Sensor and Simulation Notes

Note 551

February, 2010

Line-Source Switched-Oscillator Antenna

Carl E. Baum, Prashanth Kumar and Serhat Altunc
University of New Mexico
Department of Electrical and Computer Engineering
Albuquerque, NM 87131

Abstract

This paper extends the concept of an array of THz resonant elements to sets of distributed elements that can be used as the rows of an array.

1 Introduction

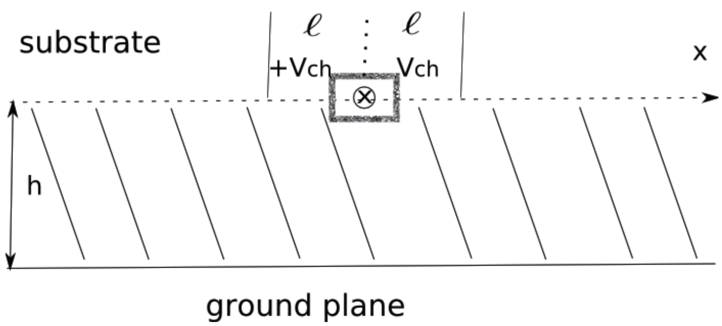
Recently [1] we started exploring a second kind of THz antenna. Instead of a switched oscillator driving a zig-zag (or similar) antenna [2], where the switched oscillator had a conducting strip very close ($<< \lambda/4$) to a ground plane(with problems that entails), let us raise the switched oscillator conductor toward $\lambda/4$ from the ground plane and use the switched oscillator as the antenna. This latter choice may have some advantages (and perhaps some disadvantages) compared to the previous case.

We shall first consider a basic switched-oscillator/antenna element. Then we extend it as a line source (making it part of an array). Suppression of unwanted modes is then considered.

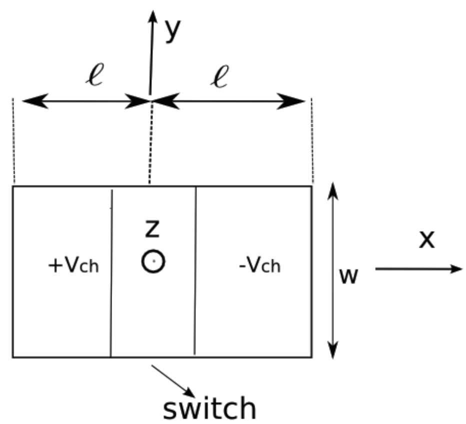
2 Basic Element

2.1 Description

As illustrated in Fig. 2.1, we have a basic antenna element as an equivalent electric dipole, including a reflection from a metal ground plane to force the radiation in the forward (+z) direction.



(a) Side view



(b) Top view

Figure 2.1: Basic Switched-Oscillator Antenna

The thickness of the dielectric substrate is such that

$$\begin{aligned} h &\simeq \lambda_d/4 \text{ or less} \\ \lambda_d &\equiv \text{wavelength in dielectric of relative permeability } \epsilon_r \end{aligned} \tag{2.1}$$

The antenna length, 2ℓ, is a half-wavelength long as

$$\ell \simeq \lambda_d/4 \tag{2.2}$$

since most of the energy is stored in the substrate. We can estimate the wavelength as

$$\lambda_d = v/f, \quad v = c/\sqrt{\epsilon_r} \tag{2.3}$$

where v is the wave velocity in the dielectric substrate.

2.2 Typical numbers

For some typical numbers we can estimate the frequency as

$$f = .3 \text{ THz} \tag{2.4}$$

associated with a local null in the atmospheric attenuation [3]. For a typical substrate SiO_2 we then have

$$\begin{aligned} \epsilon_r &\simeq 3.7 \\ \lambda &= c/f \text{ free-space wavelength} \\ &\simeq \sqrt{\epsilon_r}\lambda_d \\ &\simeq 1mm \end{aligned} \tag{2.5}$$

For an assumed ϵ_r of 3.7 we have

$$\begin{aligned} \epsilon_r &\simeq 3.7 \text{ silicon dioxide} \\ \sqrt{\epsilon_r} &= 1.92 \\ \lambda_d &= .52 \text{ mm} \\ \lambda_d/4 &= .13 \text{ mm } \textit{or } 130\mu\text{m} \end{aligned} \tag{2.6}$$

This implies a thin substrate. Also note that since $\lambda_d < \lambda$, this raises the Q of the oscillation.

