World Academy of Science, Engineering and Technology
International Journal of Physical and Mathematical Sciences
Vol:9, No:5, 2015

High Gain Broadband Plasmonic Slot Nano-Antenna

H. S. Haroyan, V. R. Tadevosyan

Open Science Index, Physical and Mathematical Sciences Vol:9, No:5, 2015 publications.waset.org/10001208.pdf

Abstract**—**High gain broadband plasmonic slot nano-antenna has been considered. The theory of plasmonic slot nano-antenna (PSNA) has been developed. The analytical model takes into account also the electrical field inside the metal due to imperfectness of metal in optical range, as well as numerical investigation based on finite element method (FEM) has been realized. It should be mentioned that Yagi-Uda configuration improves directivity in the plane of structure. In contrast, in this paper the possibility of directivity improvement of proposed PSNA in perpendicular plane of structure by using reflection metallic surface placed under the slot in fixed distance has been demonstrated. It is well known that a directivity improvement brings to the antenna gain increasing. This method of diagram improving is also well known from RF antenna design theory. Moreover the improvement of directivity in the perpendicular plane gives more flexibility in such application as improving the light and atom, ion, molecule interactions by using such type of plasmonic slot antenna. By the analogy of dipole type optical antennas the widening of working wavelengths has been realized by using bowtie geometry of slots, which made the antenna broadband.

Keywords**—**Broadband antenna, high gain, slot nano-antenna, plasmonics.

I. INTRODUCTION

OPTICAL antennas, analogues of microwave and radio wave antennas, are a new concept in physical optics [1]. They are an enabling technology for manipulating optical radiation at subwavelength scales [2]. This research is stimulated by a variety of promising applications: for enhancing the efficiency of photo detection [3], [4] light emission [5], [6] sensing [7], heat transfer [8], [9] and spectroscopy [10], particularly in receiving modes for enlarging the effective absorption cross section of molecules, quantum dots, or atomic emitters placed near the antenna.

Traditionally, in the field of optics and photonics light is commonly controlled by using elements such as mirrors, lenses, fibers and diffractive elements. Such type of manipulation relies on the wave nature of electromagnetic field and does not provide an ability to control the light on the subwavelength scales. On the other hand, in the radiowave and microwave regime, using antennas of various designs to control electromagnetic fields on the subwavelength dimensions is a well-established technique. From this point of view, the optical analogues of radiofrequency (RF) antennas can overcome the challenges of light subwavelength control and help surpass the diffraction limit, making it possible to manipulate, control, and visualize optical fields on nanometer scale.

Good approach to confine electromagnetic energy has been to take advantage of surface Plasmon polaritons (SPP). The SPP is quasi-two-dimensional electromagnetic excitations, propagating along a dielectric–metal interface and having the field components decaying exponentially into both neighboring media [11], [12] offering the possibility of realizing subwavelength confinement.

While RF antennas are a key enabling technology for devices like cellular phones and televisions using radiofrequency range of electromagnetic radiation, their optical counterparts are basically absent in today's optics technology. The absence of optical antennas in technological applications is basically associated with their small size. The characteristic dimensions of an antenna are of the order of the radiation wavelength, and for optical antennas this requires fabrication accuracies down to a few nanometers. However, this length scale has become increasingly accessible as the tools of nanoscience and nanotechnology have improved. The objective of optical antenna design is equivalent to that of classical antenna design: to optimize the energy transfer between a localized source or receiver and the free-radiation field [13]. So the optical antenna could be defined as a device to efficiently convert free-propagating optical radiation to localized energy, and vice versa [14]. Theory of optical antennas is generally developed in the analogy of their RF counterparts. But it should be noted that it is not the directly extension of RF antenna theory on the optical counterparts, due to the crucial differences in their physical properties and scaling behavior. Most of these dissimilarities appear because metals are not perfect conductors at optical frequencies. Moreover, optical antennas can take various unusual forms (tips, spheres, nanoparticles, etc.) and their properties may be strongly shape and material dependent owing to surface plasmon resonance. Surface plasmon resonances make optical antennas particularly efficient at selected frequencies-an attribute that also holds promise for biological sensing and detection [15], [16]. Various types of optical antennas (gap antennas, Yagi-Uda antenna, bowtie, etc.) have been designed, and their scattering and directivity features are investigated [17], [18].

