Equivalent Radius of Dipole-patch Nanoantennas with Parasitic Nanoparticle at THz band

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***Abstract*-Recent developments in nano-technology have jumped from well established radiowave concept and analogy. Many designs have been proposed to investigate the capabilities of this high frequency regime. In this article, the dipole-patch nanoantenna has been designed based on effective wavelength scaling and equivalent radius concept. The square cross-sectional dimension has been adapted from circular radius equivalent geometry. The concept that has been used could be a prime knowledge for designing more complex patch nanoantennas structures. In addition, the nanoantennas have a unique interest because of its capability in focusing light into a small gap region and it can be tuned at various frequency bands. Due to this, a parasitic nanoparticle is introduced at the center of the feed gap to provide a double gap region. This has enabled the field radiation to increase by approximately 22%. The enhancement factor of the field radiation will increase the efficiency of energy collector and light-emitting applications.**

I. INTRODUCTION

Terahertz (THz) technology has received voluminous attention worldwide. Devices exploiting this waveband are set to become increasingly important in a very diverse range of applications. Despite such a great potential, the analysis to describe the properties of THz devices is still lacking and more investigation are needed to be done. Numerous efforts have been published in employing radio frequency analogy into THz regime. Those works are now being realized and it is interesting to see how radiowave design analogy is being redefined at THz region.

A straightforward design rules for radiowave is not valid at THz. The design parameters are not proportional to wavelength, λ, because the penetration of wave cannot be ignored anymore [1]. The different concept between radiowave and THz antennas has been discovered through plasmonic nanowire antennas where the volume current is considered for THz analysis [2]. Furthermore, the frequency dispersion of the effective permittivity must be taken into account for THz region [3].

Taking into account of the design rules, the performance of nanoantennas need to be further considered. The field enhancement is one vital property in THz. The bowtie antenna is studied with dipole, where the bowtie is capable in enhancing the field better than dipole [4]. Numerous articles have been reported, to demonstrate the field enhancement in order to increase their performances [5], [6], [7].

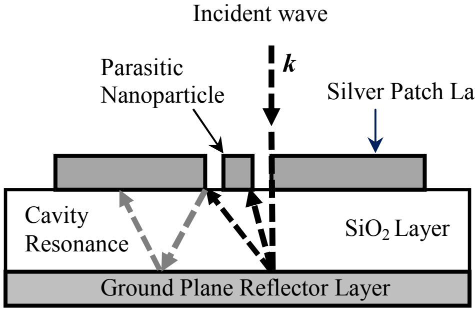


Figure 4. Cross sectional geometry of a dipole-patch with parasitic nanoparticle

II. DIPOLE PATCH NANOANTENNA DESIGN

The dipole-patch nanoantenna was designed based on effective wavelength, λ_{eff}. The direct scaling law for effective wavelength, λ_{eff} has been derived from [8] as

$$\lambda_{eff} = n_1 + n_2[\lambda/\lambda_p] \tag{1}$$

where λ_p is the plasma wavelength and $n_1 + n_2$ are dependent coefficients of dimensions with regard to the antenna geometry.

A single antenna segment (rod wire) has been used to derive the effective wavelength for a half-wave dipole. The antenna radius, R is assumed to be smaller than the wavelength, λ $(R << \lambda)$. The effective wavelength can be written as:

$$\lambda_{eff} = \frac{\lambda}{\sqrt{\varepsilon_s}} \sqrt{\frac{4\pi^2 \varepsilon_s \left(R^2/\lambda^2\right) \tilde{z}(\lambda^2)}{1 + 4\pi^2 \varepsilon_s \left(R^2/\lambda^2\right) \tilde{z}(\lambda^2)}} - 4R \tag{2}$$

where ε_s is dielectric constants for vacuum medium [8].

Later, the Drude theory has been generalised to define the frequency dependency of silver permittivity at THz band. According to [7],[9], the silver permittivity is given by $\varepsilon_{Ag} = \varepsilon_\infty - \omega_p^2/\omega(\omega - i\delta)$. The properties of silver, Ag used are $\varepsilon_\infty \approx 3.57$, $\lambda_p \approx 135$ nm and $R = 5$ nm. The symbol of ε_∞ is defined as a contribution of dielectric function due to interband transitions. The silicon oxide, SiO_2 has been applied to be dielectric layer with bulk dielectric constant of 2.13. The correlation of effective wavelength based on Equation (2) is shown in Fig. 1.

At this point, an equivalent radius concept is used by substituting the circular rod radius, R with noncircular cross section, l x l which is the equivalent radius of the circular rod as depicted in Fig. 2a. The equivalent radius correlation can be referred to [10] as

$$R = 0.59l \tag{3}$$

By replacing R = 5 nm, $l \cong 8.5$ nm. The proposed dipole-patch cross section will then become l x l = 8.5 nm x 8.5 nm as depicted in Fig. 2b. In this article, two cases has been studied, which are $L_1 = 300$ nm and $L_2 = 200$ nm. The feed gap distance between dipole-patch arms is set at 2 nm.

