Electrical and Radiation Properties of a Horn Nano-Antenna at Near Infrared Frequencies

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Abstract—In this contribution, we present the electrical and radiation properties of a horn nano-antenna working at near infrared frequencies. The proposed nano-antenna consists of an Ag-SiO₂-Ag nano-transmission line terminated in a tapered horn. We numerically demonstrate that such a nano-antenna is able to efficiently capture/radiate light at the frequencies of interest. The obtained impedance bandwidth and simulated gain make the proposed nano-antenna a promising solution for telecommunication and energy harvesting applications.

Keywords: Nano-antennas, nano-horn, energy harvesting, optical communications.

I. INTRODUCTION

At radio and microwave frequencies, the antenna is one of the key element of wireless systems. Due to the recent advancements in nano-technology, antenna concepts have been widely discussed also in the physics and optical communities and interesting applications are envisaged for both telecommunications and energy harvesting systems. The design of an antenna working at optical frequencies is not a straightforward task, due to the inherent nature of the optical radiation and to the dispersive properties of the materials in such a frequency range.

Following the previous works by Alù and Engheta [1]-[3], from an electrical engineering perspective, a possible way to design nano-antennas consists in adapting the concepts commonly used at radio and microwave frequencies to the design of optical nano-antennas. Such an approach has been successfully employed in the case of nano-dipoles and nano-dimers [1]-[3], but also for more complex radiators, such as the bow-tie [4], the spiral [5], and the Yagi-Uda [6] antennas.

Typical studies on nano-antennas working at optical and near-infrared frequencies [7]-[20], are currently devoted to explore and solve fabrication-related, impedance matching, efficiency, gain, and impedance bandwidth issues. Another interesting and widely discussed aspect concerns the extraction (or feeding) of the electromagnetic energy captured (or radiated) by the receiving (or transmitting) nano-antenna,

which is of paramount importance in the applications (e.g. energy harvesting and telecommunication links).

In this contribution, in order to address some of the aforementioned hot topics in the field, we propose the design of a horn nano-antenna consisting of an Ag-SiO₂-Ag nano-transmission line [21]-[22] tapered at its end in the same fashion as a microwave horn antenna. In the receiving mode, the proposed configuration allows capturing electromagnetic energy from free-space, guiding it through the nano-transmission line, and making it available to the detector. Exploiting the reciprocity theorem, a dual behavior is expected when the antenna works in the transmitting mode: injected electromagnetic energy is guided by the nano-transmission line and radiated in free-space by the nano-horn. The physical length of the nano-horn is a few hundred of nanometers and the materials used are silver (for the nano-transmission line plasmonic cladding) and silica (for the waveguide core). The proposed antenna has been simulated through CST Studio Suite [23], taking into account material losses and dispersion.

The structure of the paper is as follows. In Section II, we briefly describe the design of the nano-transmission line, while in Section III we present the design of the horn nano-antenna and discuss the results obtained in terms of impedance matching and gain.

II. NANO-TRANSMISSION LINE DESIGN

As previously anticipated, exploiting the reciprocity theorem, antenna performances can be studied either in the receiving or in the transmitting mode. Without generality loss, in this paper we preferred to consider the antenna working in the transmitting mode.

The first step consisted in the design of a nano-transmission line used to feed the horn nano-antenna. Among the different configurations proposed in the literature, we decided to consider the Ag-SiO₂-Ag symmetric nano-transmission line, which has been extensively studied in the past [21]-[22]. A sketch of the line is reported in Fig. 1. The plasmonic behavior of silver at near-infrared frequencies allows obtaining the required series inductance behavior along the line, while the dielectric nature of silica returns the shunt capacitance. As

widely discussed in [21]-[22], such a structure supports a fundamental forward mode confined between the two metallic layers.

For what concerns the constitutive properties of the materials, silver has been described through the complex permittivity function presented in [24] (approximated by a Drude model with plasma and damping frequencies set to 2175 THz and 4.35 THz, respectively), while the dielectric properties of silica have been modeled according to the permittivity function found in [25]. Such models, which fully take into account material losses and dispersion, have been implemented in CST Studio Suite, a commercial code based on the finite integration technique.

In order to have propagation in the near-infrared (we have considered the design frequency at a wavelength of 1500 nm), the thicknesses of silver and silica layers have been set to 30 nm and 50 nm, respectively. The nano-transmission line is excited through a waveguide port and the expected forward propagation of the fundamental mode has been correctly obtained at the design frequency. The electric field of such a mode is almost vertically polarized, as it happens in a metallic microwave waveguide.

Figure 1 3D representation of an Ag-SiO₂-Ag nano-transmission line infinitely extended in x - and y - directions.

III. HORN NANO-ANTENNA DESIGN

The second step of our work consisted in the design of the horn nano-antenna excited by the nano-transmission line described in the previous section. As it is well known in microwave engineering, an horn antenna is made of a metallic waveguide shaped at one of its end like an horn in order to 1) increase the physical aperture (and, thus, the antenna gain) and to 2) progressively match the wave-impedance of the waveguide to the one of free-space.