2.3 Stored energy

The stored energy (before switch closure) is

$$\begin{aligned} U_0 &= \frac{C[2V_{ch}]^2}{2} = 2CV_{ch}{}^2 \\ C &\simeq \frac{\epsilon_r\epsilon_0\ell w}{2h} \text{ two halves in series} \end{aligned} \tag{2.7}$$

Larger h means a larger V_{ch} is allowed within breakdown limitations of the substrate. Let, as a rough approximation, the allowable charge voltage be

$$\begin{aligned} V_{ch} &= E_0 h \text{ (or a little less)} \\ E_0 &= \text{breakdown electric field} \end{aligned} \tag{2.8}$$

With (2.1) this gives

$$U_0 = \frac{\epsilon_r \epsilon_0 \ell w h E_0^2}{2} \tag{2.9}$$

So, while increasing h lowers the capacitance, it also increases the allowed stored energy through increased V_{ch}. This argues, from (2.1),

$$\begin{aligned} h &\simeq \lambda_d/4 \\ U_0 &= \frac{\epsilon_r \epsilon_0 \ell w \mathrm{h} \lambda_d [E_0]^2}{8} \end{aligned} \tag{2.10}$$

Now λ_d is approximately

$$\lambda_d = \frac{\lambda}{\sqrt{\epsilon_r}} \tag{2.11}$$

giving

$$\begin{aligned} U_0 &= \frac{\sqrt{\epsilon_r} \epsilon_0 \ell w \mathrm{h} \lambda E_0^2}{8} \\ &= \frac{\epsilon_r \epsilon_0 w \ell^2 E_0^2}{2} \end{aligned} \tag{2.12}$$

This gives some feel for how much stored energy one can achieve for a given frequency for oscillation.

Typical numbers for solid dielectrics (say for SiO_2) are

$$\begin{aligned} \epsilon_r &\simeq 3.7 \\ E_0 &\simeq 500 \text{ MV/m} \\ f &\simeq 0.3 \text{ THz} \\ \lambda &\simeq 1\text{mm} \\ \ell &= \frac{\lambda_d}{4} \simeq 0.13\text{mm} \\ w &\simeq \ell \\ h &\simeq \ell \end{aligned} \tag{2.13}$$

This would give

$$\begin{aligned} U_0 &= \frac{\sqrt{\epsilon_r} \epsilon_0 \ell^3 w E_0^2}{2} \simeq 9\mu\text{J} \\ V_{ch} &= h E_0 \simeq 65 \text{ KV} \end{aligned} \tag{2.14}$$

However, there are other limitations, including surface flashover (which can be minimized with dielectric coatings) and the switch properties.

2.4 Switch

For a resonant waveform to radiate most of the energy we need a photoconductive material with long career lifetime. Consider Cr doped SI-GaAs [4] For 0.3 THz with period 3.3 ps, we can see

Table 1: Properties of Cr Doped SI-Ga-AS

carrier lifetime	$50 - 100$ ps
mobility	$0.1\ \mathrm{m}^2/(\mathrm{Vs})$
resistivity	$10^5\ \Omega$ m
breakdown field E_1	50 MV/m (based on LT GaAs)
band gap	1.43 eV

that the carrier lifetime is long enough for 10s of cycles (to e^{-1}) or a Q of 30 or more. This, of course, requires that the fs laser be powerful enough to produce enough carriers to make the switch resistance small compared to Z_c as

$$\begin{aligned} R_{sw} &<< 2Z_c \qquad (2.15) \\ Z_c &= \frac{h}{w}\epsilon_r^{-1/2}\ Z_0 \\ &\equiv \text{ transmission line-impedance of antenna over ground plane} \\ Z_0 &= \frac{\mu_0}{\epsilon_0} \simeq 377\Omega \\ &\equiv \text{wave impedance of free space} \end{aligned}$$