The parasitic nanoparticle is then introduced at the center of feed gap. The distance between nanoparticle and dipole arm is 2 nm. The objective is to enhance the field strength of the dipole-patch nanoantenna. Higher field strength is predicted as incident waves having two feed gap to trap and collect the field. The presence of a ground plane reflector will enable a directive lobe. This will furthermore resulted in the incident wave to be collected more effectively through the beam angle. The dipole-patch with parasitic nanoparticle is illustrated in Fig. 3.

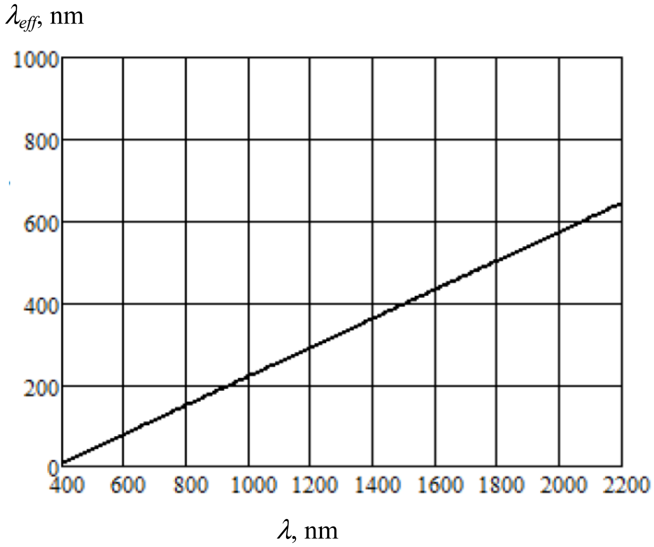
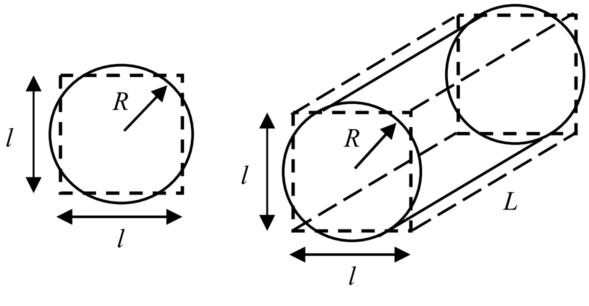


Figure 1. Cross sectional geometry of a dipole-patch with parasitic nanoparticle



(a) (b)

Figure 2: Circular cylinder geometrical shape and equivalent noncircular cross section.

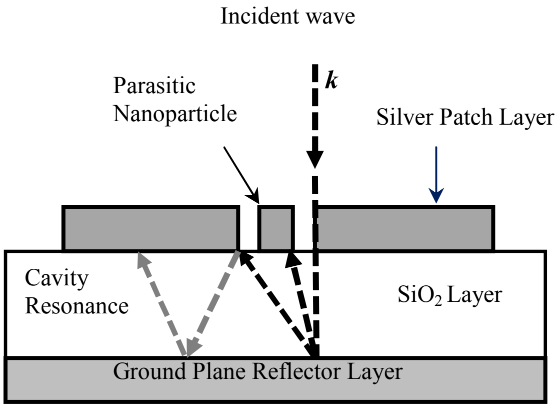


Figure 3. Cross sectional geometry of a dipole-patch with parasitic nanoparticle

III. RESULTS AND DISCUSSION

In order to verify the theory of equivalent radius concept at THz band, half-wave dipole-patches is simulated and numerically analysed. A dipole-patch of $L_1 = \lambda_1/2 = 300$ nm has been designed. The dominant peak is observed at $\lambda_1 = 2068$ nm (or 145 THz) as shown in Fig. 4. On the other hand, an effective wavelength is calculated as $\lambda_{eff1} = 2L_1 = 600$ nm which agrees well with an incident wavelength of $\lambda = 2080$ nm as portrayed in Fig. 1. A second dipole-patch of $L_2 = \lambda_2/2 = 200$ nm is designed to further investigate the theory. The simulated dominant peak is observed at $\lambda_2 = 1580$ nm (or 190 THz) and the calculated $\lambda_{eff2} = 2L_2 = 400$ nm is shown at $\lambda = 1520$ nm. All results are tabulated in Table 1. It has been demonstrated that the effective wavelength described in (2) with noncircular equivalent geometrical is closely equivalent to the simulated result.

