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Improving the directivity of the plasmonic sectoral horn nanoantenna using lens in its aperture

* Masumeh Sharifi * Najmeh Nozhat * Ehsan Zareian-Jahromi
* Faculty of Electrical Engineering, Shiraz University of Technology, Shiraz, Iran

Abstract
Horn antennas can result in good impedance matching between the waveguide and free space due to the gradual increase in the aperture size. In this paper, a novel plasmonic sectoral horn nanoantenna based on using lens in the aperture is proposed. It is investigated that in addition to improvement of the directivity, the reflection coefficient is also reduced using the proper lens structure. The maximum directivity improvement is about 2 dBi compared to the structure without lens. Also, it is shown that the radiation pattern can be controlled by utilizing electro-optical material as the lens.

Keywords: Directivity, Electro-optic effect, Plasmonic Horn Nanoantenna, Reflection Coefficient.

1. Introduction

Antennas are used for optimum energy transmission to free space in a wide range of electromagnetic spectrum. According to the development of the basic principles of microwave antennas performance at higher frequency regime, metal nanoantennas can be used to transmit and receive lightwaves. Although metals behave almost as perfect electric conductor at microwave frequencies, they support surface plasmon polaritons (SPPs) at optical frequencies and hence, have a plasmonic response. Plasmonic antennas are used in various applications such as near-field spectroscopy [1], photovoltaic [2], detectors [3], light propagation [4, 5], sensors [6], nonlinear light applications [7], and wireless communications [8-10]. Monopole, dipole, and Yagi-Yoda plasmonic antennas have been proposed and analyzed at optical frequencies so far [11-13].

In recent years, the researches on nanoantennas are focused on manufacturing problems, better impedance matching, higher efficiency, and bandwidth improvement. Despite the applications of horn antennas at microwave frequencies, these antennas have attracted less attention at optical frequencies. A gradual increase of the horn antenna aperture improves the impedance matching between the exciting waveguide and free space. Moreover, a proper design of these antennas can increase the directivity.

In this paper, a new plasmonic sectoral horn nanoantenna is proposed to improve the directivity and reflection coefficient at 1550 nm wavelength based on utilizing a proper lens structure in the antenna aperture. In addition, we have used the electro-optical materials to control the antenna radiation pattern.

2. The proposed structure and simulation results

A schematic view of a sectoral horn nanoantenna is shown in Fig. 1. The antenna aperture is opened in the *z* direction (electric field direction) and coupled to a light transmission line. The entire structure is constructed of silver and embedded in glass with the refractive index of *n*=1.44. The dielectric constant of silver is selected to be $\varepsilon_m = -132.8 + j3.32$ at the wavelength of 1550 nm, based on Johnson and Christy's data [14].

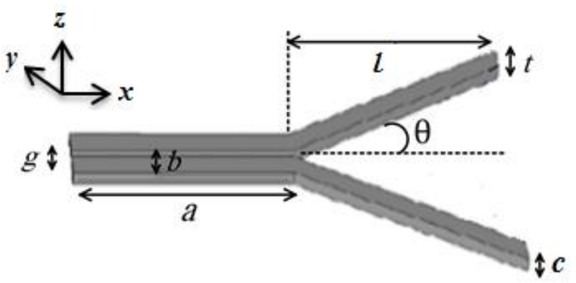


Fig. 1: Geometry of the sectoral horn nanoantenna

The parameters of the transmission line are selected to be *a*=1000 nm, *g*=30 nm, *b*=100 nm, *c*=50 nm, and *t*=100 nm. Also, the length of the horn antenna and the flaring angle are *l*=1000 nm and $\theta = 26.6^{\circ}$, respectively. The simulated radiation pattern of the antenna is depicted in Fig. 2.