Recently the theory of plasmonic nanowire antenna has been developed in [19]. The analytical model takes into account also the electrical field inside of the wire due to imperfectness of metal in optical range. As is known from RF antenna theory the solutions are obtained for wire dipole antenna could be extended for slot antennas by changing $E \leftrightarrow H$, $Z \to -1/Z$, where Z is the free space impedance. So the developed theory could be applied for plasmonic slot antennas. Recently numerical study of slot Nano antenna have been realized in [20] and have been demonstrated similar responses with dipole antennas (see Fig. 1 (a)). To extend the

H. S. Haroyan and V. R. Tadevosyan are with the Department of Microwave Radiophysics and Telecommunication, Yerevan State University, Yerevan, 1 Alex Manoogian, CO 0025, Armenia (e-mail: hharoyan@ysu.am, vahetad@ysu.am).

bandwidth of dipole optical antennas the bowtie antenna is proposed in [21] by the same way as in RF range, such approach could be applied also for slot antennas (see Fig. 1 (b)).

To improve the directivity of simple dipole (or monopole) optical antenna the Yagi-Uda antenna has been proposed in analogous with RF range antenna. It should be mentioned that Yagi-Uda configuration improves directivity in the plane of structure. In contrast of this the directivity of slot antenna could be improved in perpendicular plane of structure by using reflection metallic surface placed under slot in fixed distance (see Fig. 1 (c)). This method of directivity improving is also well known from RF antenna design theory. It is also worth mentioning that in the RF range the reflecting metal surface is a perfect conductor and for protecting of the no desire currents the high impedance surfaces are designed.

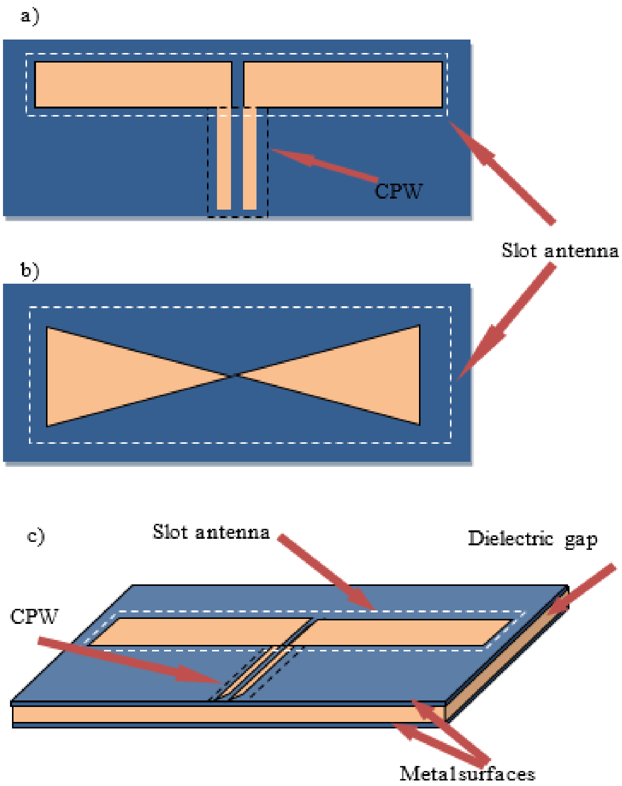

Fig. 1 (a) Slot antenna with coplanar waveguide (CPW), (b) bowtie slot antenna, (c) slot antenna with metal reflector

In optical range metals are non-perfect conductors and plasmonic fields are decaying rapidly and it is not necessary to construct such compound surfaces. Moreover the improvement of directivity in the perpendicular plane gives more flexibility in such application as improving the light and atom, ion, molecule interactions by using such type of plasmonic slot antenna.

