# Numerical Simulation of Photoconductive Dipole Antennas: the Effect of the DC bias Striplines

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***Abstract*— We perform numerical simulations to evaluate the effect of the dc bias striplines on the performance of photoconductive dipole antennas. We find that the resonance frequency and the maximum of the input impedance of the antenna shift to lower frequencies as the length of the striplines is increased. In addition, we compare the performance of impedance matched antennas with that of more realistic antennas which are characterised by a severe mismatch between source and antenna structure.**

***Index Terms*—photoconductive dipole antennas, photomixing**

## I. INTRODUCTION

Photoconductive dipole antennas are widely used to optoelectronically generate and detect pulsed and continuous wave (CW) THz radiation [1-4]. They consist of a piece of semiconductor onto which metal structures are deposited. These structures can be of different shapes corresponding to different antenna designs. One of the most popular designs is the dipole antenna which exhibits a resonant behaviour and on which we focus in this paper. The typical structure of a photoconductive dipole antenna is shown in figure 1.

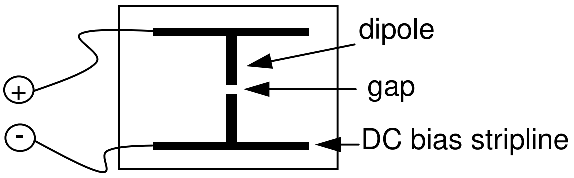

Fig. 1 Schematic drawing of a photoconductive dipole antenna.

To use the antenna as a THz emitter a bias is applied to the dipole through two parallel striplines. The dipole structure with a typical length between 50 and 200 µm is interrupted by a small gap whose width is typically 10 µm. Due to the applied bias, the field strength within the gap amounts to several kV/cm. To operate the antenna, carriers are optically excited within the gap. The excitation can be either pulsed, using femtosecond laser pulses, or continuous wave (CW), if the output of two single CW laser diodes is superimposed in the gap region. The carriers are accelerated in the bias field which gives rise to a small current that is the source for THz radiation. While the first excitation mechanism produces broadband THz pulses and is used in THz time-domain spectroscopy, the latter is referred to as photomixing, and it generates CW THz radiation. In both cases the role of the antenna is to effectively radiate the terahertz energy.

Over the last few years a lot of theoretical and experimental work has been done on the analysis of photoconductive dipole antennas. Jepsen et al have used the Drude-Lorentz theory to model the photo-current in the semiconductor and compare the predictions of theory to experimental results [5]. Tani et al have experimentally compared the radiation performance of different types of antennas using the Finite Difference Time Domain (FDTD) method [6]. Cai and coworkers have pointed out that the efficiency of THz antennas can be enhanced by using pointed contacts [7].

However, in the typical design shown in Fig. 1, the striplines act as an end capacitance and affect the dipole resonance. Here, we use a commercial software package to investigate this effect. We find that the resonance frequency and the maximum of the input impedance of the antenna shift to lower frequencies as the length of the striplines is increased.

In addition, we investigate a second aspect: one of the main design challenges in using THz antennas with photomixers is the severe impedance mismatch between the high internal impedance of the photoconductor and the much lower input impedance of the antenna structure. It is almost impossible to achieve impedance matching with such a big difference. It was pointed out by Duffy et al. in 2001 that the most effective way to optimise the radiated THz energy is to increase the input resistance of the antenna [8].

As we will show here, our simulations confirm this statement. In essence, the maximum THz power is not radiated at the antenna resonance obtained for the matched case, but at

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the frequency where the antenna input impedance has a maximum. i.e. at the frequency of the lowest impedance mismatch.

## II. SOFTWARE AND METHODOLOGY.

We use the software package Computer Simulation Technology (CST) to simulate the antenna and stripline structures. CST works on the finite integration technique developed by Weiland. It is based on the idea of using the integral, rather than the differential form, of Maxwell's equations in the discretisation. The program requires considerable computing power, hence it is the advent of powerful computers that has made the use of this technique possible. CST is widely used to simulate antenna and stripline structures in the GHz range. Since the finite integration method is frequency-independent, CST is expected to give accurate results also at THz frequencies.

We assume a dipole antenna with a length of 200 µm deposited on a GaAs substrate. In the 5 µm gap between the two arms of the dipole a current source, in the form of a discrete port, is introduced and the appropriate boundary conditions are specified. The current source simulates the current in the photoconductive gap. The first run of the simulation is carried out with the default value of the source internal impedance (50 Ω). The result of the simulation gives the value of the input impedance of the antenna. The source impedance is then matched to this value and a second simulation run is carried out to get results for a matched source-load situation.

