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Nano-Scale Vee Yagi-UDA Antenna Based Nano Shell-Silver Coated Silica for Tunable Solid – State Laser Applications

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Abstract

A numerical study on the performance of the nano-scale antenna based on VeeYagi-Uda geometry that is constructed from Nano Shell-Silver Coated Silica (NSSCS) chains is investigated for tunable solid-state laser applications. In this study, a Finite Integral Technique (FIT) based on the formulations of Computer Simulator Technology-MicroWave Studio (CST MWS) software package is invoked to evaluate the antenna parameters such as: Reflection coefficient (S_{11}), gain/ directivity, and directivity. Before conducting the simulation study, the refractive index properties of the NSSCS are evaluated according to Lorentz distribution function of a hetero-structure junction. The proposed antenna shows three resonance modes at 75 THz, and 175 THz, and 266 THz. It is found the best antenna matching, S_{11}<-10dB, at 75 THz and 175 THz about -23 dB and -15 dB, respectively. However, at 266 THz, it is found -3 dB in max. The antenna shows acceptable gain values at the three considered frequencies about 2.5 dBi, 3.5 dBi, and 2 dBi, consistently. Therefore, the antenna exhibits a high directivity at 175 THz and 266 THz in comparison to the first mode at 75 THz. Next, a matching circuit is coupled to a nano-circuitry to tune antenna around 175 THz. The maximum emitted electric field is found to be around 175 THz. Finally, it is found that the introduction of the matching circuit has a significant tuning ability on the second mode at 175 THz; however, at the other two modes the tuning does not show a significant change.

***Keywords*:** Antenna, laser, Silica.

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1.Introduction

The electromagnetic interactions with metal nano-particles induce a coherent transition of electrons in their atomic orbital that generates a unique optical response due to Localized Surface Plasmon Resonances (LSPR) [1]. The LSPR is affected by the geometrical dimensions and the material properties as reported in [1]. Therefore, nano-scale structures are excellent example of such materials which attracts the potential applications for optical antennas [2, 3]. Nano Shell – Silver Coated Silica (NSSCS) is also considered to be efficient nano-scale structures for optical antennas due to their intrinsic nonlinearities [4-7] that are suitable for coherent tunable optical sources. It has reported in [9] that noble metals, such as sliver and gold, nano-structural material provide a broad spectrum from visible to infrared frequencies, which is strongly associated with LSPR of the particle [8]. Furthermore, these structures show inversion population symmetry in there orbital, the second-order nonlinear response of individual nano-particle may not dominate and negligible, the second-harmonic generation is very weak and the inversion symmetry does not effect on the third order nonlinear response of these nanoscale structures that helps to provide higher generation of the third-harmonic [4].

The electromagnetic interactions between two nanoparticles have been reported through several theoretical and experimental studies as in [9-14]. This junction of the nanoparticle pairs shows a strong field localization enhancement which yields to a strong nonlinear response. Recently, a pair of golden nanoparticles was introduced as a highly sensitive tunable source; in which changing the separation distance within few nanometers is enough to tune the coherent radiation [15].

In this work, a tunable nanoscale source based on VeeYagi-Uda antenna is investigated for tunable solid-state laser applications. The antenna is constructed from chains of NSSCS. Moreover, a tuning circuit based on a theoretical material of variable relative permittivity is coupled to the antenna arms to re-localize the coherent radiation to the desired wavelength in the LSPR band. It is shown that the tuning circuit is efficiently modulator so it can match the input impedance to the appropriate resonant frequencies.

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2.Antenna Geometry and Operational Considerations

The antenna geometry is performed from 45 nanoparticles of NSSCS to shape a nano-scale antenna based VeeYagi-Uda structure as shown in Figure 1. The NSSCS are arranged in a 3-D pattern to provide an excellent matching at 75 THz and 175 THz to suit the tunable solid-state lasers applications in the near infrared bands. Another mode is observed at 266 THz that is suitable for mid infrared region with poor matching. The maximum geometrical dimensions of the proposed antenna are 1000 × 380 × 440 nm^3.