In this paper the high gain broadband PSNA has been investigated. The theoretical model has been developed based on permutation duality between dipole and slot antennas, as well as numerical calculation has been carried out. Directivity of PSNA can be improved by applying reflective metallic substrate separated from slotted surface by dielectric gap in analogy with RF counterpart. It is well known that directivity and gain of antenna are interconnected. But the improvement of directivity does not mean increasing of gain. To obtain high gain it is necessary to improve also antenna efficiency, which can be performed by realizing impedance matching. The impedance matching between antenna and source or waveguide can be checked by using standing wave ratio (SWR) parameter. SWR is determined from the voltage (or electric field) measured along a transmission line leading to an antenna. SWR can be defined as the ratio of the peak amplitude of a standing wave to the minimum amplitude of a standing wave.

The broadbandness of PSNA has been realized by using bowtie slots in analogous with RF range antenna.

It is worth to mention, that from point of view interaction mechanism with sample, there is a fundamental difference between dipole type and slot type antennas. In the case of dipole antenna where currents flow in one direction and subwavelength interaction between antenna and sample (molecules, quantum dots, or atomic emitters placed near the antenna) is generally performed via strong localized electric field. In contrast of dipoles, in the slots near-field interaction is basically realized via magnetic field. This fact opens up new possibilities of slot antennas application in optical range, such as improvement and investigation of fine and quadrupole interactions and transitions, quadrupole excitation of nucleus.

II. Theory and Simulations

As was mentioned the theory of plasmonic slot antenna can be obtained from wire dipole plasmonic antenna theory owing to principle of permutation duality. According to theory developed in [19], due to imperfect conductivity of metal additional electrical field is appears inside the wire. So the boundary condition will have the following form: $E_z^{(\mathrm{inc})} + E_z^{(\mathrm{sca})} = E_z^{(\mathrm{inside})}$, where $E_z^{(\mathrm{inc})}$ is the incidence field component on the z direction (axis z is coincide with wire longitudinal direction), $E_z^{(\mathrm{sca})}$ is the scattering filed projection on z axis and $E_z^{(\mathrm{inside})}$ is the inside component of the field. The scattered field $E_z^{(\mathrm{sca})}$ associated with the current density across the wire and surface currents, can be expressed by vector potential $A(z,r,\phi)$ [22],[23]:

$$A_z(z,r,\phi) = \frac{1}{4\pi}\int_{V'} I_z(z')\frac{e^{-ikR}}{R}\mathrm{d}V' \qquad (1)$$

where R –is the distance of integration point in the wire volume V' and observation point there the field component will be calculated. For the current density inside of the wire could be finding from following relation $I(\mathrm{r}) = \sigma E^{(\mathrm{inside})}(r)$ [19]. Finally, by applying $E \leftrightarrow H$, $Z \rightarrow -1/Z$ interchanges field distributions can be found for slot antenna.

Investigation of radiation dependence of proposed PSNA on frequency has been carried out by spectral analysis. To perform the spectral analysis the simulation model has been built (see Fig. 2). In model presented in Fig. 2 as a metal has been chosen silver (Au), bowtie shape has been cut out from metallic surface and filled by dielectric (ε_a is permittivity of dielectric filled in the slot antenna). Plasmonic waveguide supporting SPP propagation has been placed in the center of the symmetric parts of antenna. Coupling between plasmonic waveguide and slot is well seen from simulated and calculated field distribution (see Fig. 2).