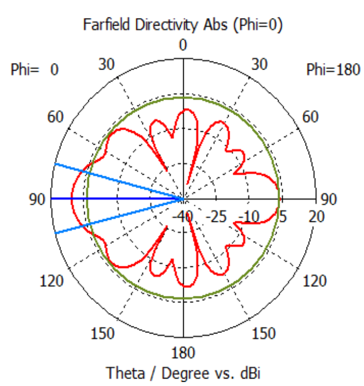


Fig. 2: Radiation pattern of the sectoral horn nanoantenna of Fig. 1

An antenna with higher maximum directivity can transfer the input power to the radiating power in a specified direction more efficiently. In many applications, directive antennas are desired. Although increasing the size of the antenna can be utilized to obtain high directivity, it would result in more loss and therefore less efficiency due to the effect of supporting surface plasmon polariton waves in the optical range. To overcome this disadvantage, a novel structure has been proposed in which the directivity of the antenna has been increased without enlarging the relative size of the antenna. In addition to directivity improvement, the reflection coefficient of the antenna is also reduced. The proposed structure is based on utilizing a proper lens at the aperture of sectoral horn nanoantenna resulting in the improvement of the radiation pattern. This improvement is achieved according to the reduction of the electric field phase variation at the antenna aperture. The geometry of the sectoral horn nanoantenna utilizing a lens structure in its aperture is shown in Fig. 3. The parameter k is the width of the lens and is chosen to be 550 and 450 nm for the *Si* and As_2S_3 lenses, respectively.

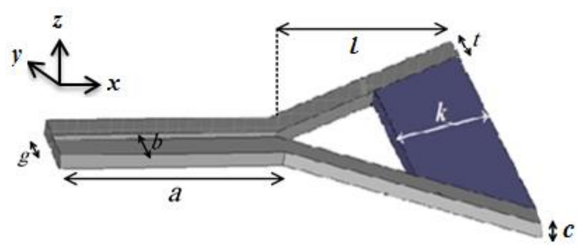


Fig. 3: Geometry of the proposed sectoral horn nanoantenna utilizing a flat lens in its aperture

The radiation patterns of the proposed nanoantenna structure with *Si* and As_2S_3 lenses are depicted in Fig. 4.

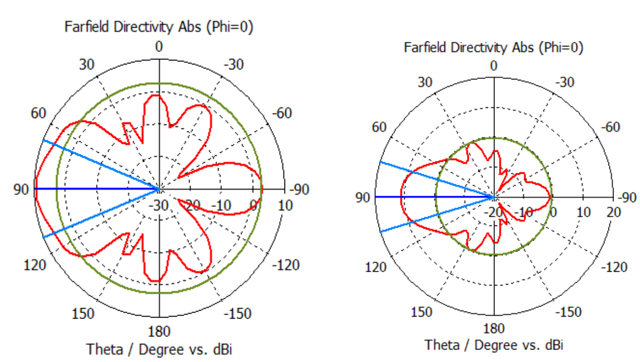
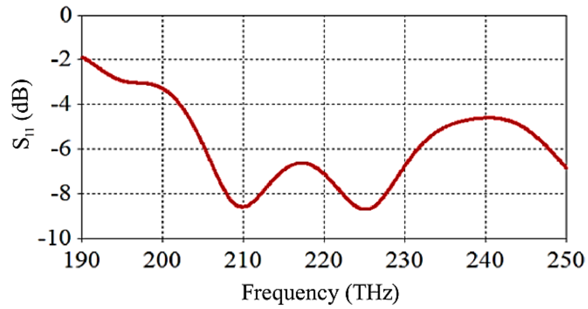
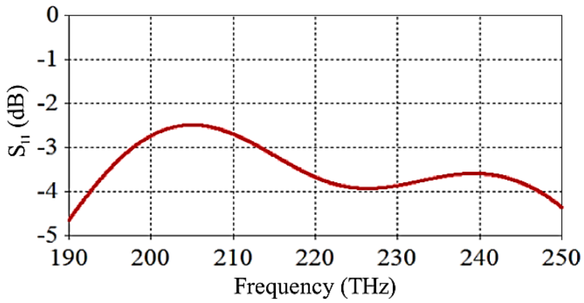


Fig. 4: Radiation pattern of the sectoral horn nanoantenna of Fig. 3 with (a) *Si* and (b) As_2S_3 lenses in the aperture

In Fig. 5, the S_{11} parameter of the sectoral horan antenna without and with the lens is demonstrated. It can be seen that by using the lens in the antenna aperture, the reflection coefficient is reduced.





