Directive Pentagon Patch Nano-Antenna for Nanofocusing Application

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***Abstract*—In this work, a novel pentagon patch nano-antenna working between 192 THz and 195 THz for nanofocusing application is proposed. In the presented design, by employing Niobium nitride (NbN) for mask layer and embedding two metallic nanoparticles instead of metallic mask layer, a balanced tradeoff between propagation loss and electric field confinement is reached. The proposed nano-antenna is designed in purpose of tightly concentrating electric field at the end-fire of the antenna, which is desired for imaging and spectroscopy applications.**

Keywords—Nano-antenna; nanofocusing application; niobium nitride

I. INTRODUCTION

Respect to attractive features of nano-antennas in manipulating and controlling the light emission within a nano-scale footprint, many efforts are investigated to design nano-antenna's with high efficiency [1-3]. Beside challenges that designers encounter in designing antenna, designers always struggle in designing nano-antennas due to deviation of optical properties of metals in optic frequencies from their characteristics at lower frequencies [4]. Employing metals in nano-antennas supports surface plasmon (SP) modes and maximize electric field confinement in purpose of preventing unwanted radiation from side and back of designed antennas [5]. However, inevitable loss of metals causes high propagation loss in designed antennas.

Another consideration is compatibility of nano-antennas with fed integrated waveguide. Among different types of fed waveguides, hybrid plasmonic waveguide (HPWG) are known as rational choice to fed nano-antennas due to balance between field confinement and propagation loss [4] and [6]. Hence, designed nano-antennas preferred to be compatible with HPWG. To this end, in many works like [1], [7] and [8], nano-antennas were designed to fed with HPWG but with minimum utilization of metal in antenna's structure in purpose of increasing antenna's efficiency.

Simple patch hybrid plasmonic nano-antennas are bidirectional and as a result they have limited applications due to existing two main lobes [8]. However, HPWG patch nano-antennas are not suitable to be used for nanofocusing application with ability to concentrating the light energy in a point volume [9-13]. Gradual mode transformation as well as focusing plasmonic SP mode are unique features of structures supporting nanofocusing based on their sharp tips as singular area. Nanofocusing attracted attentions in these years respect to importance of wave focusing on spectroscopy and imaging efficacy [12] and [14]-[15].

Nano-antennas with directive end-fire geometry are good candidate to be employed for nanofocusing. As discussed in [16], E-shaped patch has directive end-fire radiation pattern but because of lacking sharp tips in structure of E-shaped nano-antennas, they cannot be used for nanofocusig. To this end, a novel HPWG polygon (pentagon) nano-antenna is proposed in this work in purpose of tightly concentrating light's field at the end-fire of the antenna. In the proposed design, the radiation features of the nano-antenna are optimized respect to employed materials and antenna's geometry.

II. DESIGN PROCEDURE

According to unique geometry of pentagon patch (polygon geometry) with sharp tips [17], compare with simple rectangular or circular patches, pentagon patch nano-antenna, which one of its edge is at the end-fire side the structure (Fig. 1), can be nominated as focuser. However, unlike nano-antennas presented in [12], for nanofocusing, the proposed pentagon nano-antennas is not metallic due high propagation loss of metallic structures. Here, similar to hybrid plasmonic waveguide (HPWG) discussed in [4], to reach balance between field confinement and propagation loss, dielectric materials are employed as well as metals in the mask layer of the design. So, as expected, hybrid mode is produced in the proposed design by coupling between SP mode and dielectric waveguide mode. However, due high confinement feature of SP modes and consequently beating diffraction limit to reach maximum spatial confinement in nano-scale, it is preferable to suppress dielectric waveguide modes in hybrid plasmonic structures. To this end, in [4], Niobium nitride (NbN) as the lossy material (non-zero ε'') is nominated to be substituted instead of metal mask layer in purpose of reaching dominating SP mode but with less propagation loss. For maximizing wave compressing, two metallic pentagon-shaped nanoparticles are designed at sides of the nano-antenna. These side metallic nanoparticles increase guiding waves toward open-ended of the designed nano-antenna with less unwanted radiation (leakage) from sides and back of the antenna.