The practical mechanisms of electronic wavelength tuning are the free plasma carrier effects, quantum confined stark effects and temperature dependence of the reflective index [16]. One of the strongest mechanisms that can be suitable to the proposed nanoscale antenna is the plasma effect that is presented by injection electron-hole plasma into a heterostructure such as InGaAsP/InP materials; this injection is presented by flow a DC current into the heterostructure junction. The change in the relative permittivity ($\Delta\varepsilon_r$) of such junction is related to the change in the refractive index (Δn_r), where in general the refractive index $n_r = \sqrt{\varepsilon_r \mu_r}$ and μ_r is the relative permeability, for nonmagnetic materials μ_r=1. The change in Δn_r is proportional to the injected carrier density as $\Delta n_r = n_r N$, where n_r is the refractive index for a loss less hetero-structure junction and given as $n_r = -\left(e^2\lambda^2/8\pi^2c^2n\varepsilon_o\right)\ \left[(1/m_e)+(1/m_h)\right]$, where, e is the electron charge; λ is the wavelength at the frequency resonance, c is the speed of light, n is the base refractive index without DC coupling, ε_o is the free space permittivity, m_e and m_i are effective mass of the injected electrons and holes, respectively [16]. The matching of the proposed antenna is given as $1/Z = 1/Z_{Tuner} + 1/Z_{Antenna} = \left[-i\omega\varepsilon_r\left(\pi r^2/g\right)\right]$, where Z_{Tuner} and $Z_{Antenna}$ are the intrinsic impedance of the tuner circuit and the nano-scale antenna [2].

3.Numerical Results and Discussions

The proposed nano-scale antenna geometry is shown in Figure 1, which is analyzed using Finite Integral Technique (FIT) formulated by CST MWS [17]. The nano-scale antenna is existed using a discrete port as shown in Figure 1(d), which is coupled to the matching gap. The matching gap is separated with 100 nm and filed with a dielectric rod, a theoretical tuning circuit, for tuning and matching. The S_{11} spectrum of the proposed antenna is presented in Figure 2(a), in which the proposed antenna operates at a quarter of the wavelength at 75 THz due to the inherent dielectric effects of the NSSCS nano-particles. Furthermore, it is very interested to note, the matching admittance spectra, when the antenna is loaded to air and exited with a 50 Ω discrete port, are in similar fashion to the traditional microwave antennas as shown in Figure 2(b).

The electromagnetic directivity in 3-D radiation patterns for 75 THz, 175 THz and 266 THz are shown in Figure 3(a), 3(b) and 3(c), respectively. The antenna provide excellent directivity at 175 THz and 266 THz, however, the radiation directivity is much less at 75 THz. Moreover, the electric field versus frequency for the proposed antenna is shown in Figure 4. The proposed antenna shows the maximum directivity around 266 THz. Furthermore, the antenna has the maximum electric field peak around 175 THz due to the LSPR effects are maximum [14].

Now, the obtained results show the antenna shows low reflection coefficient, below -10 dB, at both 75 THz and 175 THz frequencies due to the loss reduction at these two bands, however, the losses of the NSSCS chains are found has a negative effect on the reflection coefficient. Nevertheless, these losses affected severely on the gain results, in which, the antenna gain found to be maximum at 175 THz which is about 3.5 dBi. Where, the losses are found very significant at 266 THz in which the gain is about 2 dBi as seen from the electrical field distribution in Figure 4. Such gain enhancement is attributed to the antenna size and the Vee structures that focus the main lobe in the bore-sight direction.

To provide a tunable laser source, the tuning circuit is coupled to the proposed antenna by changing the dielectric properties of the tuner within the range of 1 to 20. In this study, a theoretical range of changing ε_r from 1 to 20 of step 1 is suggested. In Figure 5, the calculated S_{11} spectra with changing ε_r from 1 to 20 of step 1, with fixing the same tuner dimensions and exciting the antenna with the 50 Ω discrete port at the internal gap, are depicted. According to the presented results in Figure 5, the proposed antenna provides good matching with excellent tuning around 175 THz. Such observation may attributed to the LSPR effects which does not appear at 75 THz and 266 THz.

