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Investigation of a nanostrip patch antenna in optical frequencies

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Abstract This is the first report and investigation of a patch antenna in optical frequency range. Variety of plasmonic nanoantenna reported so far is good at enhancing the local field intensity of light by orders of magnitude. However, their far-field radiation efficiency is very poor. The proposed patch antenna emits a directional beam with high efficacy in addition to enhancing the intensity of near field. The nano-patch antenna (NPA) consists of a square patch of gold film of dimension 480 nm^2, placed on a substrate of dielectric constant $\varepsilon_r = 3.9$ and thickness 150 nm with a ground plane of gold film of dimension 1,080 nm^2. The NPA resonates at 210 THz and has gain nearly 2 dB and radiation efficiency 45.18 %. The NPA might be useful in variety of applications such as optical communication, nano-photonics, biosensing, and spectroscopy.

1 Introduction

Plasmonic nanoantenna have caught great attention to several researchers worldwide due to their potential application in diversified fields, such as biological imaging, efficient confinement and enhancement of light at nanoscale, efficient light coupling to nanoscale, guiding and redirecting light at nanoscale, near-field and far-field inter-conversion, optical information processing at nanoscale, nanolight-emitting devices/sources, nonlinear medium as an optical switch, solar cells, and for realization of metamaterials. [1–3]. Thus, plasmonic nanoantenna may have much broader applications as compared to their RF counterparts where they are primarily used for transmission and reception of signals wirelessly. This urges for the exploration and design of novel antennas in optical frequencies.

In the last few years, several plasmonic antennas have been studied which work in optical frequencies such as dipole, bowtie, cross nanoantenna, and slot and spiral antennas [4–7]. When illuminated by light of suitable frequencies, these antennas can enhance intensity of near field by three to four orders of magnitude. However, unlike radio antennas, their far-field radiation is extremely poor, and as a result, they cannot play the effective role of their radio frequency counterparts in transmission and reception of optical signals wirelessly.

In this work, we propose and numerically investigate the properties of a nano-patch antenna (NPA) which not only can enhance the intensity of local fields but also emit far-field radiation efficiently. The proposed antenna is a planar structure, and the counterpart of microstrip patch antenna used ubiquitously in microwave frequency range [8]. The excitation of localized Plasmon in metallic nanostructures is what makes such nanoantennas different from radio antennas fundamentally.

1.1 Antenna geometry and simulation

The nano-patch antenna consists of a rectangular patch of gold film of dimension 480 nm^2, placed on a substrate of dielectric constant $\varepsilon_r = 3.9$ and thickness 150 nm with a ground plane of gold of dimension 1,080 nm^2 as shown in Fig. 1. The patch is fed by a nanostrip line which propagates light injected into this by a nanoport. There is a capacitive gap of 25 nm between the patch and the nanostrip line for better impedance match [8].

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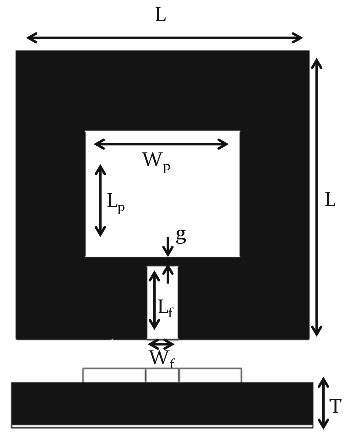

Fig. 1 Nano-patch antenna geometry

Table 1 Antenna dimension

Parameter	Value (nm)
Length of radiating patch (L_p)	480
Width of radiating patch (W_p)	480
Length of feedline (L_f)	280
Length of feedline (W_f)	120
Length of square substrate	1,080
Gap (g)	25