In this work, we have applied these concepts to the nano-transmission line reported in Fig. 1 working in the near-infrared regime. The horn, thus, is obtained divaricating the silver layers at one end of the waveguide, as reported in Fig. 2. The lengths of the waveguide and the horn, indicated by ℓ_{wg} and ℓ_{horn} respectively, are 1000 nm and 500 nm, respectively. The vertical aperture h is set to 300 nm. The radius of curvature used to taper the transmission line into the horn aperture is defined using the smoothness parameter of the loft function in the numerical simulator CST Studio Suite. In our case, this parameter is set to 0.25. Finally, the thickness of the silver layers is the same specified in Sec. II.

Figure 2 Horn nano-antenna geometry.

In a first run of simulations, the surrounding space and the inner part of the horn are both filled by silica. The idea, in fact, is to use such an antenna embedded in a module for energy harvesting purposes, capped by an anti-reflection coating. However, we are currently studying other solutions, based on a proper tapering of the silica core of the transmission line, in order to match the antenna to free-space. The results will be hopefully presented at the conference.

As previously anticipated, the nano-transmission line supports a quasi-TEM forward mode at 1500 nm, which is progressively transformed into a radiating mode by the horn shape. The electric field amplitude distribution reported in Fig. 3 clearly presents the described behavior and shows the similarities between a regular microwave horn and the proposed nano-antenna.

Figure 3 Map of the electric field amplitude distribution at the design wavelength of 1500 nm.

In microwave antenna engineering, the key parameter to describe the electrical properties of a radiator is given by the amplitude of the reflection coefficient at the input port. In Fig. 4 we report the variation of this parameter as a function of frequency. We note that the antenna is effectively matched with a reflection coefficient amplitude better than -15 dB in the frequency band between 185 and 270 THz. The absolute bandwidth is around 85 THz, corresponding to a fractional bandwidth of around 37%. In such a frequency band, thus, the optical signal is effectively leaving the source and propagating along the nano-transmission line.

In order to test how effectively the propagating energy is radiated by the horn nano-antenna, we have calculated also the antenna 3D gain pattern at the reference wavelength of 1500 nm (200 THz), at both the lower and upper boundaries of the frequency band in which we found a good matching, and at the central frequency (230 THz), as well. The corresponding results are reported in Figs. 5-8 and confirm that the energy is not only transmitted through the nano-transmission line, but

also efficiently radiated by the horn nano-antenna. In addition, as expected considering the microwave counterpart, at higher frequencies the antenna aperture becomes electrically larger and, consequently, the gain increases.

Figure 4 Amplitude of the reflection coefficient (i.e. scattering parameter S_{11}) at the input port of the horn nano-antenna reported in Fig. 3 as a function of frequency.

Figure 5 3D gain radiation pattern of the horn nano-antenna reported in Fig. 3 at 185 THz.

Figure 6 3D gain radiation pattern of the horn nano-antenna reported in Fig. 3 at 200 THz.

Figure 7 3D gain radiation pattern of the horn nano-antenna reported in Fig. 3 at 230 THz.

Figure 8 3D gain radiation pattern of the horn nano-antenna reported in Fig. 3 at 270 THz.

IV. CONCLUSIONS

In this paper, we have presented the numerical design of an horn nano-antenna consisting of an Ag-SiO₂-Ag symmetric nano-transmission line divaricated at one of its end in an horn shape. The nano-antenna has been designed to work in the near-infrared and the simulations performed have fully taken into account losses and dispersion of the involved materials.

The results obtained (around 37% of fractional impedance bandwidth for a reflection coefficient amplitude better than -15 dB and an average gain of 9 dBi within the bandwidth of operation) are rather promising and open the door to the possible implementation of such nano-antennas in modern and future telecommunication systems and innovative energy harvesting devices.

The authors are currently working also on the possibility to tune the antenna operation through the proper employment of optical nano-circuit elements [26]. One intriguing possibility could be the employment of such an antenna as the element of a planar antenna array for energy harvesting applications, whose beam is scanned in real time through tunable nano-circuits. Some considerations about this possible application will be given at the conference.