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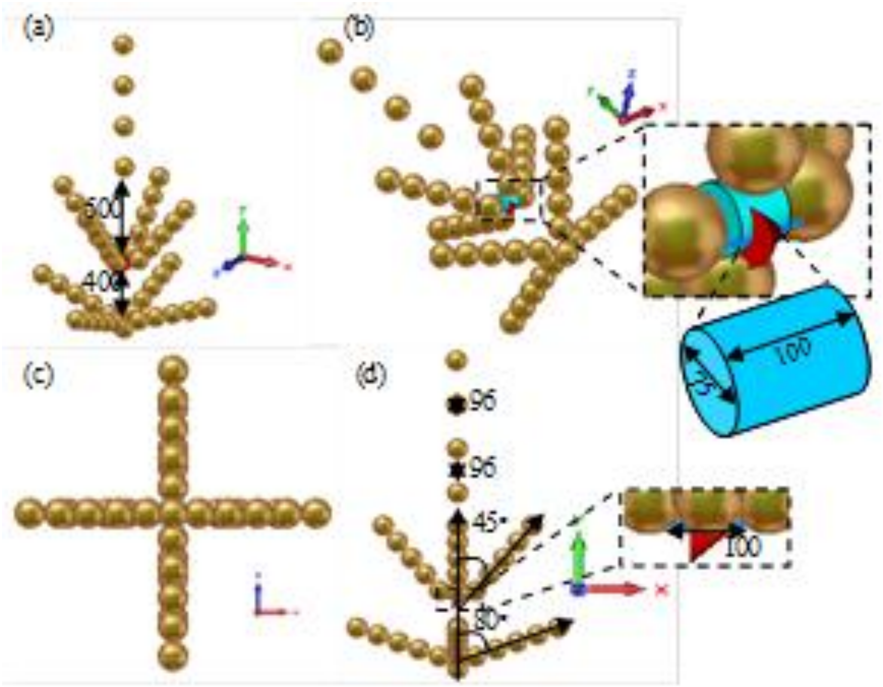

Figure 1: The antenna geometry; (a) and (b) 3-D views, (c) bottom view and (d) side view. Note: the dimensions are in (nm)

