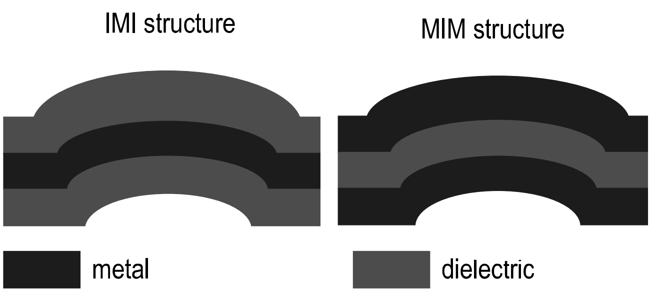


Fig. 2. Cross section view of unit cell of a corrugated multilayered freestanding nanomembrane. Insulator-metal-insulator (IMI) structure (left) and metal-insulator-metal (MIM) structure (right).

II. Theory

For most conductors based on free electrons their electromagnetic properties in the optical range are well described by lossy extended Drude model. The frequency dispersion of ther complex relative dielectric permittivity $\varepsilon(\omega)$ is given by the following relation [11]:

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

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 ($1.6 \cdot 10^{-19}$ C), ε_0 is the dielectric permittivity of the vacuum ($8.854 \cdot 10^{-12}$ F/m), and m^* is the effective mass of electrons.

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

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

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).

Coupling between propagating waves and SPP bound on metal-dielectric interface can be achieved by different impedance-matching techniques. By embedding diffractive gratings in the metal-dielectric interface, the impedance matching between SPP and propagating waves is achieved through the diffracted modes of the grating. The wave vector of the diffracted mode is determined by the 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 the following condition is met:

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

where k_p is the wavevector of the wave propagating in-plane, 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 of the propagating modes.

For multilayered metal-dielectric structures SPPs on multiple interfaces can couple, leading to the splitting of resonant states, starting with the even and odd states with only two interfaces and expanding into optical bands as the number of layers (interfaces) increases.

III. RESULTS AND DISCUSSION

We examined optical properties of the freestanding corrugated IMI and MIM nanomembranes as shown in Fig. 1. using RF module of Comsol Multiphysics software package. The width of the entire unit cell is a = 1000 nm, which is also the periodicity of the embedded diffractive grating. Embedded curvatures of the reversed troughs are modeled as ellipses with 100 nm and 200 nm semi axes (bottom curvature) and 250 nm and 350 nm semi axes (top curvature). Individual metal and dielectric 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 [12] and dielectric is polymer with a refractive index n=1.4.

Our finite element simulations determine the spatial field distributions as well as the frequency dispersion of the transmission and reflection coefficient for TM plane waves incident on the structure from various angles. Two parallel ports, one active and one passive were added above and below the structure to simulate the flow of optical radiation through the simulation domain, with light entering the domain from the top. Floquet boundary conditions are applied to the edges of the unit cell to simulate the 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 IMI structure are shown in Fig. 3. It is observed in Fig. 3 that IMI structure behaves similarly to extraordinary optical transmission (EOT) arrays, exhibiting increased transparency due to surface plasmonic modes. For normal incidence the IMI structure roughly supports two narrow transparency bands as shown in Fig. 3a with sharp resonant peak at 610 nm. For oblique incidence shown in Fig. 3b and Fig. 3c for 30º and 60º incident angles the structure exhibits a rich modal behavior with a multitude of narrow resonant peaks, especially for the 30º incident angle.

Spatial field distributions for IMI structure at some of the resonant wavelengths are shown in Fig.4-7. Presented field distributions illustrate exceptional capabilities of IMI structure in tailoring spectral and spatial near field enhancement due to plasmonic resonance. Fig. 4 and 5 present two modes for normal incidence with complementary spatial distributions each stemming from different substructure of the complex IMI structure. The first mode at 580 nm stems from the core-shell substructure (reversed troughs of the multilayer nanomembrane) with enhanced scattering on both sides of the membrane.