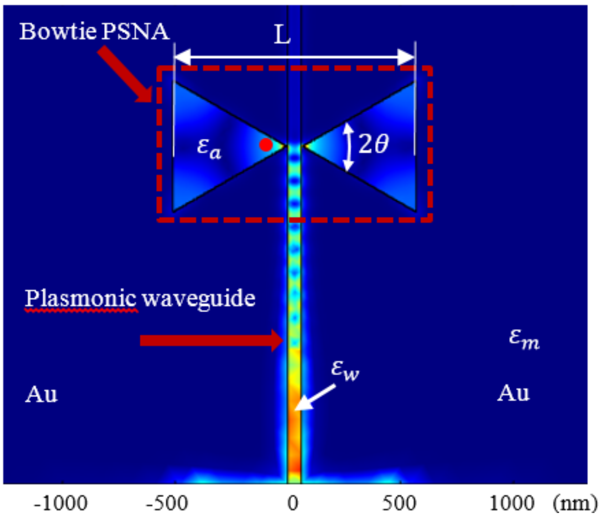

Fig. 2 Front view of simulation model

As we can see from Figs. 3 (a) and (b) existence of slot antenna influences on the spectral behavior of system. In Fig. 3 (a) spectral response of a system without antenna is presented which is broadband enough to notice spectral features of proposed antenna.

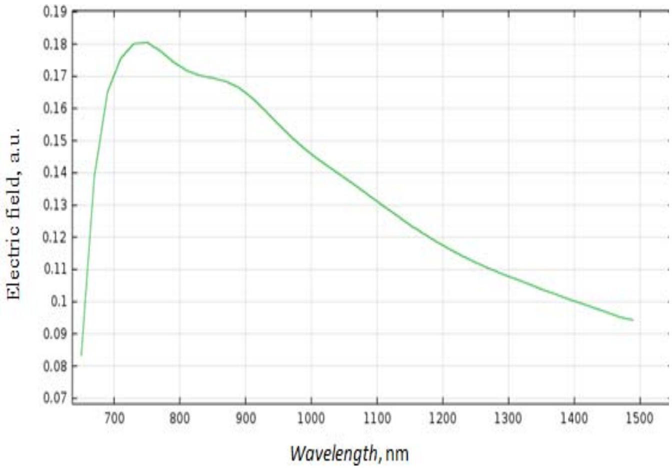

Fig. 3 (a) Spectral response of a system without antenna: If bowtie slot antenna was placed as presented in Fig. 2, near-field dependence on wavelength of antenna has a behavior presented in Fig. 3 (b). Calculations have been done at the point presented in Fig. 2 (red point near the vertex of a triangle)

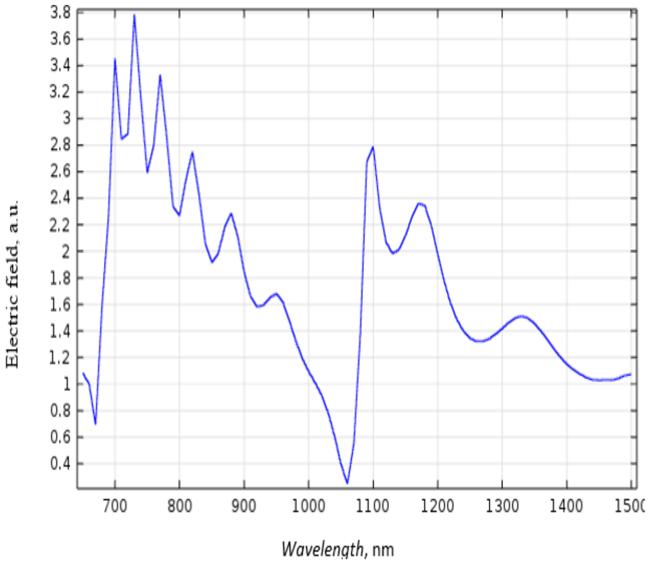

Fig. 3 (b) Near-field Electric field component spectrum

As follows from Fig. 3 (b) there is a deep dip in the electric field spectrum. It is interesting to notice that value of λ corresponding to the minimum value of E is equal to length L of slot antenna. As one side length of antenna is equal to λ/2, which means that reflected field from border of slot antenna is in antiphase with field component near the vertex of a triangle. Consequently the total electric field is dramatically decreased near the wavelengths equal to L. Calculation shows that electric field E increased by decreasing the angle θ for fixed value of L (see. Fig. 3 (b)). To investigate impedance matching between waveguide and antenna SWR calculations have been done. In Fig. 4 SWR dependence on working wavelength is presented. Fig. 4 follows the possibility of tuning bandwidth of bowtie antenna by changing opening angle θ.