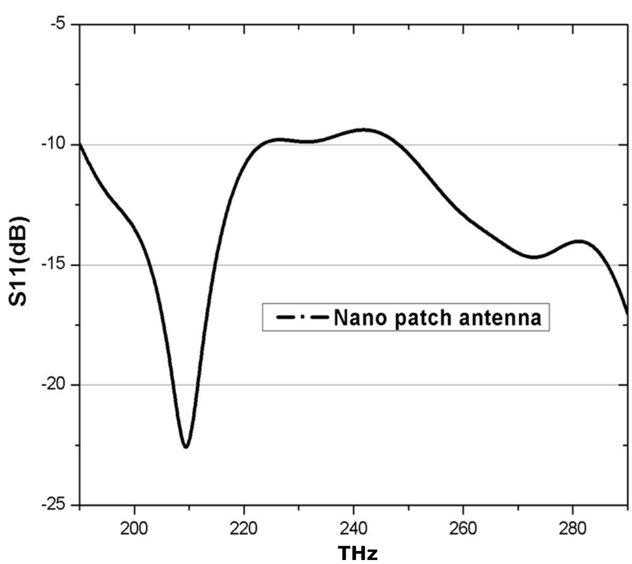

Fig. 2 S11 characteristics of NPA

Using CST Microwave studio, working on finite integration technique, the performance of the NPA is calculated. Gold permittivity has been incorporated using Drude mode:

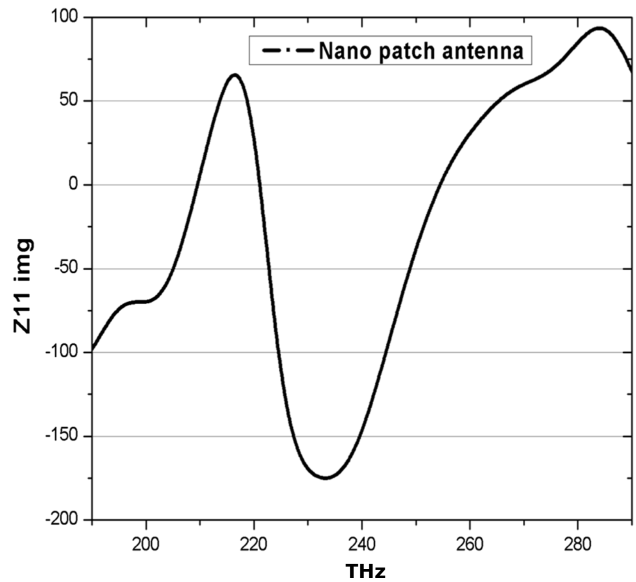

Fig. 3 Z11 imaginary part of NPA

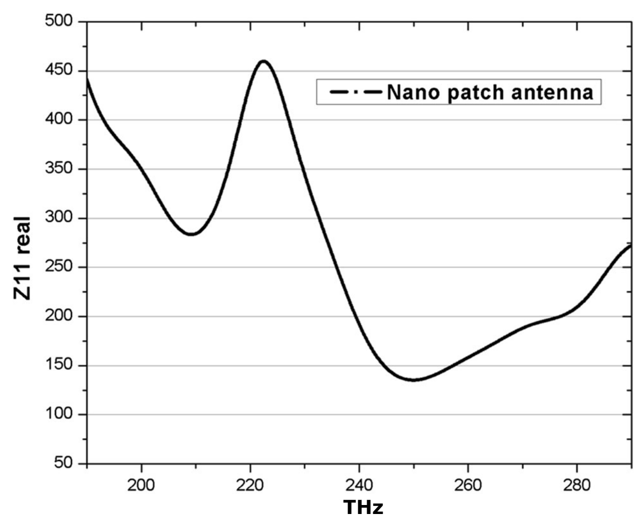

Fig. 4 Z11 real part of NPA

$$\varepsilon_{Au} = 1 - \frac{\omega_p^2}{\omega(\omega + i\omega_c)} \quad (1)$$

where plasma frequency $\omega_p = 1.296 \times 10^{16}$ rad/sec and collision frequency $\omega_c = 1.265 \times 10^{14}$ rad/sec. The antenna parameters are presented in Table 1.