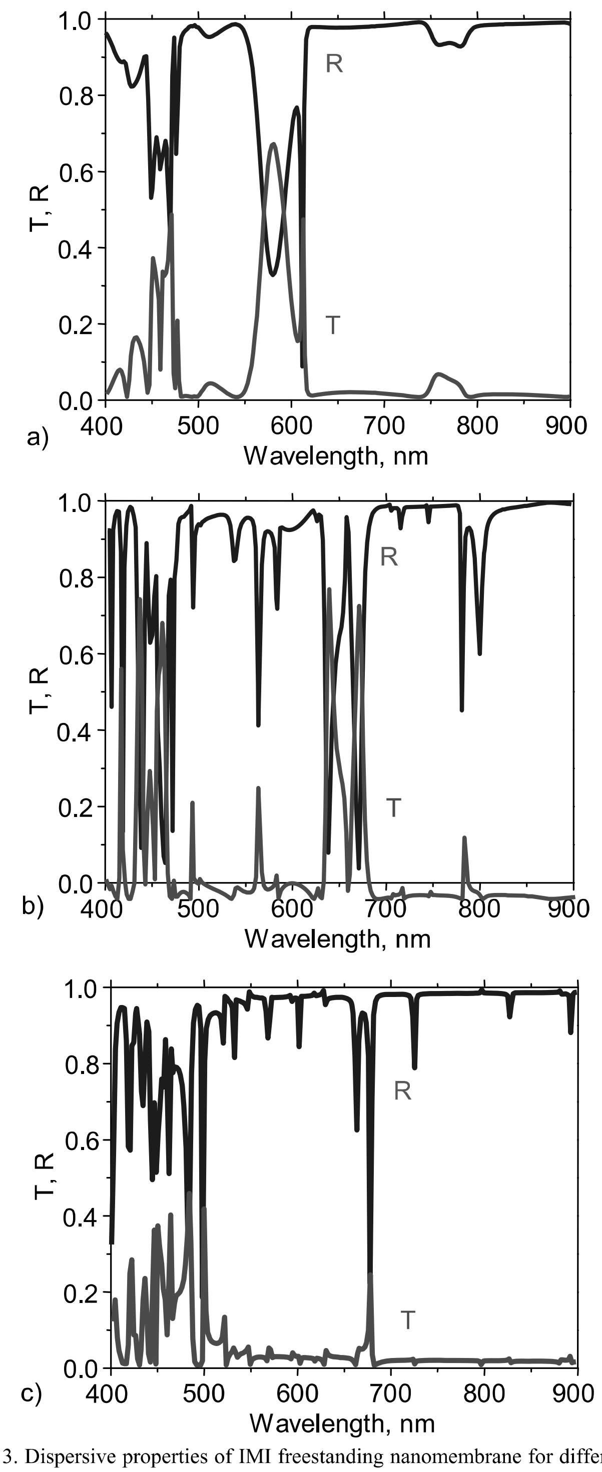


Fig. 3. Dispersive properties of IMI freestanding nanomembrane for different incident angles: a) normal incidence; b) 30º incident angle; c) 60º incident angle. Green: transmission coefficient; blue: reflection coefficient.

The second mode at 610 nm is bound to the surface at the planar part of the structure. Fig. 6 shows that near field enhancement can be localized on the back side of the structure by changing the incident angle. Fig. 7 shows hybridization of the surface modes from different parts of the structure resulting in high field localization spread across the entire structure.

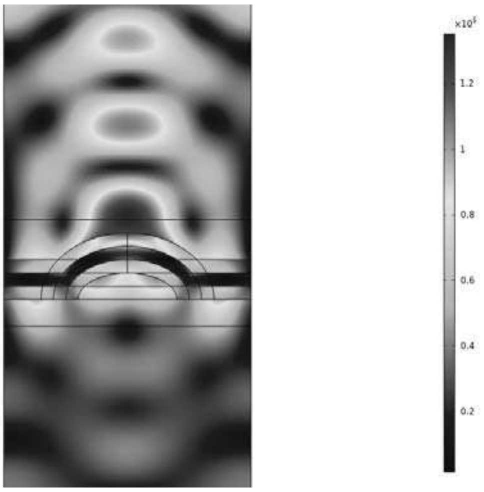


Fig. 4 IMI freestanding nanomembrane, electric field spatial distribution for normal incidence at 580 nm.

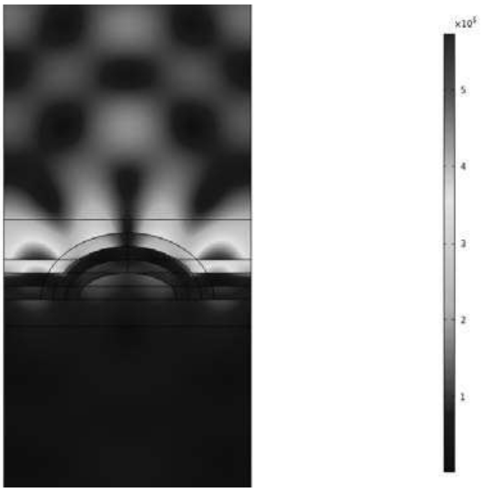


Fig. 5 IMI freestanding nanomembrane, electric field spatial distribution for normal incidence at 610 nm.