To show the advantage of the proposed hybrid plasmonic nano-antenna in suppressing dielectric modes, the distribution of Ey component (dominant component at TM mode-SP mode) of electric field is plotted in terms of z-axis at the cutline AA'. Similar to [4], Ey can be written as equation (1) and unknown coefficients A to F is derived by applying boundary conditions derived from Maxwell equations similar to [4]. To satisfy boundary condition, matrix M is written as shown in equation (2) and by equaling determination of M to zero, unknown coefficient of Ey is determined. These equations are solved and

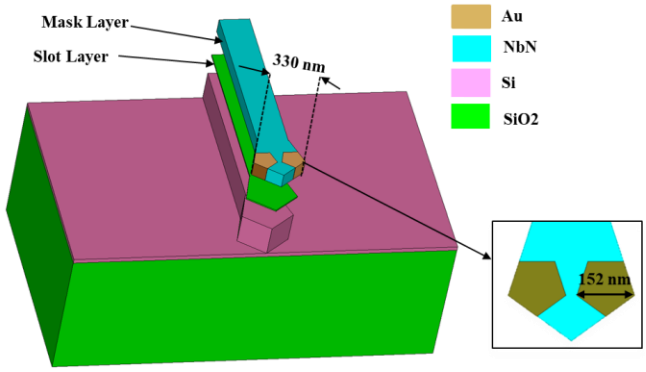

Fig. 1. The proposed pentagon patch nano-antenna with NbN mask layer and gold nanoparticles.

coefficients are found for two different states: first for metallic mask layer and then when NbN makes the mask layer. It is expected that Ey at mask, rib and slab layers in the designed nano-antenna decays faster than state two (NbN as the mask layer) and slower than state one (metallic mask layer) respect to combining gold (metal) and NbN in the mask layer. The proposed nano-antenna is designed on Silicon On Insulator (SOI) wafer similar to [4]. As shown in Fig. 1, the 10 nm slot layer and 900 nm nm slab layer are silica (SiO2), while the 240 nm rib layer is silicon (Si). The thickness of mask layer is 50 nm and the nano-antenna's dimensions are optimized to work at 193.5 THz, standard frequency for optical communication.

$$E_y = \begin{cases} A\exp(\gamma_1 y) & y<0 \\ B\exp(\gamma_2 y)+C\exp(-\gamma_2 y) & 0<y<w \\ D\exp(\gamma_3(y-w))+E\exp(-\gamma_3(y-w)) & w<y<w+a \\ F\exp(-\gamma_4(y-w-a)) & w+a<y \end{cases} \tag{1}$$

Where ɣi (i= 1,…,4) is transverse wavenumber of each region that is derived from dispersion equations at each layer similar to [4].

$$M = \begin{bmatrix} \varepsilon_1 & -\varepsilon_2 & -\varepsilon_2 & 0 & 0 & 0 \\ \gamma_1 & -\gamma_2 & \gamma_2 & 0 & 0 & 0 \\ 0 & \varepsilon_2\exp(\gamma_2 w) & \varepsilon_2\exp(-\gamma_2 w) & -\varepsilon_3 & -\varepsilon_3 & 0 \\ 0 & \gamma_2\exp(\gamma_2 w) & -\gamma_2\exp(-\gamma_2 w) & -\gamma_3 & \gamma_3 & 0 \\ 0 & 0 & 0 & \varepsilon_3\exp(\gamma_3 a) & \varepsilon_3\exp(-\gamma_3 a) & -\varepsilon_4 \\ 0 & 0 & 0 & \gamma_3\exp(\gamma_3 a) & \gamma_3\exp(-\gamma_3 a) & \gamma_4 \end{bmatrix} \tag{2}$$

Where ε_i (i=1,…,4) is the permittivity of each layer, which is complex for NbN and real positive number for Si and SiO$_2$ and negative real value for metal layer.