2 Result and discussion

Nano-patch antenna shows the broadband behavior depicted in Fig. 2, and the input impedance imaginary part of the NPA is given in the Fig. 3 and the real part

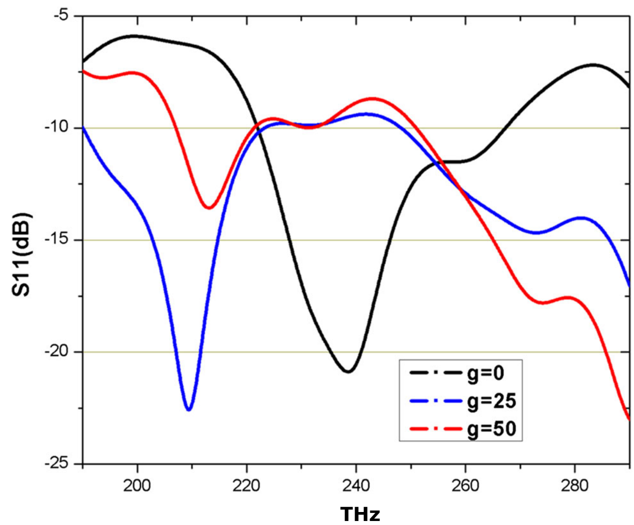

Fig. 5 S11 characteristics of NPA with respect to the Gap $g = 0$ nm, 25 nm and 50 nm

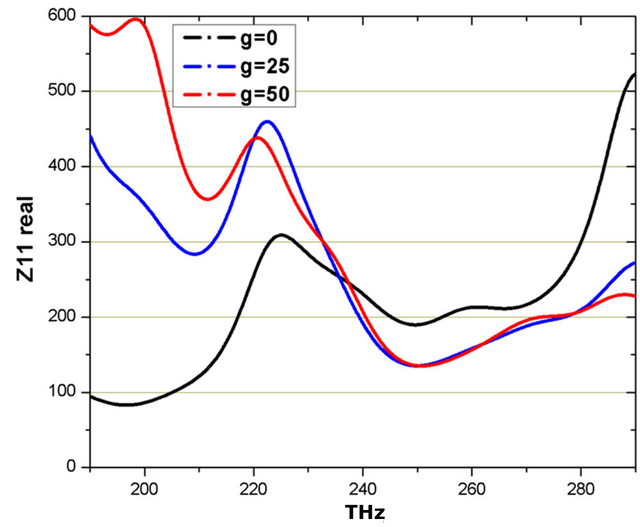

Fig. 7 Z11 real part of NPA with respect to the Gap $g = 0$ nm, 25 nm and 50 nm

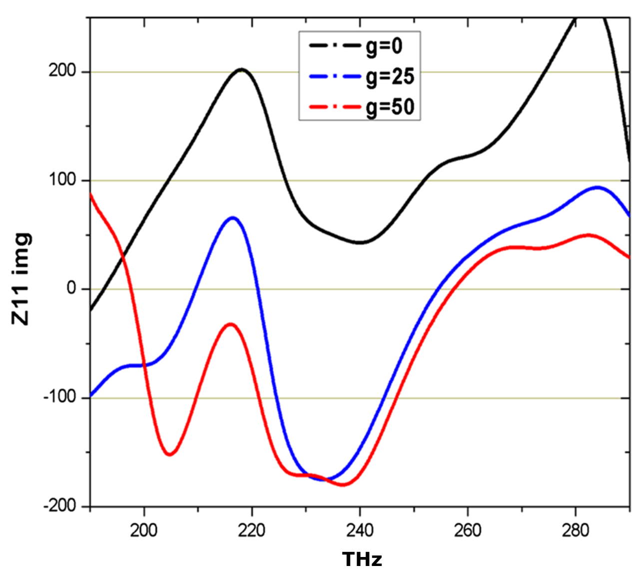

Fig. 6 Z11 imaginary part of NPA with respect to the Gap $g = 0$ nm, 25 nm and 50 nm