The striplines are introduced incrementally to the structure. For each incremental length of stripline the procedure outlined above is repeated; the incremental lengths are added until they reach the ends of the substrate. For each incremental length, results for the reflection-coefficient $S_{11}$, the far-field radiation pattern, the antenna current and the input impedance of the antenna are obtained.

Although the simulations for the matched case are quite instructive they are in a sense purely academic as real antennas have a severe mismatch between the photomixer and antenna. In a second run we simulate the mismatched case where the source impedance is set to a more realistic value of 10 kΩ.

## III. RESULTS AND DISCUSSION

The resonance frequency of a dipole antenna on a dielectric half space can be approximated by the following expression [9]:

$$\lambda_{eff} = \frac{\lambda}{\sqrt{\varepsilon_{eff}}}$$

where $\varepsilon_{eff} = \frac{1+\varepsilon_r}{2}$ is the *effective* permittivity.

For a 200 µm dipole on a GaAs substrate ($\varepsilon_r$=13), the above rule-of-thumb predicts a resonance frequency of 280 *GHz*. This compares with the following plot for a matched antenna from the simulation.

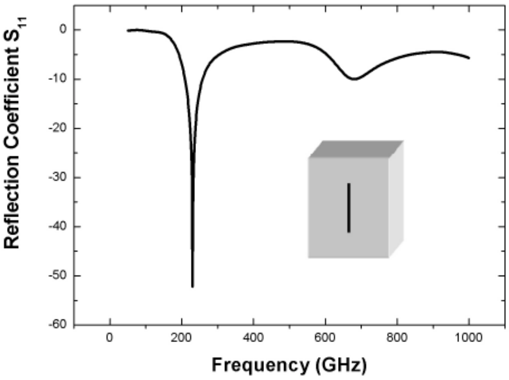

Figure 2. Reflection Coefficient for a 200 µm dipole

The difference between the predicted (280 *GHz*) and simulated (230 *GHz*) values can be attributed to the fact that the rule-of-thumb applies to dipoles of very small widths, while the simulated antenna has a finite width of 10 µm.

It is observed that increasing the length of the striplines shifts the resonance frequency of the antenna to lower values. In other words the electrical length of the antenna is increased. The plots below show the progressive shift to lower frequencies as the length of the striplines increases.

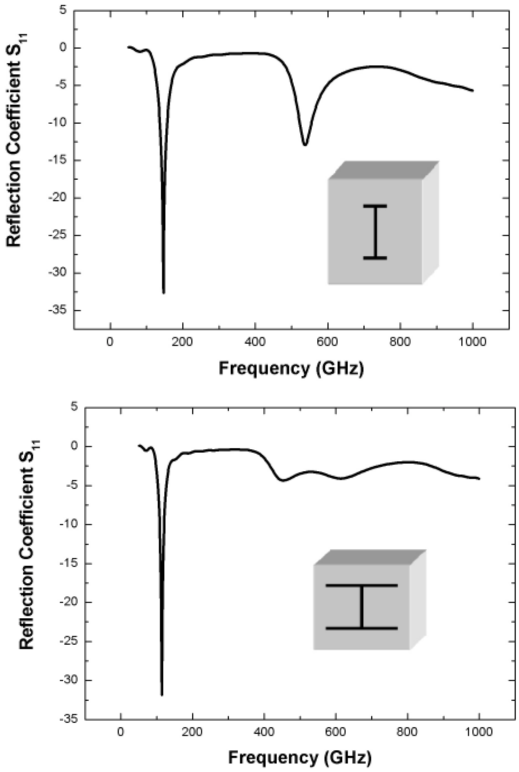

Figure 3. Reflection Coefficient for a 200 µm dipole with increasing stripline length.

This behaviour can be explained by the fact that adding the striplines amounts to adding end capacitance to the antenna, which lowers the resonance frequency of the antenna. The decrease of the resonance frequency with increasing stripline length is shown in figure 4.

