Sensor and Simulation Notes

Note 541

Integrated Switched Oscillator and Zig-Zag Antenna with Photoconductive Semiconductor Switch as a Terahertz (THz) Pulse Transmitter

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22 July 2009

Abstract

We have proposed a novel integrated system with a switched oscillator driving a zigzag antenna with a photoconductive semiconductor switch as a terahertz pulse transmitter. A planar zigzag antenna is designed to radiate at 0.4THz along with other suitable parameters to work as an integrated THz system. A micro-strip quarter wave resonator is used as a switched oscillator suitable to be coupled to the designed antenna. We use electromagnetic simulations to optimize design parameters of the integrated system to work at 0.4THz. We also propose a differential configuration of the system which doubles the radiating energy. We found a terahertz transient pulse with 10 cycles with a total of 2.5nJ of energy can be radiated out from this system with reasonable 200V bias voltage to the antenna at Terahertz frequencies. All the simulations are performed in commercial software's CST MWS and Ansoft's HFSS for a comparison and verification.

1. Introduction

Recently there has been a great interest in high power terahertz (THz) generation. Conventionally THz is generated from photoconductive semiconductor switch (PCSS) which has a dipole-like antenna on a short carrier life time (ps) semiconductor. When this switch is closed by a femtosecond laser current pulses are generated which oscillate in the dipole antenna, giving out THz radiation. Seeking improvements in this generation process to obtain high amplitude, high power, high energy and better concentration of beam on or towards a target or reflector, we have proposed a new integrated system with a zigzag antenna driven by a switched oscillator with a photoconductive semiconductor switch. We separately discuss design considerations and working of the antenna, switched oscillator and PCSS switch using electromagnetic simulations. Then, we show results of the integrated system response.

2. Design of zigzag Antenna:

A zigzag antenna [1] can be seen as a squashed helical antenna with planar geometry for ease in fabrication. Previously zigzag radiators were designed to radiate in the end-fire direction i.e. maximum radiation to occur along the axis of the antenna along the structure away from feed point [2]. Here high gain over narrow (10%) band was obtained by Sengupta et.al. using a zigzag antenna fed against a ground plane perpendicular to the zigzag axis. However, designing a zigzag antenna to radiate broadside rather than end fire is believed to have added advantages.

We have designed a zigzag antenna to operate at 0.4 THz. The antenna is at λ/4 distance from the ground plane on a dielectric substrate of relative permittivity 3 (Arlon AD 300). The antenna schematic is as shown in Fig.1. As shown in the figure, a zigzag antenna can be thought as a number of V's connected in series. The length of each element of the 'V' and angle is chosen such that radiation from all the elements add in phase along $\theta = 90^0$ (x-y plane) at the desired frequency of interest. Such an array produces maximum radiation in a direction perpendicular to the axis of the structure, and a single broadside beam occurs if the arrays are closely spaced. Now for this reason the length of each arm of 'V' should be equal to $\frac{\lambda}{2}$. However, due to the dielectric permittivity of the substrate on which the antenna is layed, the length of the antenna would be $\frac{\lambda}{2\sqrt{3}}$. At 0.4 THz, the length of the element is calculated to be $l = 216\ \mu m$. For keeping skin effect losses low [3], the width of the each element is chosen to be $\frac{l}{10} = 21.6\ \mu m$ and the thickness to be 0.5 μm.