Ey component of electric field in the design nano-antenna is plotted based on numerical simulation done by CST software. As shown, by choosing metal mask layer (gold Au in this work), SP mode is dominant due to minimum level of Ey in mask, rib and slab layers. However, when NbN- lossy dielectric is chosen for mask layer, the level of Ey is maximized in slab layer, which has low refractive index, as the sign of existing dielectric mode. In the proposed design, resect to adding two metallic pentagon nanoparticles to sides of the antenna, dielectric mode level is moderated at the open-ended of the designed antenna. Hence, there is a tradeoff between propagation loss and dielectric mode in the proposed design. Moreover, to show the ability of the proposed design in guiding electric field toward open-ended of the antenna, two dimensional (2D) electric field distribution in the slot layer is depicted in Fig. 3. As seen, massive hybrid modes with SP dominancy accumulate at the open-ended of the antenna because of presenting metallic nano-particles with responsibility to decrease lateral dimensions of the nanoantenna. To this end, the proposed design has potential to be employed for nanofocusing application.

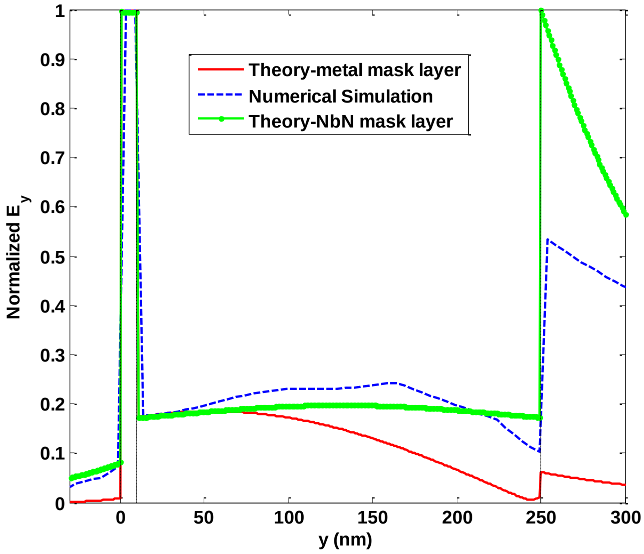

Fig. 2. Theoretical and designed antenna Ey component of electric field in the multilayer structure.

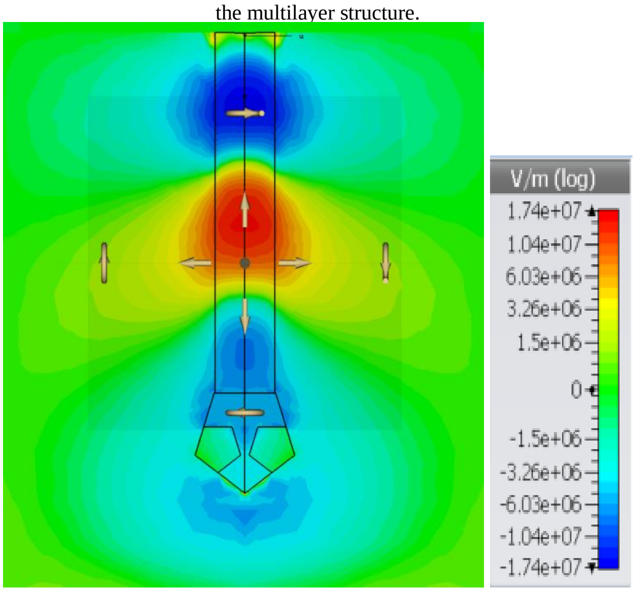

Fig. 3. Simulated (2D) electric field distribution in the slot layer.