With this low breakdown field (compared to the substrate), this will give our limitation on V_{ch}. So let

$$\ell_s \simeq \ell \qquad (2.16)$$

with the switch occupying half the antenna length so as to given a large breakdown voltage as

$$\begin{aligned} V_{ch} &= \frac{\ell E_1}{2} \qquad (2.17) \\ &\simeq 3.2\mathrm{KV} \end{aligned}$$

which is much less than the result in (2.14) based on the substrate. We can recalculate the stored energy as

$$U_1 = \frac{\epsilon_r\epsilon_0\ell^3 E_1^2}{2} \simeq 0.09\mu\mathrm{J} \qquad (2.18)$$

which is significantly less energy. The switch then dominates V_{ch} and the stored energy. One could lower h, then, to obtain more stored energy consistent with the switch V_{ch} limitation. However, this introduces other problems.

2.5 Skin-effect resistance

From [5] we have a surface resistance, say for copper at 0.3 THz, of

$$R_s \approx 0.14\ \Omega \tag{2.19}$$

Our antenna is a transmission line of characteristic impedance Z_c in (2.15). Using some typical numbers

$$\begin{aligned} \frac{h}{w} &= \frac{h}{\ell} = \frac{\lambda_d}{4\ell} \simeq 1 \qquad (2.20)\\ \epsilon_r &\simeq 3.7 \\ Z_c &\simeq 196\Omega \end{aligned}$$

With w/ℓ about 1, the end-to-end resistance of the antenna is about $2R_s$. A similar resistance applies to the ground plane. The series combination is about $4R_s$ or 0.56 Ω. This is small compared to Z_c, giving a high Q. The per-unit-length resistance is

$$R_s^{'} \frac{R_s}{w} = \frac{R_s}{\ell} = \frac{R_s}{4\lambda_d} = \frac{4R_s}{\lambda_d} \tag{2.21}$$

A simple model is transmission line with equivalent circuit as in Fig. 2.2 The propagation

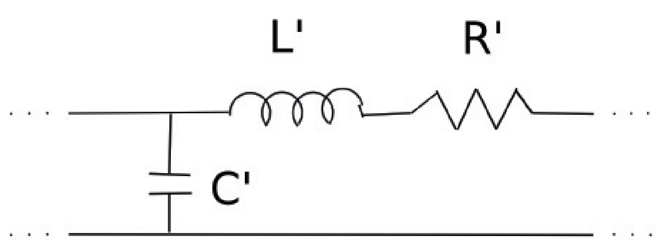


Figure 2.2: Equivalent Per-Unit-Length Transmission-Line Network for Skin-Effect Losses

constant is

$$\begin{aligned} \gamma &= \frac{s}{c} = [[sL^{'} + R_s^{'}][sC^{'}]]^{1/2} \qquad (2.22)\\ &= s[L^{'}C^{'}]^{1/2}[1 + \frac{R_s^{'}}{sL^{'}}]^{1/2} \\ &\simeq s[L^{'}C^{'}]^{1/2}[1 + \frac{R_s^{'}}{2sL^{'}} + ...]^{1/2} \\ &\simeq s[L^{'}C^{'}]^{1/2} + \frac{C^{'}}{L^{'}}\frac{R_s^{'}}{2} \\ &= s[L^{'}C^{'}] + \frac{R_s^{'}}{2Z_c} \end{aligned}$$

The wave propagates like

$$e^{-\gamma x} = \underbrace{e^{-s[L'C']x}}_{\text{delay}} \underbrace{e^{\frac{-R_s' x}{2Z_c}}}_{\text{attenuation}} \tag{2.23}$$

In one round-trip transit the wave propagates a distance λ_d. So for one cycle we have

$$e^{\frac{-2R_s'\lambda_d}{Z_c}} \simeq 1 - \frac{-R_s'\lambda_d}{2Z_c} \tag{2.24}$$

the number of cycles to e^{-1} is

$$\begin{aligned} e^{\frac{-NR_s'\lambda_d}{2Z_c}} &= e^{-1} \qquad (2.25) \\ N &= \frac{2Z_c}{R_s'\lambda_d} \\ &\simeq \frac{Z_c}{4R_s'} \end{aligned}$$

Using previous numbers

$$N \simeq 350, Q \simeq 1100 \tag{2.26}$$

This is quite high and is likely reduced by switch and radiation losses, and the switch carrier lifetime.