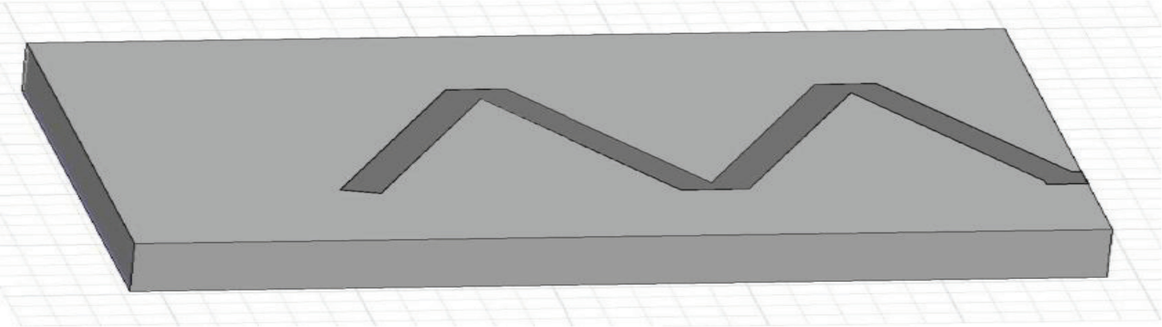


Fig. 1 Schematic of the zigzag antenna on a substrate

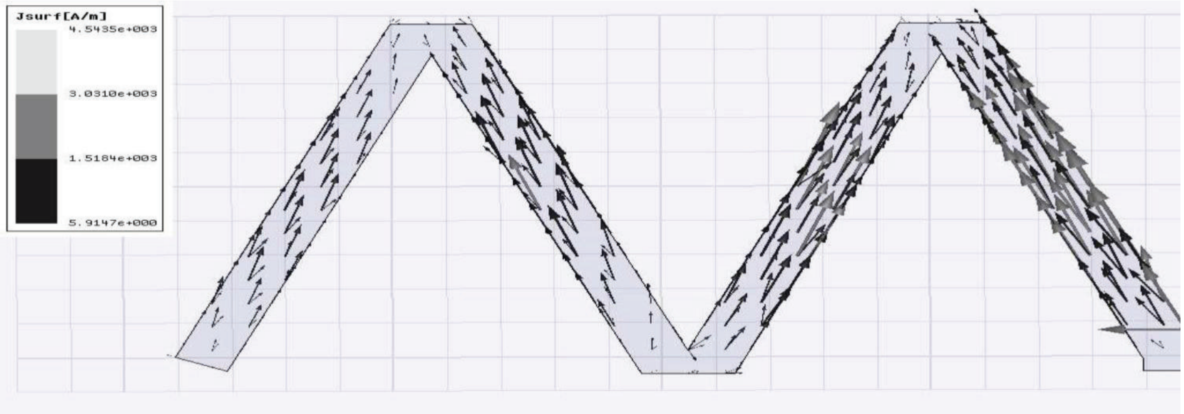


Fig.2 (a) Surface current distribution on zigzag antenna at resonance frequency (0.43THz) with phase (φ= 40^0) of the current

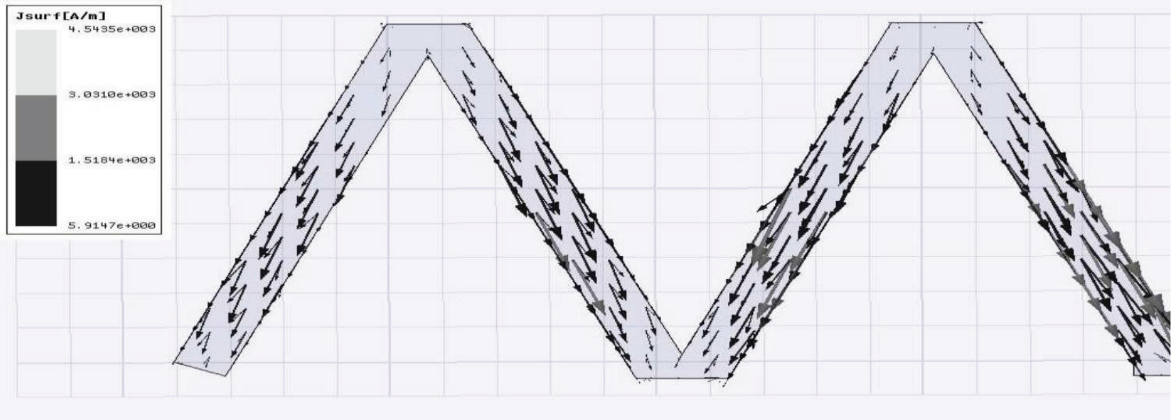
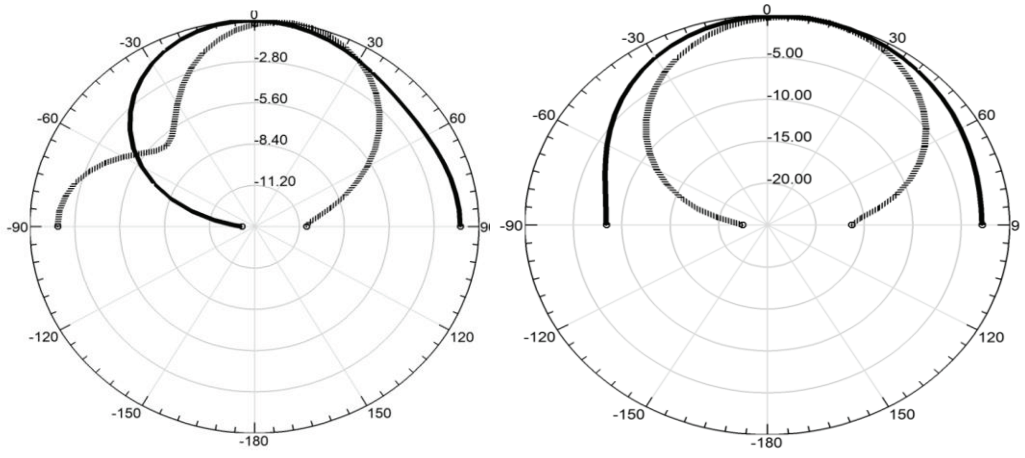