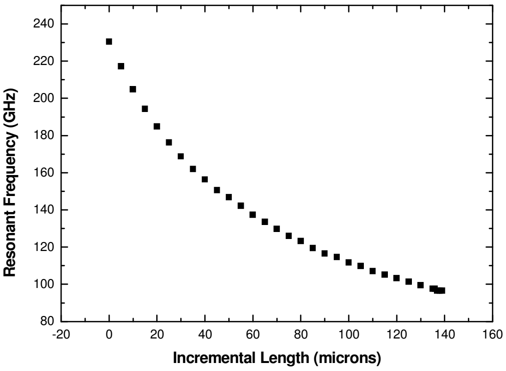

Figure 4. Decrease of the resonance frequency with increasing stripline length

The input impedance of the antenna at resonance was also investigated and was found to be in agreement with the value predicted by the rule-of-thumb. The value of the input resistance of a dipole antenna on a GaAs half-space is given by

$$R_{in} = \frac{75}{\sqrt{\varepsilon_{eff}}} = 28\Omega$$

where 75 $\Omega$ is the well-known value of the input resistance of a dipole radiating in free space. As can be seen from figure 5 the input resistance of the dipoles decreases with the increasing length of striplines.

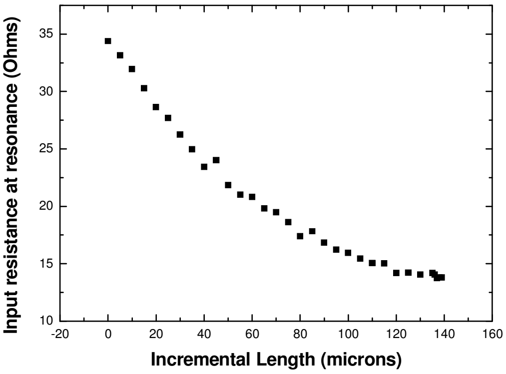

Figure 5. Decrease if input resistance with increase in stripline length.

The simulated radiation pattern of the antenna confirms the well-known fact that most of the power is radiated into the dielectric. Figure 6 shows the simulated radiation pattern of a dipole without striplines on a GaAs substrate. The substrate is positioned in the upper half space.

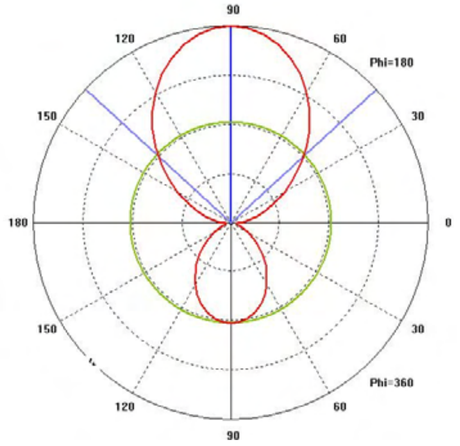

Figure 6. 2-D radiation pattern of a dipole antenna on GaAs half space

As already stated, the resistance of photomixers is very high. Therefore, to simulate the actual situation as closely as possible, a second simulation run was carried out with the source impedance set to a value of 10kΩ. Figure 7 shows the reflection coefficients for three of the structures with different stripline length. As expected the generation of THz radiation is much less efficient as compared to the matched case. While values of more than –50 db were observed in the minimum of $S_{11}$ for the matched case (Fig. 2) the values for the heavily mismatched case are always smaller than –1dB. Furthermore, the resonances are much broader for the mismatched source-antenna system.

It is interesting to note that the impedance mismatch has an interesting effect on the resonance frequency. Like in the matched case it shifts to lower frequncies with increasing stripline length. Yet, in the mismatched case the resonance frequency is always higher. The bare dipole, for example, now has a resonance frequency around 350 GHz. Interestingly, this frequency corresponds to a maximum in the real part of the antenna input impedance (not shown). This leads to the conclusion that the THz generation for a mismatched source-antenna system is most efficient at the frequency of the smallest impedance mismatch between antenna and source and not at the antenna resonance frequency that is observed in the matched case. This has important implications for the antenna design. To design the dipole length of a THz emitter antenna that has a resonance at 1 THz one should not apply the rule-of-thumb given above (or corrections of that taking into account the striplines) but make the arms of the dipole somewhat longer.