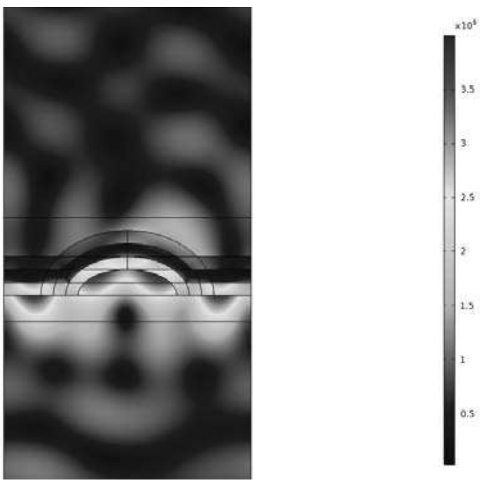


Fig. 6. IMI freestanding nanomembrane, electric field spatial distribution for 30º incident angle at 565 nm.

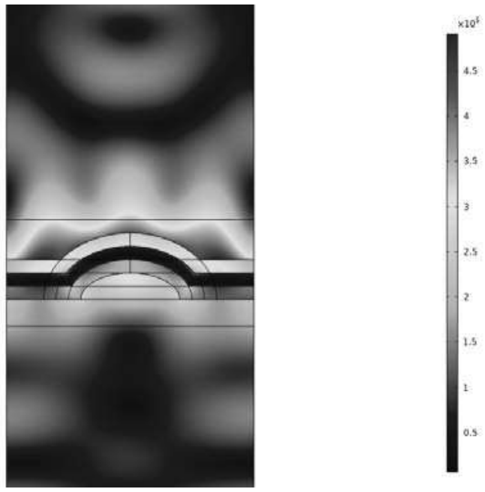
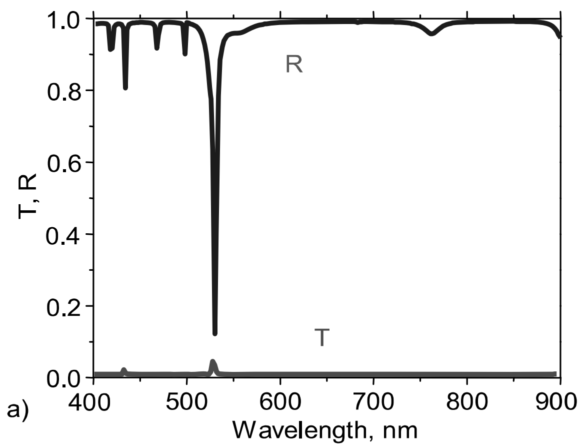


Fig. 7. IMI freestanding nanomembrane, electric field spatial distribution for 60º incident angle at 665 nm.

The dispersive properties of the MIM structure are shown in Fig. 8. Unlike the IMI structure, the MIM structure is highly opaque, denoting that the part of the energy of the propagating wave that isn't being reflected is being funneled into bound surface modes when plasmonic resonance occurs. For normal incidence (Fig. 8a) coupling between the propagating waves and the bound modes is possible due to the corrugated structure of the nanomembrane resulting in a sharp resonant reflection dip at 530 nm. Due to strong coupling between the propagating and the bound modes a high field localization is achieved within the dielectric layer of the MIM structure, as shown in Fig. 9. The number of the bound surface modes that the structure can support increases for oblique incidences, as shown in Fig. 8b and Fig. 8c. The field distribution for another mode with strong coupling for 30º incidence angle at 535 nm is shown in Fig.10. For this mode light localization is moved from the central dielectric layer to the surface of the membrane, allowing again for tailoring of field localization by changing the angle of incidence. Fig. 11 shows a situation similar to the one in Fig. 9 but with much weaker coupling between the propagating and the bound modes resulting in weaker near field enhancement, while retaining the spatial distribution.