Fig. 2 (b) Surface current distribution on zigzag antenna at resonance frequency (0.43THz) with phase (φ= 220^0) of the current.

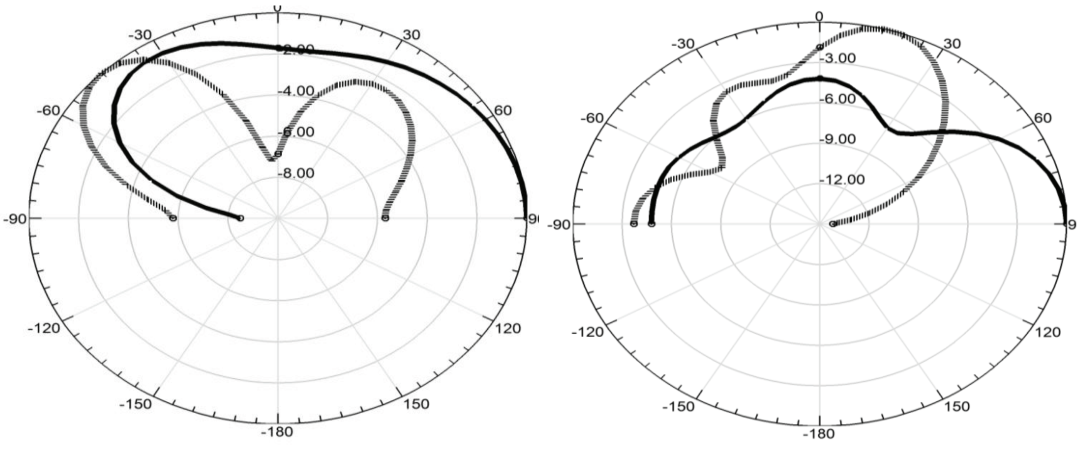
The angle between each element of the antenna (ψ) is varied to get the surface current distribution to be in phase in each element. For $\psi=45^0$ and at 0.4THz frequency a desired current pattern as shown in Fig. 2 is observed for 40^0 and 220^0 phase angles of current. The principal directional characteristics can be determined by using linear array theory. A simple first order theory for this periodic zigzag antenna can be found in [4]. The current wave decays along the conductor as the energy leaves the structure. It is therefore possible to build a periodic structure long enough so that currents are negligible at the end opposite the feed. The results of such measurements at 0.4THz show that the magnitudes of the currents are practically negligible beyond 4 elements.

3. Results from zigzag antenna

To validate the working of the antenna at 0.4THz we present the results of directivity and S-parameters of the antenna. The radiation patterns of zigzag antennas with $\psi=45^0$ for different frequencies (ranging from 0.4THz to 0.9THz) are shown in Fig. 3. As we can see around 0.4THz the radiation pattern is approximately dipolar, and after that it starts to have side lobes as the frequency increases. Figure 4 shows the return loss of the antenna having a resonant frequency around 0.43THz. The slight shift in the frequency is due to the mutual coupling of the elements in the antenna. Also the variation of the thickness of the dielectric substrate was varied to optimize the height of the antenna from the ground plane for maximum radiation as shown in Fig. 4. We found minimum return loss at 0.056mm which is equal to 0.6 times $\lambda/4$ in the dielectric. Also variation of the resonant frequency with varying dielectric permittivity of the substrate is shown in the Fig. 5. (ε_r is varied from 2 to 6.) Thus we can tune the resonant frequency of the zigzag antenna without changing the physical dimensions of the antenna. However, we can design the antenna to work for any arbitrary frequency by scaling the dimensions linearly. Also the impedance versus frequency is as shown in Fig. 6. We observe an impedance of 400Ω at 0.43THz which is optimal for resonating with a switched oscillator as discussed in a later section.