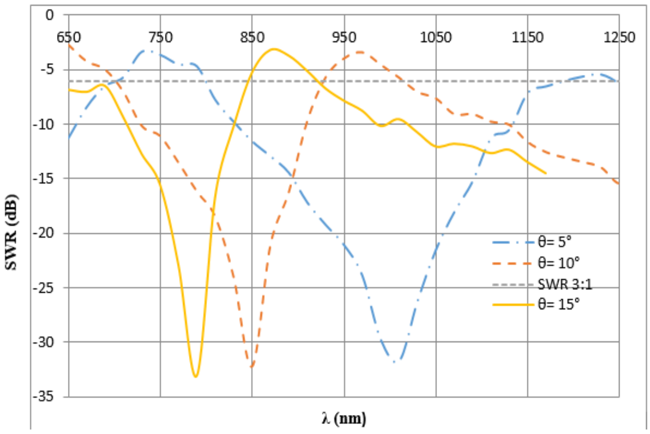

Fig. 4 SWR vs. wavelength for different values of θ

Moreover we can control the central wavelength (the wavelength then matching is the best, i.e. SWR has the smallest value) by varying opening angle. For instance in the case of θ=5° the bandwidth of antenna can be defined, by following widely used method in RF antenna theory, as wavelengths region corresponding to SWR values below -6dB level and is located from 810 nm to 1190 nm range (see Fig. 4).

SWR dependence on dielectric permittivities relationship of antenna and waveguide ($\varepsilon_a/\varepsilon_w$) has been also investigated (see. Fig. 5).

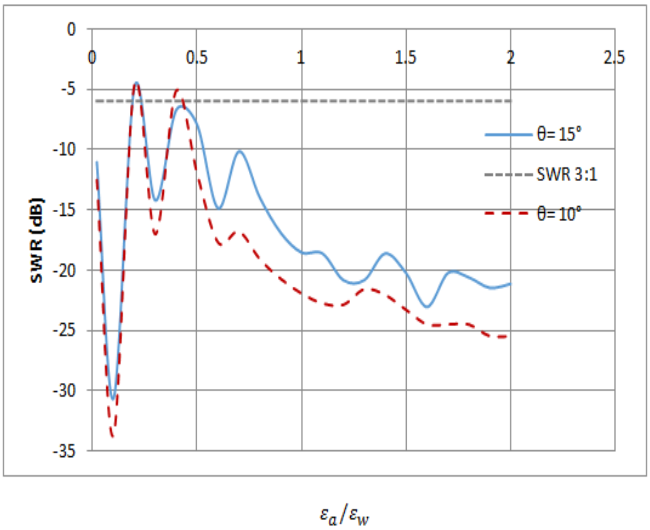

Fig. 5 SWR vs. $\varepsilon_a/\varepsilon_w$ for different values of θ

As it can see from Fig. 5 SWR behavior is almost same for different angles, and has explicit minimums for $\varepsilon_a/\varepsilon_w = 0.1$ or 0.3. It should be noted that optimal wavelengths has been chosen according to Fig. 4 and for θ=10° λ=850nm, *for* θ=15° λ=790nm. Therefore, it is possible to improve the impedance matching by selection of optimal values of working wavelengths and dielectric permittivities of antenna and waveguide, for instance by choosing bowtie antenna opening angle θ=10°, $\varepsilon_a/\varepsilon_w = 0.1$, length L=1000nm, and working wavelengths near the λ=850nm the SWR can be decreased up to -33 db.