3 Extension of Width to Arbitrarily Large Dimensions

As in Fig. 2.1, the width w has been limited to a size of the order of ℓ (or a little larger) to avoid unwanted modes of oscillation. Let us try to relax this requirement. Let us imagine a set of such antenna elements such as might be in a matrix row [6].

In Fig. 3.1 let us extend the width to arbitrarily large widths (transverse to current flow). The

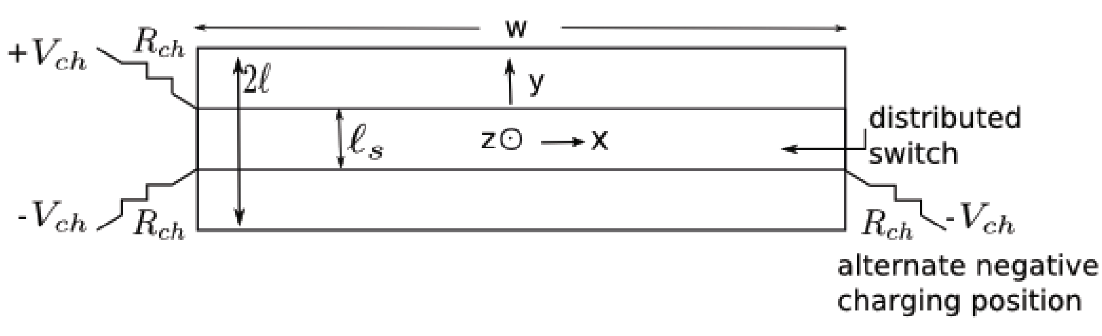


Figure 3.1: Extension of Oscillator/Antenna Width

charging ($\pm V_{ch}$) can be accomplished at one end(retaining the xz plane as a symmetry plane), or we can use alternate ends for differential charging (retaining the z axis as a C_2 rotation axis [7]).

This latter case allows + and - charging on opposite sides of the array. For really fast charging (high reputation rate). this may also produce a more uniform voltage across the long distributed switch, allowing for propagation along the switch during the charging cycle.

Currents in the x direction during the oscillation period can be somewhat suppressed by cutting slots in the antenna as indicated in Fig. 3.2. This leaves a set of elements as in Section 2, each

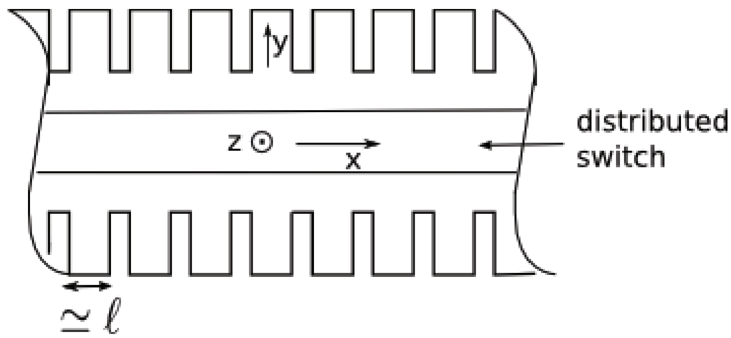


Figure 3.2: Slots to Suppress x-Directed Currents

with width $\simeq \ell$, to avoid x-directed element resonances. However, we still need a thin connection from element to element for charging the entire "row" of elements. Due to the mutual coupling of the various elements, and their difference near the ends of this distributed antenna, one may need to trim the elements near the ends for optimum performance.

The mutual impedances from one element to the other nearby ones need to be considered. We may need to space the elements some critical distance apart to obtain a desired oscillation pattern.

4 Array

Now we can think that of an array, as in Fig. 4.1, to compare to [6]. The rows are now somewhat continuous, while the columns are still discrete.

