Horn Nano-Antenna at Near-Infrared Frequencies: Design and Potential Applications

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Abstract

Antennas working at near-infrared and optical frequencies are an emerging and innovating concept. As in radiowave and microwave frequency range, their purpose is to convert localized electromagnetic energy to free-space propagating radiation, and viceversa. The aim of this work, is to present a new type of nano-antenna: a nano-horn able to radiate, guide, and harvest efficiently the electromagnetic energy at near-infrared frequencies. Possible applications of the proposed horn nano-antennas are also discussed like, for instance, light-and thermal-emitting sources or detectors, photovoltaics and energy harvesting, spectroscopy, wireless secure communications, etc.

1. Introduction

The antenna represents a key-element in the design of wireless systems and generally its physical dimensions are comparable with the operating wavelength. Optical antennas are characterized by small scales, comparable to the wavelength of visible light. It demands fabrication accuracy better than 10 nm that, nowadays, can be reached with the use of novel top-down nanofabrication tools (e.g. focused ion beam milling and electron-beam lithography) and bottom-up self-assembly schemes. From the design viewpoint, it is not possible to apply the same concepts used for the design of microwave antennas since at higher frequencies the material response to an electromagnetic (EM) excitation is determined by a collective phenomena, i.e. plasmons, which lead to a large response in presence of a small stimulus and to a frequency-dependent permittivity and permeability functions [1].

The structure of the paper is as follows. In Section II, we describe the design of the horn nano-antenna and discuss the results obtained in terms of bandwidth, impedance matching and gain. In Section III, we present some potential applications of the horn nano-antenna in energy harvesting, smart lighting, optical wireless communication links, and spectroscopy.

2. Horn nano-antenna: design and numerical results

As it is well known in microwave engineering, an horn antenna is made of a metallic waveguide shaped at one of its ends in such a way to increase the physical aperture and progressively match the wave-impedance of the waveguide to the one of free-space. Therefore, the first step in the design of a horn nano-antenna is to find a nano-waveguide configuration which is capable of effectively guiding the light and presents a topology that can be tapered at one of its ends in order to be shaped as an horn. A suitable candidate for this purpose can be found in [2]-[3], where it has been demonstrated that a symmetric nano-transmission line, consisting of a non-plasmonic material slab sandwiched between two plasmonic layers, supports a fundamental forward mode confined between the two metallic layers having a strong electric field component orthogonal to them. We consider two parallel plates made of silver separated by air. In [2]-[3] the propagating mode is infinitely extended in the transverse direction. In order to obtain a strong lateral confinement of the field and create an optical rectangular waveguide, we insert cylindrical silver pillars arranged in a triangular lattice (Fig.1). The metallic parts have been modelled in CST Studio Suite [4] according to the experimental data in [5]. The key parameter to describe the electrical properties of the nano-horn radiator is given by the amplitude of the reflection coefficient at the input port (Fig. 2a). We note that the antenna is effectively matched with a reflection coefficient amplitude better than – 10 dB in a broad frequency band. In such a fre-

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quency band, thus, when the antenna is used in the transmitting mode, the optical signal is effectively leaving the source, propagating along the nano-transmission line and progressively transforming into a radiating mode by the horn shape, as reported in Fig. 2b at the wavelength of 1.5 μm.

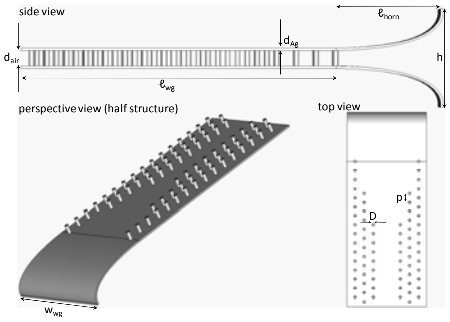

Fig. 1: Horn nano-antenna geometry. ℓ_{wg} = 6 μm, ℓ_{horn} = 2 μm, h = 2 μm, w_{wg} = 3,25 μm, d_{air} = 300 nm, d_{Ag} = 50 nm, D = 100 nm, p = 375 nm.

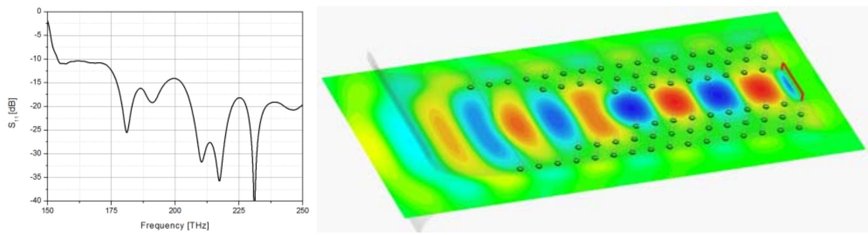

Fig. 2: (a) Amplitude of the scattering parameter S_{11} at the input port of the horn nano-antenna reported in Fig. 1 as a function of frequency. (b) Map of the electric field amplitude distribution at the design wavelength of 1.5 μm.

In order to test how effectively the propagating energy is radiated by the horn nano-antenna, we have evaluated also the 3D antenna gain pattern at the reference wavelength of 1.5 μm (200 THz) and at other four sample points within the frequency band of mono-modal operation. The corresponding results are reported in Fig. 3 and confirm that the energy is not only transmitted through the nano-transmission line, but also efficiently radiated by the horn nano-antenna: antenna gain is greater than 10 dBi within the frequency range of interest.