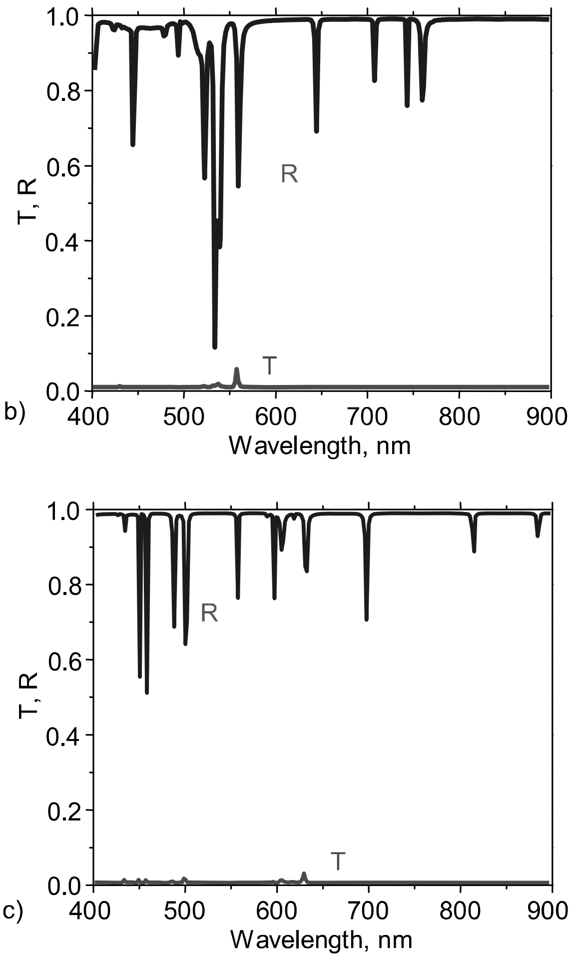


Fig. 8. Dispersive properties of MIM freestanding nanomembrane for different incident angles: a) normal incidence; b) 30° incident angle; c) 60° incident angle. Green: transmission coefficient; blue: reflection coefficient.

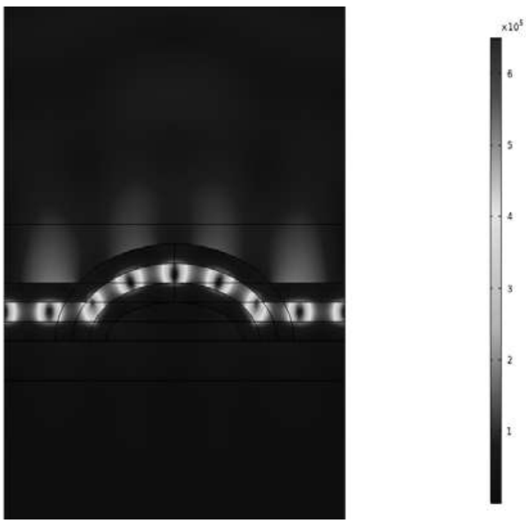


Fig. 9 MIM freestanding nanomembrane, electric field spatial distribution for normal incidence at 530 nm

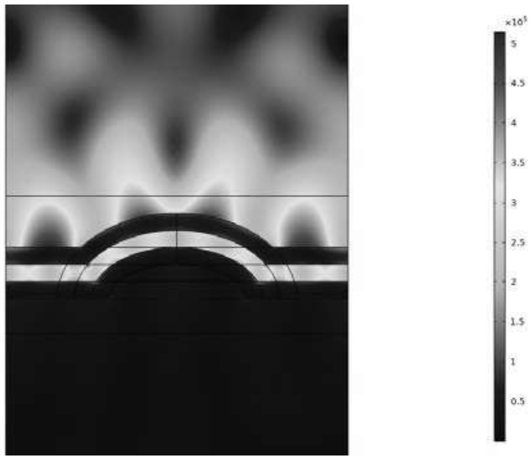


Fig. 10 MIM freestanding nanomembrane, electric field spatial distribution for 30° incident angle at 535 nm.

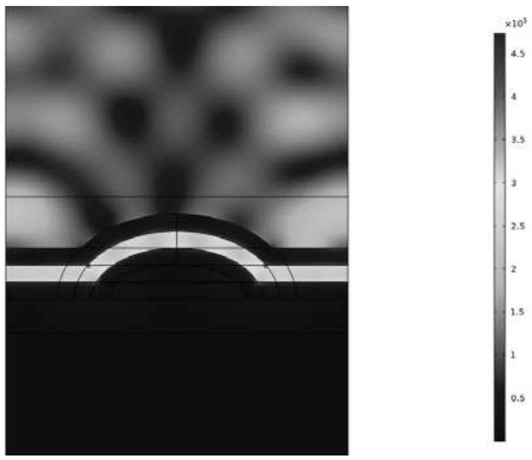


Fig. 11. MIM freestanding nanomembrane, electric field spatial distribution for 60° incident angle at 500 nm.

IV. CONCLUSION

We analyzed optical properties of corrugated IMI and MIM freestanding nanomembranes using FEM simulation. We have shown that our IMI structure exhibits a behavior similar to that of the EOT arrays, resulting in optical transparency of the structure for resonant plasmonic modes. Together with a rich modal behavior and an angular selectivity of the field spatial distributions, this allows for additional degrees of freedom in customizing the nanomembrane evanescent fields. The MIM structure offers excellent confinement of electromagnetic radiation within the dielectric layer and allows for fine tuning of both the near field enhancement and its spatial distribution by adjusting the angle of incidence.

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