(a) 200GHz (b) 400GHz



(c) 600GHz (d) 900GHz

Fig.3 Far-field radiation pattern normalized in dB at different frequencies

[--------- H - Plane, ------- E- Plane]

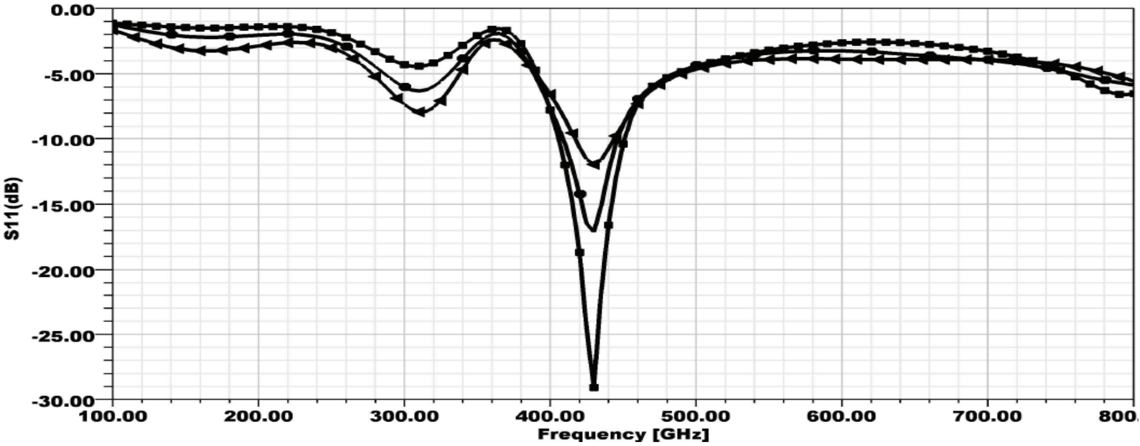


Fig. 4 Return loss for the antenna for different substrate thicknesses

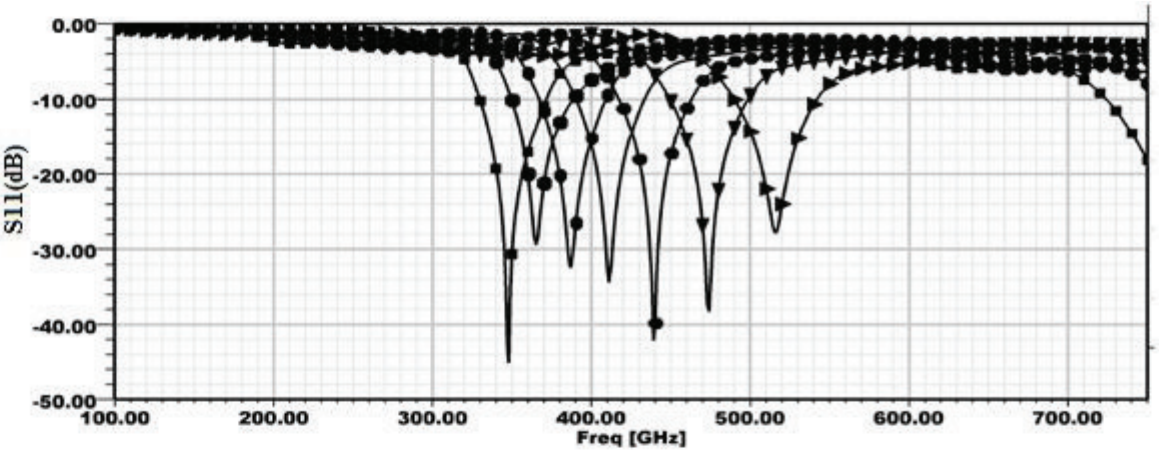


Fig. 5 Return loss of the antennas for different dielectric permittivities of the substrate varying from 2 to 6 from right to left in the order