REFERENCES

- [1] A. Alù, and N. Engheta, "Tuning the scattering response of optical nanoantennas with nanocircuit loads," *Nature Photonics*, Vol. 2, pp. 307-310, 2008.
- [2] A. Alù, and N. Engheta, "Input impedance, nanocircuit loading, and radiation tuning of optical nanoantennas," *Phys. Rev. Lett.*, Vol. 101, 043901, 2008.
- [3] A. Alù, and N. Engheta, "Hertzian plasmonic nanodimer as an efficient optical nanoantenna," *Phys. Rev. B*, Vol. 78, 195111, 2008.
- [4] H. Guo, T. Meyrath, T. Zentgraf, N. Liu, L. Fu, H. Schweizer, and H. Giessen, "Optical resonances of bowtie slot antennas and their geometry and material dependence," *Opt. Expr.*, Vol. 16, No. 11, pp. 7756-7766, 2008.
- [5] R. Singh, C. Rockstuhl, C. Menzel, T. Meyrath, M. He, H. Giessen, F. Lederer, and W. Zhang, "Spiral-type terahertz antennas and the manifestation of the Mushiake principle" *Opt. Expr.*, Vol. 17, No. 2, pp. 9971-9980, 2009.
- [6] D. Dregely, R. Taubert, and H. Giessen, "3-D optical Yagi-Uda nanoantenna array," *Photonic Metamat. and Plasmonics*, OSA Conf., Tucson, AZ, USA, 2010.
- [7] F. Gonzalez and J. Alda, "Optical antennas as nano-probes in photonic crystals and dielectric waveguide structures" *EuCAP 2010 Conf. Proc.*, Barcelona, Spain, 2010.
- [8] J. Alda, J. M. Rico-Garcia, J. M. Lopez, and G. Boreman, "Optical antennas for nano-photonic applications," *Nanotechnology*, Vol. 16, pp. S230-S234, 2005.
- [9] K.B. Crozier, A. Sundaramurthy, G.S. Kino, and C.F. Quate, "Optical antennas: resonators for local field enhancement," *J. Appl. Phys.*, Vol. 94, pp. 4632-4642, 2003.
- [10] P. J. Schuck, D. P. Fromm, A. Sundaramurthy, G. S. Kino, and W. E. Moerner, "Improving the mismatch between light and nanoscale objects with gold bowtie nanoantennas," *Phys. Rev. Lett.*, Vol. 94, 017402, 2005.
- [11] P. Mühlschlegel, H. J. Eisler, O. J. F. Martin, B. Hecht, and D. W. Pohl, "Resonant optical antennas," *Science*, Vol. 308, pp. 1607-1609, 2005.
- [12] J. Aizpurua, G. W. Bryant, L. J. Richter, F. J. Garcia de Abajo, B. K. Kelley, and T. Mallouk, "Optical properties of coupled metallic nanorods for field-enhanced spectroscopy," *Phys. Rev. B*, Vol. 71, 235420, 2005.
- [13] E. Cubukcu, E. A. Kort, K. B. Crozier, and F. Capasso, "Plasmonic laser antenna," *Appl. Phys. Lett.*, Vol. 89, 093120, 2006.
- [14] E. K. Payne, K. L. Shuford, S. Park, G. C. Schatz, and C. A. Mirkin, "Multipole plasmon resonances in gold nanorods," *J. Phys. Chem. B*, Vol. 110, 2150-2154, 2006.
- [15] P. J. Burke, S. Li, and Z. Yu, "Quantitative theory of nanowire and nanotube antenna performance," *IEEE Trans. Nanotechn.*, Vol. 5, pp. 314-334, 2006.
- [16] G. W. Hanson, "On the applicability of the surface impedance integral equation for optical and near infrared copper dipole antennas," *IEEE Trans. Antennas Propagat.*, Vol. 54, pp. 3677-3685, 2006.
- [17] L. Novotny, "Effective wavelength scaling for optical antennas," *Phys. Rev. Lett.*, Vol. 98, 266802, 2007.
- [18] M. Schnell, A. Garcia-Exarri, A.J. Huber, K. Crozier, J. Aizpurua, and R. Hillenbrand "Controlling the near-field oscillations of loaded plasmonic nanoantennas" *Nature Phot.*, Vol. 3, pp. 287-291, 2009.
- [19] P. Chen and A. Alù, "Optical nanoantenna arrays loaded with nonlinear materials," *Phys. Rev. B*, Vol. 82, 235405, 2010.
- [20] D. Dey, J. Kohoutek, R. Gelfand, A. Bonakdar, and H. Mohseni, "Composite nano-antenna integrated with quantum cascade laser" *IEEE Photon. Tech. Lett.*, Vol. 22, No. 21, 2010.
- [21] A. Alù, and N. Engheta, "Three-dimensional nanotransmission lines at optical frequencies: a recipe for broadband negative-refraction optical metamaterials," *Phys. Rev. B*, Vol. 75, 024304, 2007.
- [22] A. Alù, and N. Engheta, "Optical nanotransmission lines: synthesis of planar left-handed metamaterials in the infrared and visible regimes," *J. Opt. Soc. America B*, Vol. 23, No. 3, pp. 571-583, 2006.
- [23] CST Studio Suite 2009, Computer Simulation Technology, <http://www.cst.com>.
- [24] P. B. Johnson and R. W. Christy, "Optical constants of the noble metals," *Phys. Rev. B* Vol. 6, pp. 4370-4379, 1972.
- [25] E. D. Palik, *Handbook of Optical Constants of Solids* (Academic, 1998).
- [26] N. Engheta, A. Salandrino, and A. Alù, "Circuit elements at optical frequencies: nanoinductors, nanocapacitors, and nanoresistors," *Phys. Rev. Lett.*, Vol. 95, 095504, 2005.