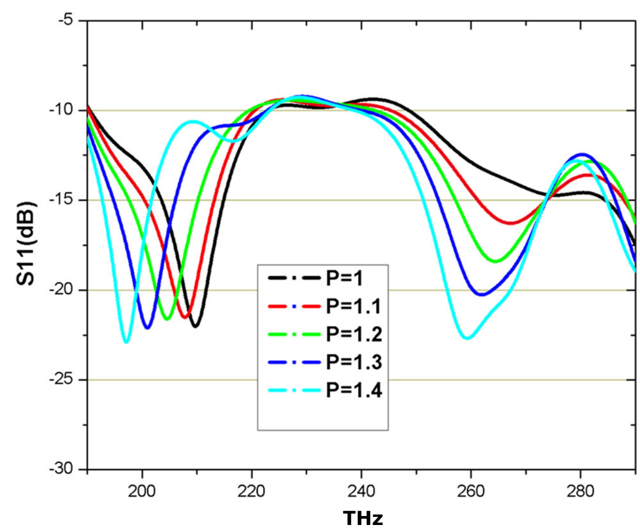

Fig. 8 S11 characteristics of NPA with respect to the aspect ratio $p = 1$, 1.1, 1.2, 1.3, and 1.4

in Fig. 4. To achieve this matching, a gap g is used. The effect of the gap on the S11 parameter of NPA is shown in Fig. 5, and the imaginary and real part of input impedance is given in Fig. 6 and Fig. 7, respectively. It is clear here that the capacitive gap tunes out the inductive behavior of the feed and improves the bandwidth of the NPA. With an increase in aspect ratio, the resonant frequency decreases, as shown in Fig. 8 and Table 2, and this is in conformity with the behavior of patch antenna in radio frequency.

Table 2 Variation of gain and efficiency with patch

Aspect ratio $p = \frac{L_p}{W_p}$	Gain (dB)	Radiation efficiency (%)	Resonant frequency (THz)
1	2.51	45.18	210
1.1	1.59	44.90	206.2
1.2	1.40	47.20	202.0
1.3	0.59	47.53	197.8
1.4	0.543	44.41	194.3