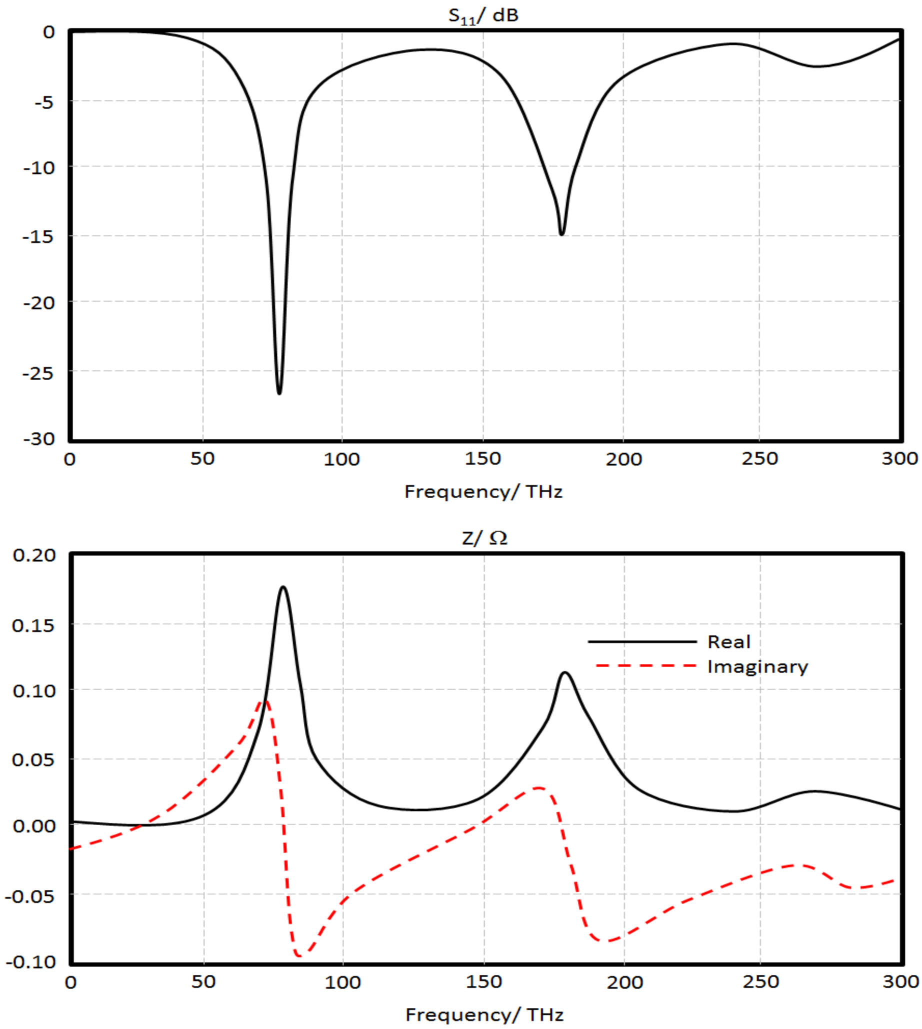

Figure 2: Numerical results; (a) S_{11} spectrum and (b) Matching admittance

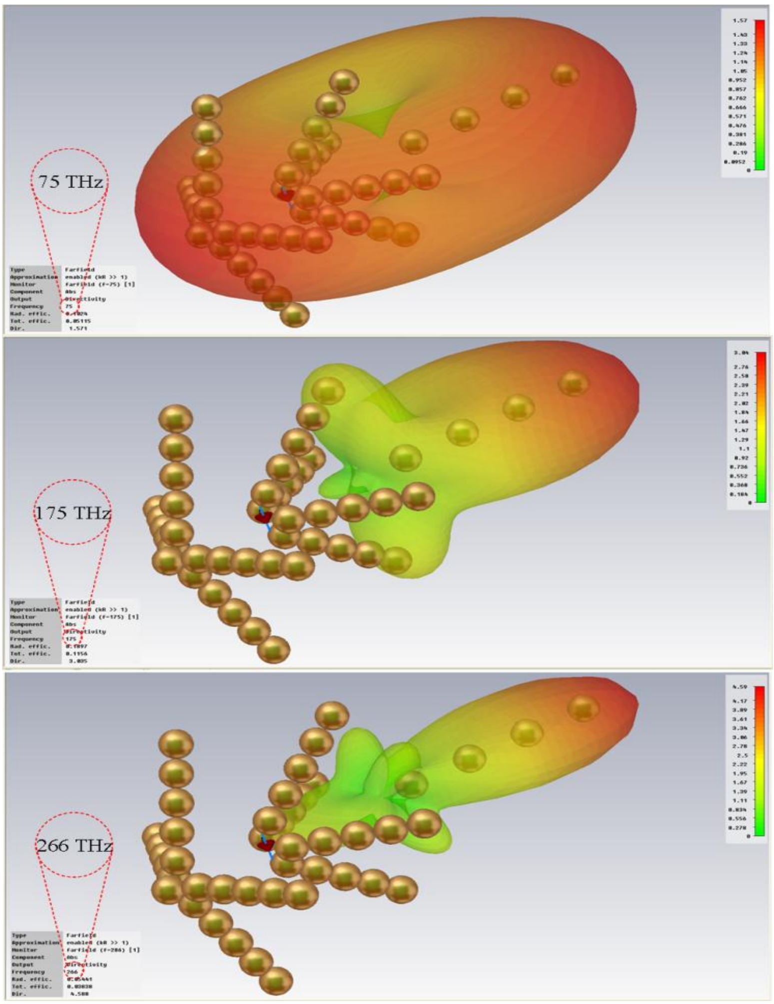

Figure 3: The radiation patterns of the directivity in 3-D view; (a) 75 THz, (b) 175 THz and (c) 266 THz