Table 1: Simulations and calculations of dipole-patch resonance with respect to effective wavelength

Half-wave dipole, L (nm)	Effective Wavelength, λ_{eff} (nm)	Resonances	
		Simulations (nm)	Calculations (nm)
$L_1 = 300$	600	2068	2080
$L_2 = 200$	400	1580	1520

Next, the local electrical field strength is probed at the location of the centre feed gap. The plane wave is used to excite the dipole-patch antenna with a value of 1 V/m. Fig. 3 shows the local electrical field for L_1 and L_2 where the values are recorded at 392 V/m and 380 V/m, respectively.

Then, the field increment with parasitic nanoparticle is studied. The nanoantennas are denoted as L_{1p} and L_{2p}. The field distributions for both nanoantennas are shown in Fig. 5. The corresponding dominant resonances peaked at 145 THz and 190 THz, respectively. The peak resonance remains the same with the results shown in the dipole-patch without parasitic nanopartical. It is that the dominant resonance has not been controlled by the parasitic element. On other hand, higher field strength is observed as expected. The corresponding field radiations have been increased approximately at 440 V/m and 418 V/m, respectively. The increments for both cases are ≅11% at each gap. If two feed gaps are considered, the total field collection can be achieved up to 22%.

The local electrical field distribution for L_1 is observed at the reference plane through y-axis. It can be seen that the field distribution is concentrated higher at the feed gap as depicted in Fig. 6. Moreover, for L_{1n}, two peaks of electrical field concentrated at the two feed gaps in order to double the field strength as depicted in Fig. 7. The model has been generated using electromagnetic modeling software, CST Studio illustrated that the field flows and concentrated at the feed gap. This evidence signified a correct location to amass the energy and transfer it for conversion process. Therefore, an efficiency of nanoantennas can be enhanced for energy collector and light emitting applications.

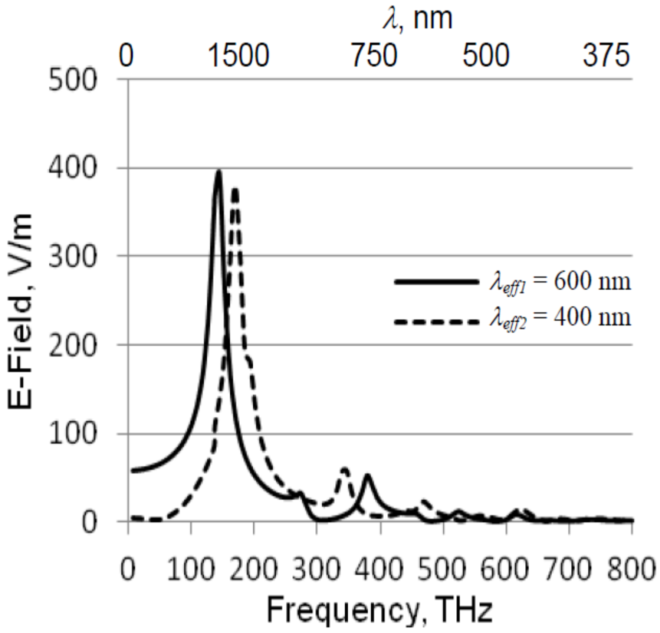


Figure 4: Spectral resonances of half-wave dipole-patch nanoantenna.

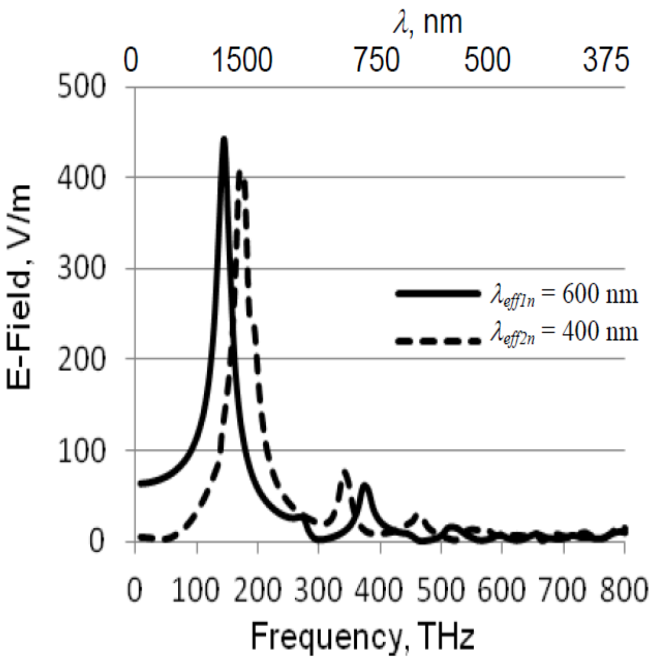


Figure 5: Spectral resonances of dipole-patch nanoantenna with parasitic element.