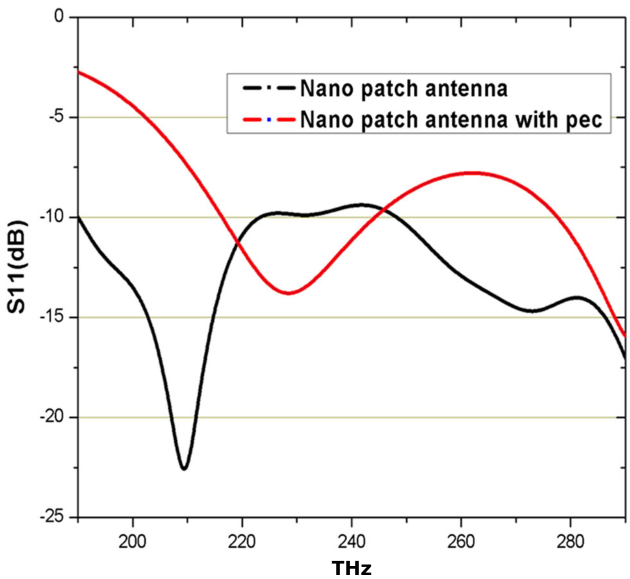

Fig. 9 S11 characteristics comparison of NPA and NPA with pec

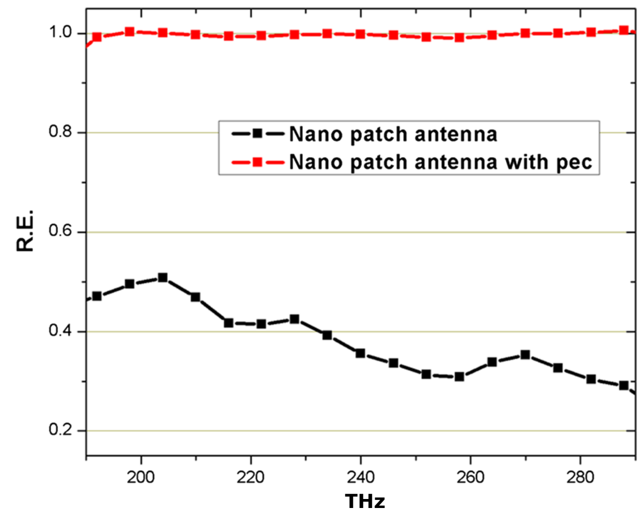

Fig. 10 Radiation efficiency comparison of NPA and NPA with pec

The comparison of S11 parameter in term of material lossy gold and PEC (perfect electric conductor) is given in Fig. 9. The radiation efficiency of the NPA is substantially high (45.18 %) in spite of lossy gold used for patch and ground plane depicted in Fig. 10. Gain of the NPA is maximum (2.51 dB) when the patch is square of each side 480 nm and its resonant frequency is 210 THz. The far-field radiation from NPA is directional having 3 dB beamwidth 72.9° in the vertical plane shown in Fig. 11. Assuming the patch and ground plane of NPA made of perfect electric conductor without any loss, the resonant frequency is found to be 225 THz, gain 8.4 dB, and radiation efficiency close to 100 %, as given in Table 3. The NPA made of gold resonates at lower frequency due to excitation of surface plasmon and has lower gain and radiation efficiency due to lossy gold material in optical frequency range.

Table 3 Comparison of NPA and NPA with pec

Patch material	HPBW	Gain (dB)	Radiation efficiency (%)	Resonant frequency (THz)
Gold	72.9°	2.51	45.18	210
PEC	128°	8.4	100	225

3 Conclusions

We have proposed and designed a nano-patch antenna to work in optical frequency range. Different from optical

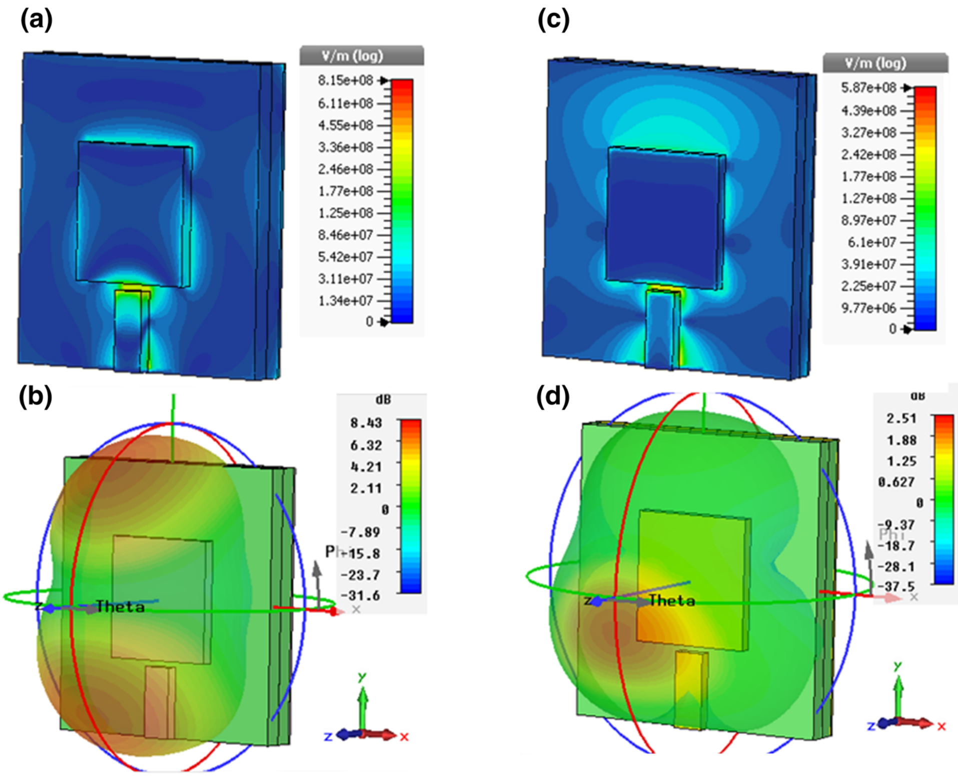

Fig. 11 NPA with pec near-field excitation at 225 THz (**a**), NPA with pec Far-field at 225 THz (**b**), NPA near-field excitation at 210 THz (**c**), NPA far-field excitation at 210 THz (**d**)

antennas reported so far the nano-patch antenna emits far-field radiation with high radiation efficiency. This may catch the attention of several researchers who may allude to use this in variety of applications.

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