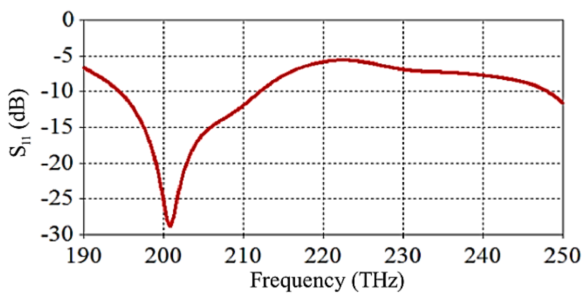


Fig. 5: S_{11} parameter of the horn antenna of Fig. 3 (a) without lens, (b) with *Si* lens, and (c) with As_2S_3 lens

The dielectric constant of an electro-optical material is changed by the applied electric field. Therefore, the antenna radiation pattern can be automatically controlled by using the electro-optical materials as the lens structure. The refractive index of materials with the quadratic electro-optic effect is given as [15]:

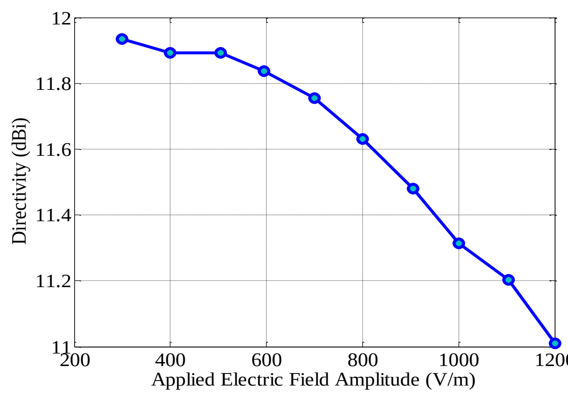
$$n = n_o + n_2 I, \tag{1}$$

where n_0 and n_2 are the linear and nonlinear refractive indices, respectively and I is the optical intensity. The linear and nonlinear refractive indices of Si and As_2S_3 materials are depicted in Table. 1.

Material	n_o	$n_2\left(cm^2/W\right)$
Si	3.4	2.7×10^{-14}
As_2S_3	2.4	2×10^{-13}

Table 1. Linear and nonlinear refractive indices of Si and As_2S_3 [15].

The antenna directivity versus the applied electric field amplitude for Si and As_2S_3 lenses are shown in Fig. 6. The refractive index of electro-optical materials is enhanced by increasing the applied electric field according to Eq. 1.



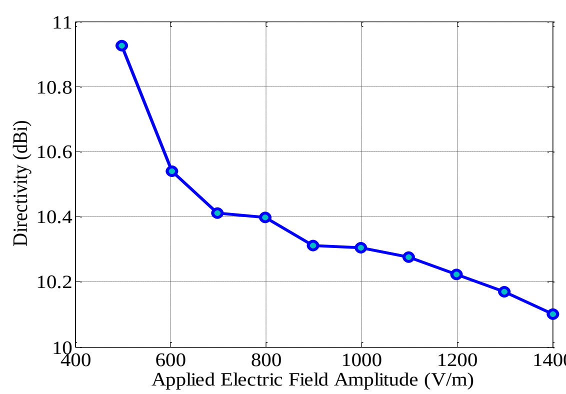


Fig. 6: Antenna directivity versus the applied electric field amplitude for (a) *Si* and (b) As_2S_3 lenses in the aperture

Therefore, the antenna directivity is decreased. The threshold amplitudes of the applied electric field for the sectoral horn nanoantenna with Si

and As_2S_3 lenses are 300 V/m and 500 V/m, respectively.

The second proposed sectoral horn nanoantenna utilizing a lens structure in its aperture is shown in Fig. 7. The outer surface of the lens is flat and its inner surface is determined as:

$$z = \frac{x^2}{ln'}, \qquad (2)$$

where the length of the antenna is l=1000 nm and n' is a variable parameter to achieve maximum directivity.

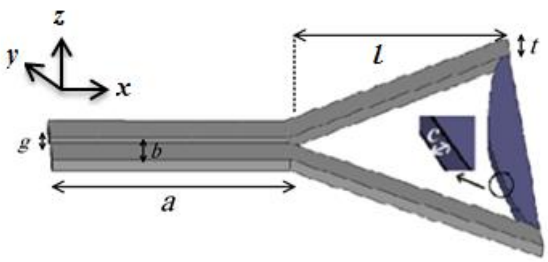


Fig. 7: Schematic view of the proposed sectoral horn nanoantenna with the lens in its aperture

The radiation patterns and S_{11} parameter of the proposed nanoantenna of Fig. 7 with *Si* and As_2S_3 lenses are demonstrated in Figs. 8 and 9, respectively.