5 Concluding Remarks

Here we have an interesting and intriguing extension of the switched oscillators as a THz radiator. Extending the width, of course, increases the stored energy. However, one needs to be careful to avoid unwanted modes of oscillation. Using slots to make the wide element more like a set of narrow elements should help in this regard. This also lets one think of this as as set of small elements, extended in one direction, to make a row in an antenna array. There are detailed calculations and experiments to be done to optimize the design.

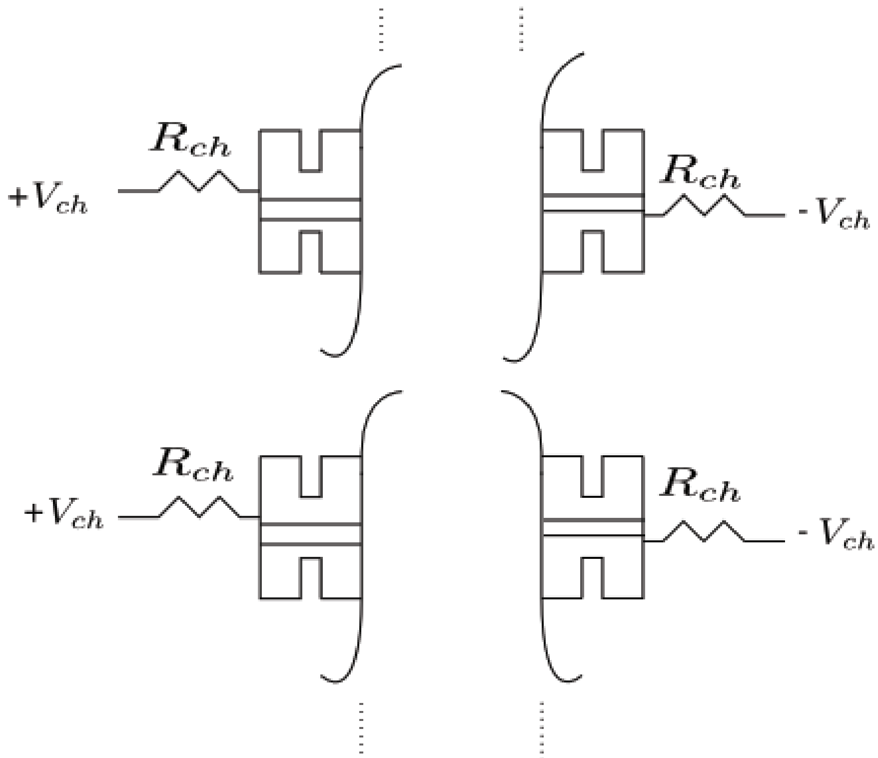


Figure 4.1: Array of Rows of Distributed Elements

References

[1] P. Kumar, S. Altunc, C. E. Baum, C. G. Christodoulou and E. Schamiloglu, "Switched oscillator as an antenna." Terahertz Memos 1, 2009.

[2] C. E. Baum, "Meander and Zig-Zag Antennas in Periodic Resonance for THz Application." Sensor and Simulation Note 539, Dec. 2008.

[3] R. W. McMillan, "Advances in sensing with security applications." pp. 1 - 26, in J. Byrnes(ed.), *Terahertz Imaging Milimeter-Wave Radar*, Springer, Dordrecht, The Netherlands, 2006.

[4] K. Sakai, *Terahertz Optoelectronics*. Springer, Germany, 2005.

[5] C. E. Baum, "Terahertz Antennas and Oscillators Including Skin-Effect Losses." Sensor and Simulation Note 535, Sept. 2008.

[6] M. E. Shaik, C. E. Baum and C. G. Christodoulou, "Arrays of Zig-Zag Antennas Driven by Switched Oscillators." Sensor and Simulation Note 542, 2009.

[7] C. E. Baum and H. N. Kritikos, "Symmetry in electromagnetics." pp. 1 - 91, Ch. 1, in C. E. Baum and H. N. Kritikos *Electromagnetic Symmetry*, Taylor & Francis, 1995.