# A Switched Oscillator as an Antenna for High Power THz Generation

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## Abstract

This paper presents an approach to high power THz generation that uses a Switched Oscillator (SwO) as a photoconductively-switched antenna. A simplified model is used to demonstrate the SwO as an effective THz radiator. Numerical simulations are used to optimize various parameters of interest with the primary objective of maximizing the radiated energy and minimizing lossess. The radiation $Q$ and resonant frequency are obtained as function of each parameter.

## 1 Introduction

Despite great scientific interest since the late 1920s, the terahertz (THz) frequency range remains one of the least tapped regions of the electromagnetic spectrum. Lying in the far-infrared region, it has received little commercial emphasis over the years [1]. The exact definition varies among authors [1, 2] but the following definition is adopted here [3],

$$0.1 \text{ THz} < f < 10 \text{ THz} \tag{1}$$

THz radiation is used in various applications, such as imaging, security surveillance, spectroscopy, submillimeter astronomy, *etc.* Our focus is on secure communication and radar applications. At present, most wireless communication networks exploit the radio wave and microwave portions of the electromagnetic spectrum. Communication and radar applications require transmission through the atmosphere, perhaps for kilometers. Attenuation of the propagating signal is therefore of primary concern for such applications. Measurements have been made of the propagation (attenuation) of THz radiation through both dry and moist air [4]. On examining these measurements, a frequency of approximately 0.3 THz (attenuation $\approx 4-12$ dB/Km) is found to be most suitable for transmission over large distances [3].

One pulsed power approach to THz generation uses photoconductively (PC) switched planar antennas illuminated by ultra short optical pulses. Recent advances in femtosecond lasers and ultrafast PC semiconducting thin films have made this approach practically attractive [2]. The use of a PC-switched switched-oscillator as an antenna is outlined in this paper. Compared to other sources of THz radiation, such as traveling wave tubes, backward wave oscillators, free electron lasers, *etc.* PC-switched antennas (PCSAs) are attractive due to their conceptual simplicity, small size and their ability to radiate high-energy resonant pulses.

The material properties of the PC switch and the antenna geometry play an important role. In our design, hundreds of volts will be applied across the switch. The antenna is designed such that the radiated energy decays as a damped sinusoid, *i.e.*, the carrier lifetime of the PC switch gap material is required to be much longer than the duration of the input pulse. Therefore, the PC switch material must have long carrier lifetime, high mobility, and high breakdown voltage. Of the currently used PC materials, Cr-doped SI-GaAs (semi-insulating galium arsenide) is found to satisfy these design constraints [2]. It has a long carrier lifetime, $50-100$ ps, a mobility of 0.1 $\text{m}^2/\text{V s}$, a high resitivity, $10^4$ $\Omega$ m, and a high breakdown field strength of 50 MV/m.

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## 2 The Switched Oscillator as a Terahertz Radiator

The SwO is an electrical, shock-excited resonant structure (*e.g.*, a transmission line). The excitation may come in the form of the discharge of some slowly charged capacitance through a fast closing switch. The waveform delivered to the load is characterized by one or more damped sinusoids [5].

Here we adapt the SwO as the planar antenna in the PCSA scheme. As the most basic formulation of the problem, consider the setup shown in Fig. 1, where the SwO is operated, in a differential form, as a half-wave micro-strip resonator to maximize the energy in the radiated pulse.

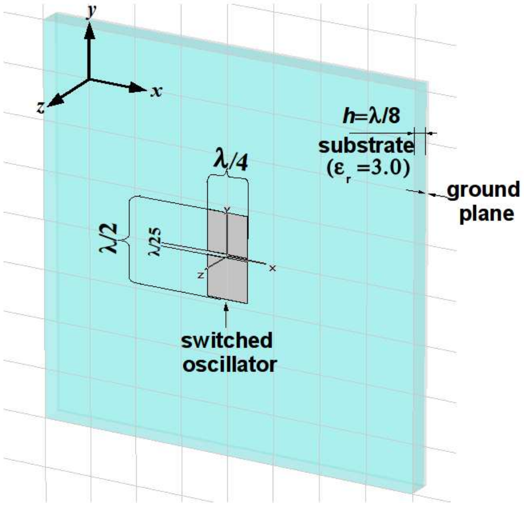

Figure 1: Schematic of a switched oscillator mounted over a substrate.

The structure in Fig. 1 was simulated in CST Microwave Studio®[1], a commercially available finite integration time domain (FITD) electromagnetic software. In the simulations, the SwO is assumed to be a perfect electric conductor (PEC) and the substrate dielectric material is assumed to be lossless and dispersionless. The SwO dimensions are determined for a free space wavelength of $\lambda_0 = 500\ \mu$m corresponding to a (resonant) frequency of 0.6 THz. The wavelength $\lambda$ in the substrate is $\lambda_0/\sqrt{3} = 346.1\ \mu$m. A 1 V ramp rising excitation with a 0.1 ps rise time was applied to the switch gap. A far-field electric field probe, oriented in the $+y$ direction at a distance of 1 cm from the origin on the $z$-axis was used to monitor the electric fields radiated by the antenna. Further details of the simulation setup are provided in [6].

The electric field waveform is shown in Fig. 2(a). The damped sinusoidal electric field profile decays to zero in approximately 50 ps. The Fourier transform of the electric field indicates a resonance at 0.4 THz, Fig. 2(b). The radiation pattern is dipole-like [6]. Note that, while the dimensions were determined for a frequency of 0.6 THz, the SwO is found to resonate at 0.4 THz.

While previous researchers have focused on generating a single transient pulse [2], the pulse radiated from a SwO antenna is of a much longer duration. This results in roughly an order of magnitude increase in the energy in the pulse.