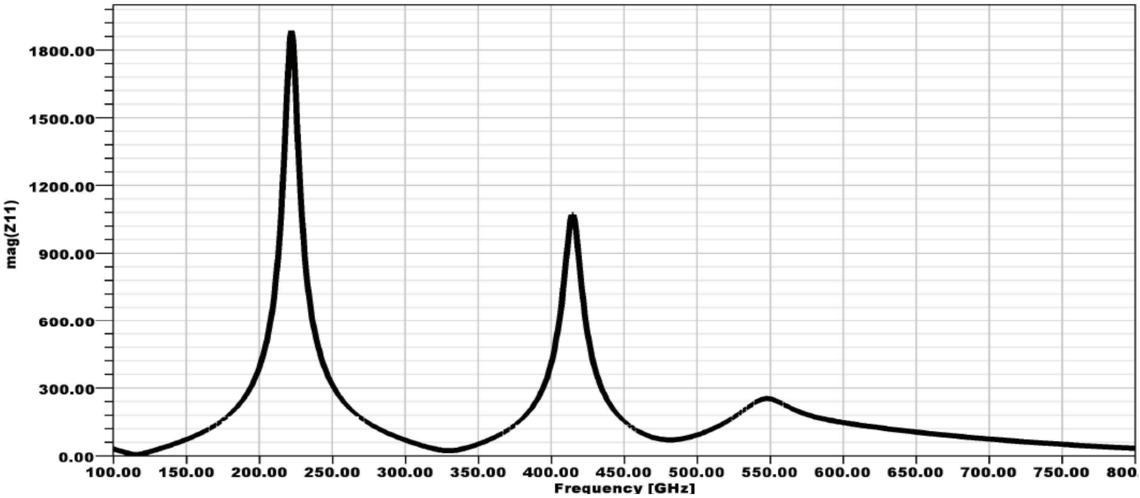


Fig.6 Magnitude of Input impedance at different frequencies

4. Switched oscillator

Switched oscillators are possible sources for driving antennas of the kind explained above (zigzag). Previously there are various kinds of structures proposed like coaxial conductors [5] as possible switched oscillators, but here we propose a simple planar quarter wave micro-strip resonator, which is easier to fabricate and integrate with the designed antenna. The structure of the switched oscillator is as shown in the Fig. 7. This is designed to operate at 400GHz to match with the resonant frequency of the previously designed zigzag antenna. A switched oscillator (SWO) is a quarter wave long ($\lambda/4$) which is l_{os}= 0.108mm at 400GHz. To reduce the skin effect losses [3], the width of the SWO (w_{os}) should be large, but needs to be small compared to l_{os}. So we choose $w_{os}=l_{os}/2$ = 56μm. The characteristic impedance of the oscillator (Z_{os}) should be an order of magnitude less than the impedance of the antenna (Z_a) to give a voltage increase into the antenna. This SWO is placed at a height of 3μm from the ground (less than $\lambda/4$). The impedance of the SWO is calculated to be around 10Ω which is verified by numerical simulations. The oscillator is charged through the high impedance zigzag antenna at one end (so as not to load the oscillator after the switch fires). There is a PCSS at the other end.

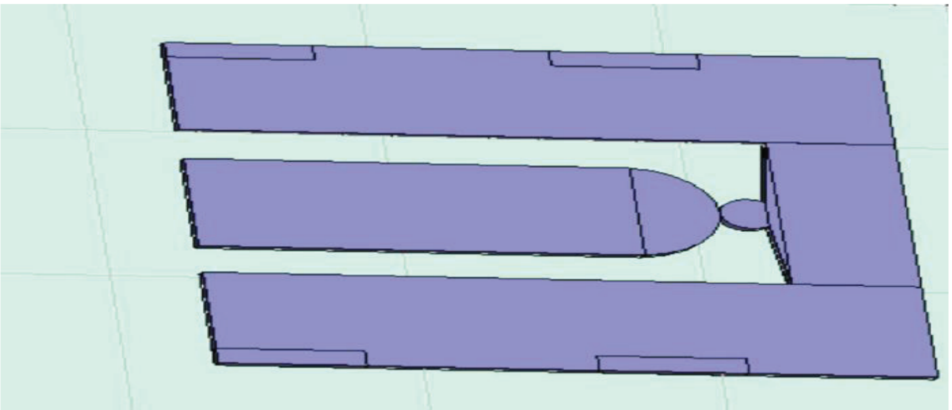


Fig. 7 Schematic of the switched Oscillator (SWO)

For a quarter-wave resonator at 400GHz the transit time $t_t = \frac{1}{4f}$ = 0.625ps. The switch is chosen to have a switching rise time, t_r , of the order of 0.1ps which is short compared to the transit time of the wave along the SWO. However, semiconductor switches will have a fall time greater than the rise time governed by their carrier life times.