III. CONCLUSION

High gain broadband plasmonic slot nano-antenna has been considered. The theory of PSNA has been developed, as well as numerical investigation based on FEM method has been realized. The possibility of directivity improvement of proposed PSNA in perpendicular plane of structure by using reflection metallic surface placed under the slot in fixed distance has been demonstrated. By the analogy of dipole type optical antennas the widening of working wavelengths has been realized by using bowtie geometry of slots, which made the antenna broadband. Based on SWR analysis method the impedance matching conditions has been clarified, as well as bowtie antenna bandwidth in different conditions has been estimated. The possibility of bandwidth tuning by varying angle θ has been demonstrated. In contrast of dipoles, in the slots near-field interaction is basically realized via magnetic field. This fact opens up new possibilities of slot antennas application in optical range, such as improvement and investigation of quadrupole magnetic interactions and transitions, quadrupole excitation of nucleus.

ACKNOWLEDGMENT

This work was supported by the State Committee of Science of Armenia (13YR-1C0046).

REFERENCES

[1] P. Bharadwaj, B. Deutsch, L. Novotny, Adv. Opt. Photon. vol. 1, 2009, pp. 438–483.
[2] T. H. Taminiau, F. D. Stefani, N. F. van Hulst, Opt. Express, vol.16, 2008, pp. 10858–10866.
[3] L. Tang, et al. Nature Photon. vol. 2, 2008, pp. 226–229.
[4] L. Cao, J.S. Park, P. Fan, Clemens, B. & Brongersma, M. L. Resonant, Nano Lett., Vol. 10, 2010, pp. 1229–1233.
[5] E. Cubukcu, E. A. Kort, K. B. Crozier, F. Capasso, Appl. Phys. Lett., vol. 89, 2006, p. 093120.
[6] S. Pillai, K. Catchpole, T. Trupke, M. J. Green, Appl. Phys., vol. 101, 2007, p. 093105.
[7] J. N. Anker, et al. Biosensing with plasmonic nanosensors. Nature Mater. vol. 7, 2008, p. 442.
[8] Y. DeWilde, et al. Nature, vol. 444, 2006, p.740.
[9] J. A. Schuller, T. Taubner, M. L. Brongersma, Nature Photon., vol. 3, 2009, p.658.
[10] L. Novotny, S. J. Stranick, Ann. Rev. Phys. Chem., vol. 57, 2006, p.303.
[11] H. Raether, Surface Plasmons (Springer 1998).
[12] W. Barnes, A.Dereux, T. Ebbesen, Nature, vol. 424, 2003, p.824.
[13] L. Novotny and N. van Hulst, Nature Photonics, vol. 5, 2011, p.83.
[14] B. Hecht et al., Elsevier, 275, 2007.
[15] H. Frey, S. Witt, K. Felderer, and R. Guckerberger, Phys. Rev. Lett. 93, 2004, p.200801.
[16] A. Schuller et al., Nature Mater, vol. 9, 2010, p.193.
[17] J. Alda, J. Rico-Garcia, J. Lopes-Alonso, G. Boreman, Nanotechnology vol. 16, 2005, S230.
[18] F. Gonzalez, and G. Boreman, Infrared Phys. Technol., vol. 146, 2004, p.418.
[19] J. Dorfmuller, R. Vogelgesang, W. Khunsin, C. Rockstuhl, C. Etrich, K. Kern, Nano Lett., vol. 10, 2010, p. 3596.
[20] V. Dinesh Kumar, Kiyoshi Asakawa, Photonics and Nanostructures – Fundamentals and Applications, vol. 7, 2009, p.161.
[21] R. Grober, R. Schoelkopf, D. Prober, Appl. Phys. Lett., vol. 70, 1997, p.1354.
[22] D. Jackson, Classical Electrodynamics, 3rd Ed, Wiley, New York 1999.
[23] S. Orfandis, Electromagnetic Waves and Antennas, NJ 2008.