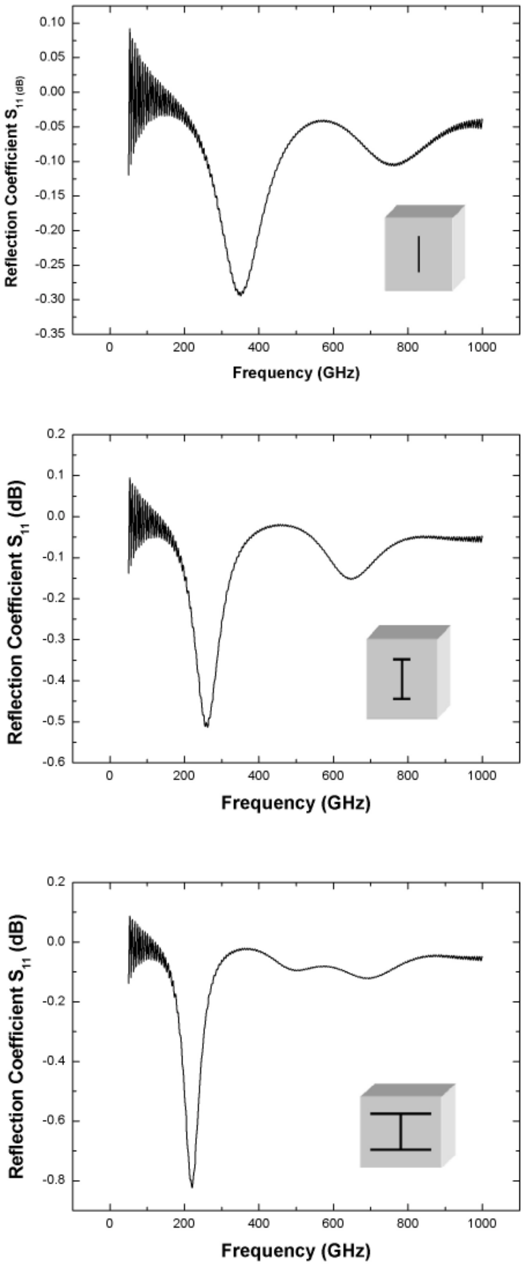

Figure 7. Shift towards lower resonance with increasing stripline length for mismatched structures

## IV. SUMMARY

In summary we have studied the effect of the striplines on the performance of the dipole antenna using the simulation software CST. We find that the resonance frequency and the maximum of the input impedance of the antenna shift to lower frequencies as the length of the striplines is increased. We have also investigated the effect of an impedance mismatch between the photoconductor and the dipole antenna as this is the real life case.

## V. REFERENCES

[1] P. R. Smith, D. H. Auston, and M. C. Nuss, “Subpicosecond photoconducting dipole antennas,” *IEEE J. Quantum Electron.* Vol. 24, p. 255, 1988

[2] J. E. Pedersen, S. R. Keiding, C. B. So rensen, P. E. Lindelhof, W. W. Rühle, and X. Q. Zhou, "5 THz bandwidth from GaAs-on-silicon photoconductive receiver," *J. Appl. Phys* .Vol 74, p. 7022-7024, 1993

[3] M. Tani, K. Sakai, and H. Mimura, “Ultrafast Photoconductive Detectors Based on Semi-Insulating GaAs and InP,” *Jpn. J. Appl. Phys.* Vol 36, p. 1175-1178, 1997

[4] S. Matsuura, M. Tani, and K. Sakai, “Generation of coherent terahertz radiation by photomixing in dipole photoconductive antennas,” *Appl. Phys. Lett.* vol. 70, no. 5, p. 559, 3 February 1997

[5] P. U. Jepsen, R. H. Jacobsen and S. R. Keiding, “Generation and Detection of terahertz pulses from biased semiconductor antennas*,” J. Opt. Soc. Am B*., Vol. 13, No. 11, p. 2424, November 1996

[6] M. Tani, S. Matsuura, K. Sakai, and S. Nakashima, “Emission Characteristics of Photoconductive Antennas based on Low-Temperature-Grown GaAs and Semi-Insulating GaAs” *Applied Optics*, vol. 36, No. 30, p. 7853, 20 October 1997

[7] Y. Cai, I Brener, J. Lopatta, J. Wynn, L. Pfeiffer, and J. Federici, “Design and performance of singular electric field terahertz photoconducting antennas,” *Appl. Phys. Lett.* vol. 71, no. 15, p. 2076, 13 October 1997

[8] S. M. Duffy, S. Verghese, K. A. McIntosh, A. Jackson, A. C. Gossard and S. Matsuura, “Accurate Modeling of Dual Dipole and Slot Elements Used with Photomixers for Coherent Terahertz Output Power,” *IEEE Trans. Microwave Theory Tech*., vol.49, no. 6, p.1032, June 2001

[9] C. R. Brewitt-Taylor, D. J. Gunton, and H. D. Rees, “Planar antennas on a dielectric surface,” *Electron. Lett.,* vol. 12, pp. 729-731, Oct.1, 1981