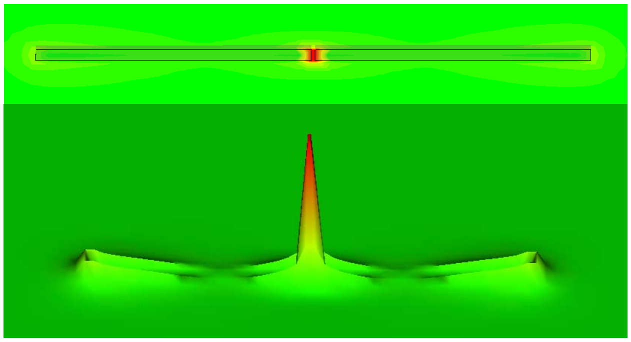


Figure 6: Local electrical field amplitude distributions of dipole-patch nanoantenna.

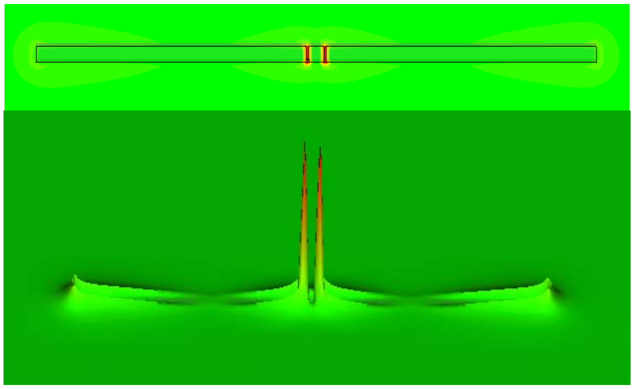


Figure 7: Local electrical field amplitude distributions of dipole-patch nanoantenna with parasitic nanoparticle.

IV. CONCLUSION

This article presents an analytical model to describe the dipole-patch nanoantennas with parasitic nanoparticles at THz band. The effective wavelength analogy of circular wire has been successfully transformed to noncircular cross-section of dipole-patch. Having obtained an equivalent radius concept, it is simple to expand the radiowave theory into THz region. The agreement is not limited to the equivalent radius of cross-section only. It can also enhance the electrical field radiation with the introduction of parasitic nanopartical at the feed gap. The increment of 11% has been achieved through the proposed design. This field enhancement is a crucial property for energy collector and light-emitting applications.

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REFERENCES

[1] Lukas Novotny and Niek van Hulst. 2011. Antennas for light. *Nature Photonic*. Vol. 5. pp. 83-90

[2] Jens Dorfmuller, Ralf Vogelgesang, Worawut Khunsin, Carsten Rockstuhl, Cristoph Etrich and Klaus Kern. 2010. Plasmonic Nanowire Antennas: Experiment, Simulation and Theory. *Nano Letter*. Vol. 10. pp. 3596-3603

[3] F. J. Gonzalez, G. Almpanis, B. A. Lail, and G. D. Boreman. 2004. Wave propagation in planar antennas at THz frequencies. *Antennas and Propagation Society International Symposium*. Vol. 1. pp. 113-116

[4] Sakhno M. V and Gumenjuk-Sichevska J. V. 2010. Electric Field Enhancement Computation for Intergrated Detector of THz range. *International Kharkov Symposium on Physic and Engineering of Microwave, Millimeter & Submillimeter Wave (MSMW)*

[5] Hideaki Tanaka, Yusuke Sugitani, Jiro Kitagawa, Yutaka Kadoya, Francois Blanchard, Hideki Hirori, Atushi Doi, Masaya Nagai and Koichiro Tanaka. 2010. Enhancement of THz field in a gap of dipole antenna. *35th International Conferences on Infrared, Millimeter and Terahertz Wave (IRMMW- THz)*

[6] Matthias D. Wissert, Andreas W. Schell, Konstantin S. Ilin, Michael Siegel and Hans-Jurgen Eisler. 2009. Nanoengineering and characterization of gold dipole nanoantennas with enhanced integrated scattering properties. *Nanotechnology*. Vol. 20. 7pp

[7] Bhuwan P. Joshi and Qi-Huo Wei. 2008. Cavity resonance of metal-dieletric-metal nanoantennas. *Optics Express*.Vol. 16, No. 14. pp. 10315-10322

[8] Lukas Novotny. 2007. Effective Wavelength Scaling for Optical Antennas. *Physical Review Letters*. Vol. 98. No. Issue 26. 4pp.

[9] Paul R. West, Satoshi Ishii, Gururaj V. Naik, Naresh K. Emani, Vladimir M. Shalaev and Alexandra Boltasseva. 2010. Searching for better plasmonic materials. *Laser & Photonics Rev.* Vol. 4. Issue 6. pp. 795-808

[10] Constantine A. Balanis. 2005. Antenna Theory: Analysis and Design. *3rd Edition, New York, Chichester, Brisbane, Toronto, Singapore, John Wiley & Son*.