Next, to show the efficacy of NbN mask layer with gold nanoparticles in suppressing unwande radiation from sides and back of the nanoantenna, farfield radiation pattern in E-plane (Phi = 0°) is depicted in Fig. 4 and compare with results when the mask layer is fully or partially metalic. As shown, the level of side and back lobe level of the farfield radiation pattern is less when the mask layer is NbN compare with side and back lobe level for gold mask layer. As a result of less leakage radiation from side and back of the nanoantenna, directivity and antenna's gain increases at the main lobe direction. As seen, by putting two gold nanoparticles in the NbN mask layer, back lobe of the proposed nano-antenna decreases to -20 dB.

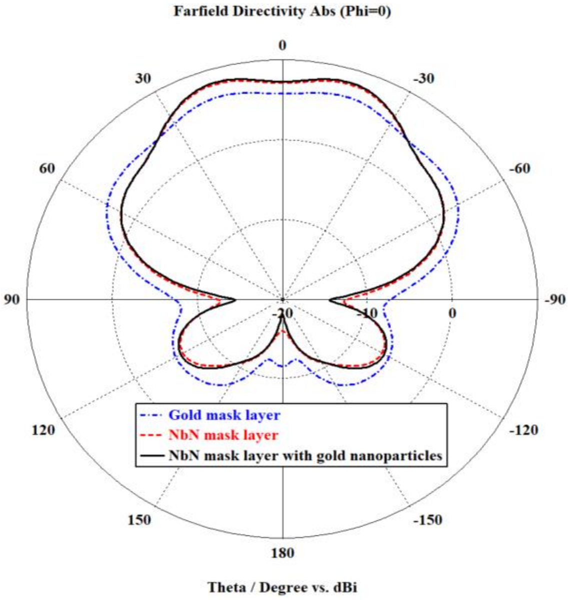

Fig. 4. Farfield radiation pattern in E-plane (Phi = 0°) at 193.5 THz for different mask layer's material.

Finally, simulations are prepared for different mask layer's thickness and results are illustrated in Fig. 5. As shown, for 50 nm thickness, reflction coefficient from 192 THz to 195 THz is minimized and as a consequent, matching between the photonic waveguide with NbN mask layer and pentagon patch nano-antenna increases. The precise mask layer thickness is acheivable by employing different deposition techniques. As discussed in [18-19], metal organic chemical vapor deposition (MOCVD) technique is well known deposition method to control desired thickness of deposed materials with nanometer accuracy.

III. CONCLUSION

A pentagon patch nano-antenna with NbN mask layer and gold nanoparticles is designed to work around 1550 nm waveleght, known for the standard transmission. The proposed design has end-fire rsdiation with approximately 5 dB gain and -20 dB back lobe level, which its baklobe level is around 7 dB less than the design with metalic mask.

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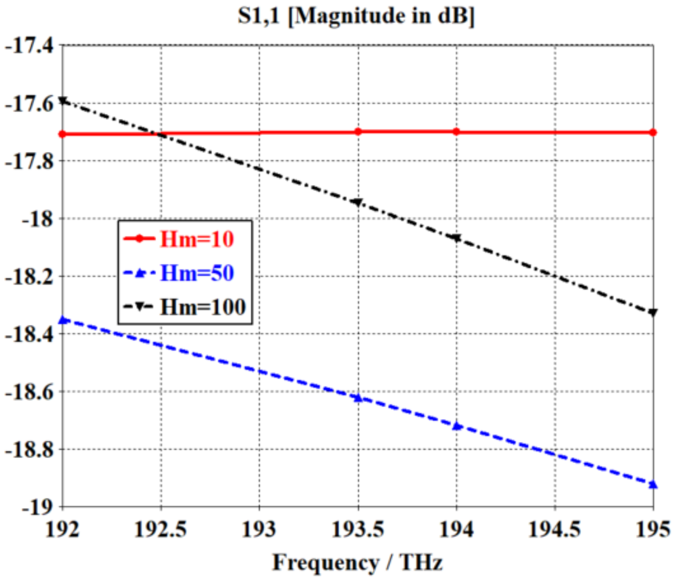

Fig. 5. Reflection coefficient from 192 THz to 195 THz for different mask layer's thickness.

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