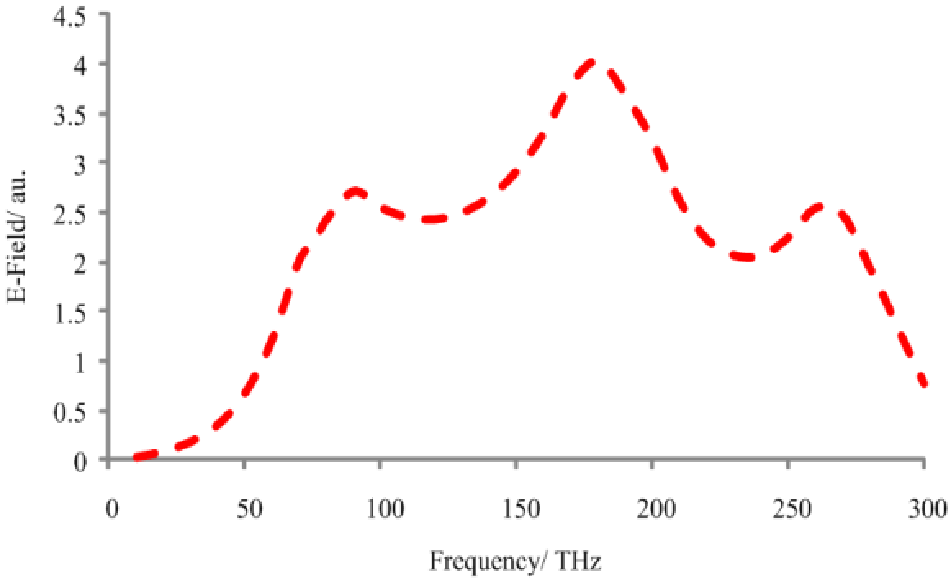

Figure 4: The electric field spectra

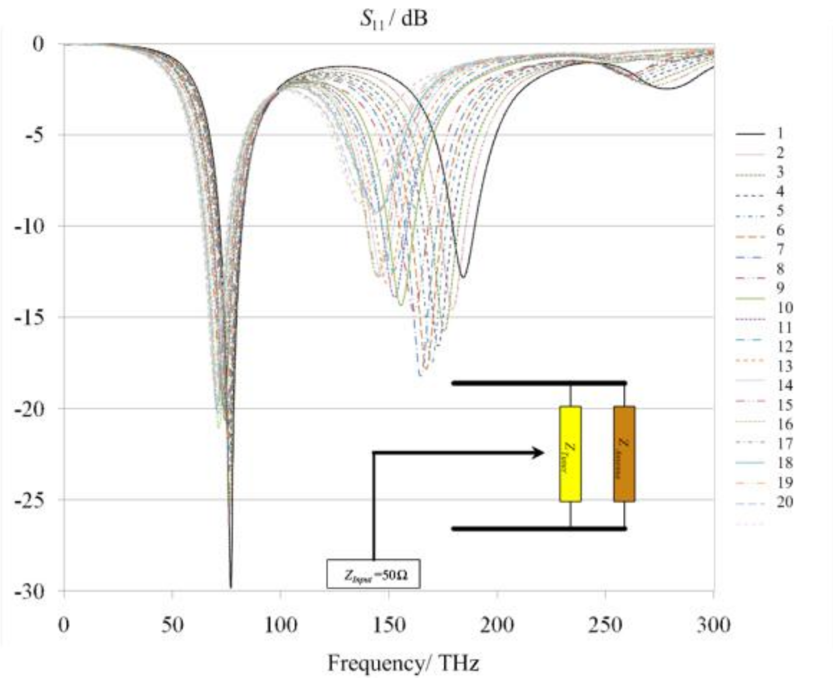

Figure 5: The tuned S_{11} spectra using the nano tuner circuit

4.Conclusion

In this paper, a nano-scale VeeYagi-Uda antenna based NSSCS chains is investigated for tunable solid-state laser application using numerical simulations based CST MWS formulations. This study is invoked for the first time in the literature by conducting the use of such structure for the laser antenna applications. The antenna shows three resonance modes at 75 THz, and 175 THz, and 266 THz. Moreover, the antenna provides high directivity around 175 THz and 266 THz, however, at 75 THz, the directivity is less. The proposed antenna is coupled to a nano-circuit tuner; this tuner shows excellent effects around 175 THz. This is due to the fact that the two resonant modes at 75 THz and 266 THz are based on the electronic transitions of the nano structure signature. While, the resonant mode at 175 THz is generated from the electromagnetic behaviors in which the introduction of the tuner circuit effects on the frequency shift. Finally, the emitted electric field from the proposed antenna is maximum around 175 THz due to the LSPR effects.

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