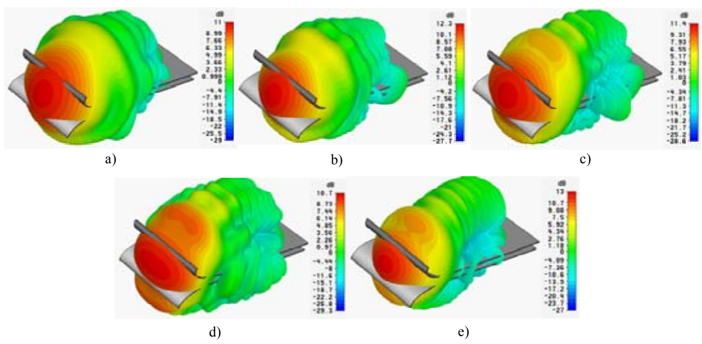

Fig. 3: 3D gain radiation pattern of the horn nano-antenna reported in Fig. 2 at a) 160 THz, b) 180 THz, c) 200 THz, d) 220 THz, and e) 240 THz.

3. Potential applications

The introduction of antenna concepts in optics will provide access to new technological applications. So far, most of the studied nano-antennas are nano-dipoles and nano-sphere, but also more complex radiators, such as the bow-tie slot [6], the spiral [7], and the Yagi-Uda [8] antennas, have been successfully investigated. Some of them have been studied in array configurations, showing a more directive radiation diagram. Even the proposed horn nano-antenna can be arranged in a dense array: in 1 mm^2, up to 150.000 nano-horns can be placed with a reduced mutual coupling between elements. The proposed topology, in fact, allows for low interactions between two adjacent antennas, due to the presence of the silver pillars. In addition, proper phase shifts between the different elements can be envisaged (e.g. by using the optical nano-circuit concepts presented in [9]), allowing for a beam direction control. By using phase transition materials (e.g. vanadium oxide) we may expect to electrically or thermally control the response of the loading nano-circuits, leading to real-time beam steering of the antenna beam. Such properties can be successfully used in several application fields. In photovoltaics, the incoming light causes a charge separation in a semiconductor material. The horn nano-antenna with its high gain and large bandwidth can harvest efficiently the solar radiation and localize it in proximity of the solar cell, making the transfer of energy between the two more efficient. In spectroscopy, an incident EM field excites the sample under study, which re-irradiates. The wavelength of the emitted light is related to the energy-level structure of the material, allowing for chemical identification. In this case, the horn nano-antenna placed at the end of an NSOM probe makes the evanescent waves from the surface into propagating mode into the pillar waveguide and guides them throughout the detector. In wireless security, one of the advantages of using infrared radiation as part of the physical medium for indoor wireless communications lies in the fact that infrared light, sharing many of the features of visible light, does not have the ability to propagate through opaque barriers, leaving the signal confined within the room from which it originated. From a security perspective, having the ability to target the data flow on the network to particular users and devices, straight from the physical layer, provides us with a great advantage towards any form of passive or active eavesdropping. An array of nano-horns can be used as directive transmitters of an optical access point which is able to direct the data flows towards the receiver. In order to compromise the communication, a malicious user would have to be physically present within the transmitter-receiver line-of-sight and have the ability to fool the receiving party towards the origin of the received data. Finally, antenna reciprocity can open the door to other interesting applications. Nowadays, in fact, light-emitting sources and light detectors are separate devices (e.g. a laser and a photodiode, respectively). Exploiting the horn nano-antenna concept, instead, it is possible to think of a system made of a nano-horn directly coupled to an optical fiber guiding the signals through an optical circulator at which a classical light source and a detector could be connected.

4. Conclusion

In this contribution, we have presented a new type of nano-antenna: a nano-horn consisting of an Ag-air-Ag symmetric nano-transmission line divaricated at one of its ends in an horn shape. The broadband operation and high gain are rather promising and open the door to possible implementations of such nano-antennas in several application fields.

References

[1] U. Fano, A common mechanism of collective phenomena, *Rev. Mod. Phys.*, Vol. 64, pp. 313-319, 1992.

[2] A. Alù and N. Engheta, Three-dimensional nano-transmission lines at optical frequencies: A recipe for broadband negative-refraction optical metamaterials, *Phys. Rev. B*, Vol. 75, 024304, 2007.

[3] A. Alù and N. Engheta, Optical nano-transmission lines: synthesis of planar left-handed metamaterials in the infrared and visible regimes, *JOSA B*, Vol. 23, pp. 571-583, 2006.

[4] CST Studio Suite 2010, Computer Simulation Technology, http://www.cst.com.

[5] P.B. Johnson and R.W. Christy, Optical constants of noble metals, *Phys. Rev. B*, Vol. 6, pp. 4370–4379, 1972.

[6] 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. Express,* Vol. 16, 7756, 2008.

[7] R. Singh, C. Rockstuhl, C. Menzel, T. Meyrath, M. He, H. Giessen, F. Lederer, W. Zhang, Spiral type terahertz antennas and the manifestation of the Mushiake principle, *Opt. Express* Vol. 17, 9971, 2009.

[8] J. Li, A. Salandrino, and N. Engheta, Optical spectrometer at the nanoscale using optical Yagi-Uda nanoantennas, *Phys. Review B,* Vol. 79, 195104, 2009.

[9] N. Engheta, Circuits with light at nanoscales: optical nanocircuits inspired by metamaterials, Science, 317, 1698, 2007.