For our present applications we need to have long carrier life time (~50ps) so that the switch conducts for a long time after it is triggered so as the energy in the SWO to radiate. Out of the existing many semiconductor materials presently employed for THz generation SI (Semi insulating) - GaAs is more suitable for the present application [6] with 50-100ps carrier life time. Using this material over conventionally used LT-GaAs gives an inherent advantage of high mobility (1000 $cm^2/V.s$) and high resistivity (10^7 Ω. cm) of SI-GaAs.

When the switch is closed a wave (ideally a step function) of amplitude $-V_0$ propagates to the left towards the antenna. When the voltage reaches the antenna, almost twice is transmitted to the antenna and part of it is reflected back as ($Z_c << Z_a$). We have nearly a +1 reflection coefficient which gives voltage doubling onto the antenna. The reflected voltage travels to the switch and it is reflected again with a sign change. The voltage is progressively attenuated after each reflection and tends to decay in an exponential way, with dominant frequency of 400GHz as reflected in the far-field in Fig. 8 and Fig.9. From detailed analysis [5] the waveform delivered to the antenna feed will be

$$Va = \frac{4}{\pi} V_i \, e^{-\alpha\,(t-t_t)} \sin(\omega(t - t_t))$$

$$\alpha = \frac{-1}{2t_t} \ln(\rho) = \frac{Z_c}{Z_a} 4f_0 \qquad (1)$$

which is a damped sinusoid as shown in Fig.8. In N cycles the amplitude reduces to ρ^{2N}. If we set this equal to e^{-1} we get N = $-\frac{Z_c}{4Z_a}$ = 10. The quality factor of the antenna Q= π N = 31.4. From Fig.8 we observed number of cycles is very close to the calculated value. The bandwidth can be adjusted by changing the ratio between Z_c and Z_a.

The stored energy in the SWO is calculated as

$$E = \frac{1}{2} CV^2 = \frac{t_t}{2Z_c} V^2 \qquad (2).$$

When calculated with 200 V (breakdown voltage) we get energy stored as 1.25nJ. When a differential SWO driving differential zigzag antenna (DSDZ) as shown in Fig. 10 is considered the energy will be doubled, which is 2.5nJ**.** If array of 100 DSDZ on a chip is formed then the total energy would be 0.25μJ**.** Also total calculated area on chip would be 100 x (750 x 540) μm^2 = $40mm^2$, which is considerably small.