## 3 Optimization of Various SwO Antenna Parameters

Pursuing the design of a pulsed (damped sinusoid) SwO THz radiator we need to find some optimization conditions. Given some frequency, $f_0$, how much energy can we radiate in a damped sinusoidal pulse? This

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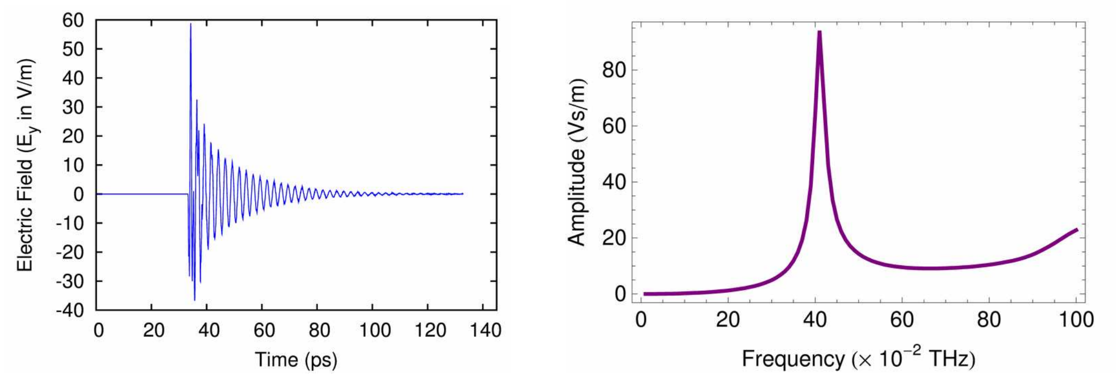
[1] `http://www.cst.com`



(a) Electric field response, $E_y$, from far-field probe at 1 cm from the origin on the $z$-axis.

(b) Fourier transform of the electric field response, $E_y$, from the far-field probe.

Figure 2: Electric field response and its Fourier transform.

depends on the various parameters of the antenna and the source. An extensive theoretical analysis of the problem is given in [7] wherein three approaches are used to determine suitable ranges for the parameters of interest: (1) A simple capacitance model is used to assess the approximate antenna length ($l_a$), antenna width ($w$), switch length ($l_s$), substrate permittivity ($\epsilon_{\text{rs}}$), and substrate height ($h$), to maximize the stored energy and avoid breakdown. (2) A dipole model where two electric-dipoles are used to determine the SwO parameters in terms of the radiation quality factor, $Q$. (3) A transmission line model is used to estimate the skin effect and switch losses.

CST MWS® was used for the parameter study. The primary objective is to maximize the radiated energy. The validity of CST as a reliable tool was established by comparing the numerical results with previously published data; excellent agreement was obtained [8]. The simple model of the problem adopted in the parameter study, akin to that in Fig. 1, does not consider the physics of the photoconductive-switch region (carrier lifetime, carrier mobility, *etc.*). Nevertheless, the idealized switch model provides valuable insight into the interdependence between various parameters. For complete details of the excitation, simulation setup, probe placements and CST simulation parameters the reader is directed to [9].

Simultaneous variation of all parameters is too resource intensive and therefore only one parameter was varied at a time while keeping the other parameters fixed.The empirical fit relations for various parameters are summarized in Table. 1. Each parameter is related to the radiation $Q$ and the resonant frequency $f_0$. It

Table 1: Summary of parametric study of the SwO.

| Parameter | Range | Empirical Relations | |
|---|---|---|---|
| | | $Q$ | $f_0$ |
| $h$ | $\frac{\lambda}{20} \le h \le \frac{\lambda}{4}$ | $\frac{3}{2}\left[\frac{h}{\lambda}\right]^{-1.2}$ | Constant |
| $\epsilon_{\text{rs}}$ | $2 \le \epsilon_{\text{rs}} \le 10$ | Constant | $\frac{\sqrt{\epsilon_{\text{rs}}}}{4}$ |
| $l_s$ | $\frac{\lambda}{50} \le l_s \le \frac{\lambda}{5}$ | $125\sqrt{\frac{l_s}{\lambda}}$ | $0.22\left[\frac{l_s}{\lambda}\right]^{-0.15}$ |
| $w$ | $\frac{\lambda}{20} \le w \le \lambda$ | $36\left[\frac{w}{\lambda}\right]^{1.35} + 14$ | $-0.35\sqrt{\frac{w}{\lambda}} + 0.6$ |

was found that the antenna width plays the most crucial role in the design. For $h, \epsilon_{\text{rs}}$ and $l_s$, in Table. 1, the peak radiated power density is, for all values explored, less than 30 mW/m$^2$. This is approximately 500%

less than that observed for $w = \lambda/8$ and $w = \lambda/2$ [9–11]. It was also observed that for all the $h, \epsilon_{\rm rs}, l_s$ and $w$ values investigated the far-field radiated power density patterns, at the respective resonant frequencies, are dipole-like [10, 11].

The empirical relations in Table. 1 are constrained as they apply only to specific SwO dimensions since only one parameter is varied at a time. Nevertheless, these results provide valuable quantitative insight, and a much needed starting point, for the antenna design.

## 4 Conclusions

An approach to high power THz generation using a photoconductively-switched switched-oscillator radiator has been presented in this paper. Numerical simulation results from a proof-of-concept design show that the device functions as expected (resonant frequency, radiation pattern, *etc.*). A simplified model is used to optimize various antenna parameters. Future work involves experimental realization of the antenna as this will enable a more thorough investigation of various non-linearities and material parameters not considered in this work.

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