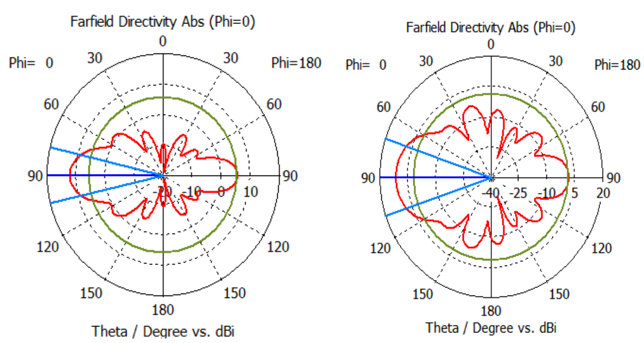


Fig. 8: Radiation pattern of the sectoral horn nanoantenna of Fig. 7 with (a) *Si* and (b) As_2S_3 lenses in the aperture.

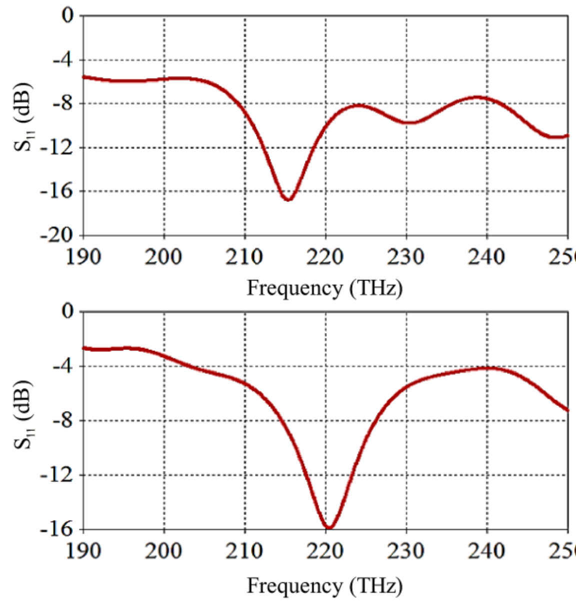


Fig. 9: S_{11} parameter of the horn antenna of Fig. 7 with (a) *Si* and (b) As_2S_3 lenses

The radiation parameters of the plasmonic sectoral horn antenna without and with *Si* and As_2S_3 lenses are listed in Table. 2.

Antenna	n'	D (dBi)	S_{11} (dB)
Horn	-	10.2	-3.36
Horn + *Si* lens of Fig. 3	-	9.93	-4.22
Horn + As_2S_3 lens of Fig. 3	-	11.42	-8.81
Horn + *Si* lens of Fig. 7	2.3	11.92	-4.44
Horn + As_2S_3 lens of Fig. 7	2.3	10.92	-5.98

Table 2. The radiation parameters of the horn antenna without and with Si and As_2S_3 lenses

The maximum directivity is obtained about D=11.92 dBi for the horn antenna of Fig. 7 with *Si* lens and $n'=2.3$. Although the maximum directivity of the antenna is attained for the structure of Fig. 7, but due to the smaller value of the S_{11} parameter of the horn antenna of Fig. 3 with As_2S_3 lens, the lens profile of Fig. 3 is more suitable. Also, the S_{11} parameter and the directivity of the plasmonic sectoral horn nanoantenna are improved by utilizing the lens in the antenna aperture.

3.Conclusion

In this paper, a new sectoral horn nanoantenna based on utilization of lens in its aperture is proposed to improve the directivity and reflection coefficient. It is investigated that by us using the Si and As_2S_3 lens structures the directivity is increased about 2 dBi compared to the nanoantenna structure without lens. Moreover, the S_{11} parameter is decreased by the value of 5.45 dB. Also, it is shown that the radiation pattern can be controlled by using electro-optical material as the lens.

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