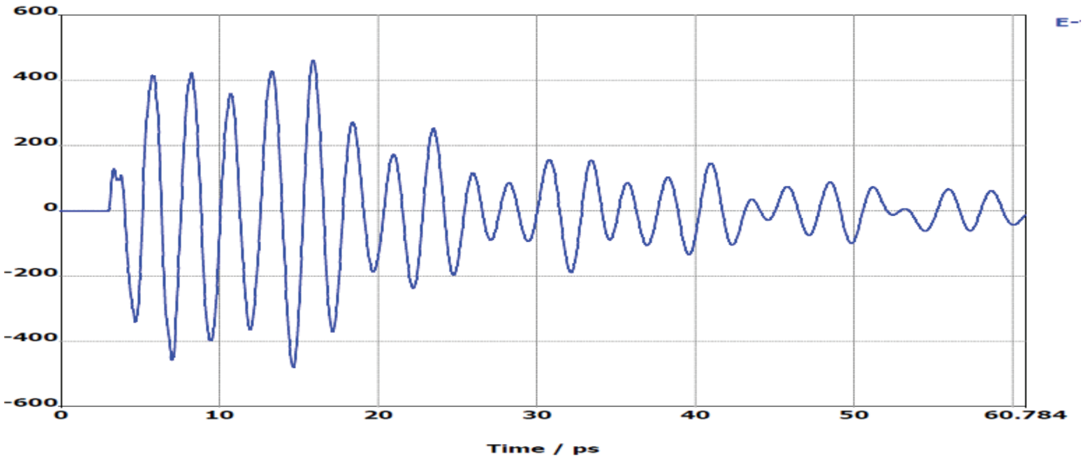


Fig.8 E-field (in a.u.) (far field) measured at 0.8mm from antenna

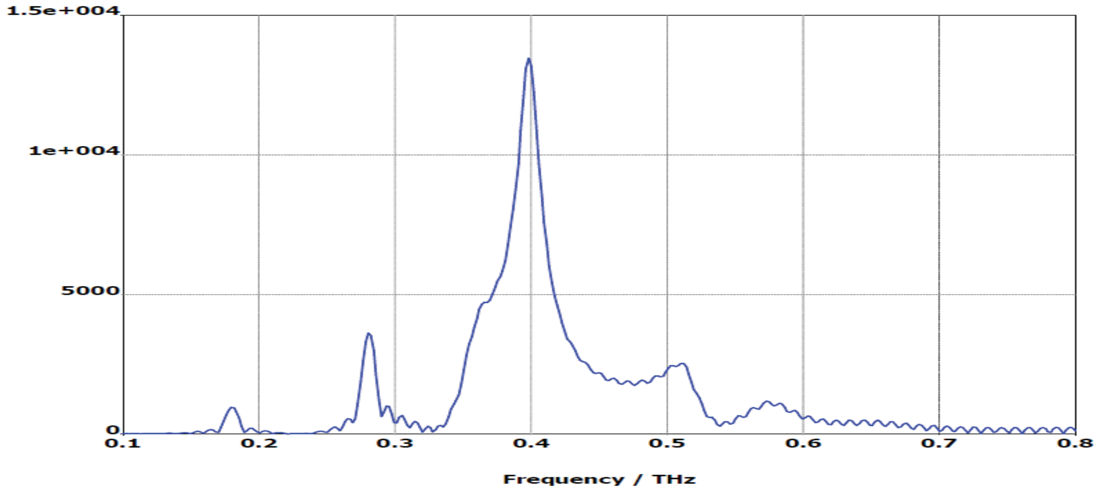


Fig.9 Magnitude of electric field (in a.u.) showing resonance at 0.4THz.

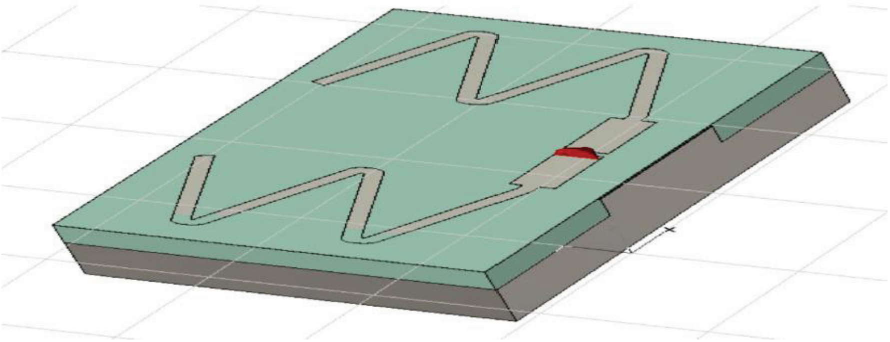


Fig. 10 Schematic of differential SWO driving differential zigzag antenna

5. Conclusion

We have proposed a novel method of generating high energy THz radiation, adapted from previously proposed methods in the low frequency regime. We have designed a planar zigzag antenna for this application. We have proposed a differential configuration of the system. We have also performed numerical simulations for optimizing the design parameters for obtaining the best radiation. The calculated energy is found to be 0.25 μJ for an array of 100 such elements when operated at 200V bias to the antenna. However, careful attention needs to be payed to the precise synchronization of these sources. Also scaling to any frequency in the terahertz region is possible by adjusting the dimensions of the antenna and dielectrics by a constant factor. Fine tuning of frequency with varying dielectric permittivity is also possible. We have to explore the ease of fabrication process for the current design.

6. References

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[6] T. Sakai, “Terahertz Optoelectronics”, Springer, Berlin, 2003.