THE GENERATION OF HIGH ENERGY ULTRA WIDE BAND PULSES

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Abstract

We present a theoretical discussion of the performance of photoconductive switches mounted in a matched transmission line structure, which addresses issues of risetime and power density. In the analysis we define a switch performance parameter, α, which results in a recipe for optimizing the performance of photoconductive switches. We also discuss the limits on α due to materials' properties and conclude with a discussion of experimental life-testing and a comparison between the theory and experimental results.

1 Introduction

The requirements of ultra wideband (UWB) radar systems include high power, fast risetime, beam agility, and the ability to generate rapidly changing complex waveforms with precision. This translates to the ability to generate multiple, high power, fast risetime pulses which are synchronized to a master clock, since this allows pulses to be added sequentially to synthesize complex pulses and, similarly, pulses can be generated in independent sources to be either added in parallel for increased power, and in phase to provide beam steering.

This paper deals with the methods and existing limitations in the generation of jitter free, fast, high power pulses. Ultra wideband radar in particular requires us to push the limits in power and speed of electrical pulses. The generation of fast, high power pulses yields the best performance with the discharge of a charged transmission line (TL) into a matched TL which in turn provides the transition to the load, in this case a radiating aperture. Independent of the switching process, it is intuitively obvious that the simultaneous requirements of power and risetime conflict, since power goes up with size and larger systems are inherently slower. Secondly, we recognize that the performance limits are achieved by the optimum integration of the switch and TL so that both operate at their respective fundamental limits. Accordingly, we have established a performance parameter to gauge how close a given experimental system comes to the optimum achievable for a given choice of switch and TL materials. The performance parameter, α, equals the power output per unit width (or circumference for circular geometry) of the TL, divided by the risetime of the combined system. We discuss the analysis of this parameter in terms of the switch and TL materials' limits and how they in turn dictate the optimum geometry. Furthermore, we show how α depends on the respective switch and TL electric field limits only, for slow systems. The analysis shows that as the risetime becomes smaller, an increased switch current density is required. The risetime of a switch depends foremost on the switching process and then on various field and geometry related limits which will be discussed in detail. The switching process is the means by which a carrier-free medium is filled with carriers. Diffusion, drift, avalanche and light activation (photoconductance) and combinations thereof are the processes available. Since all involve transit time, whether carrier or photon, we note that their respective velocities in cm/sec are 10^4, 10^6, 10^7, and 10^{10}. With avalanche, the distance travelled is only the collision mean free path times the number of generations (assume 10 for a gain of 1000, ignoring carrier lifetime) which can be much smaller than the switch size. We therefore recognize that only avalanche and light activation, or a combination of the two, are of interest for UWB radar systems due to their high speed requirement. Avalanche has both bulk and filamentary modes, both of which have limitations in their current density (averaged over the entire device cross-sectional area) and thus on the performance parameter α. In addition, since the onset of avalanche is an inherently statistical process, the generation of electrical pulses by avalanche is always accompanied by jitter: on the other hand, jitter is absent when linear photoconduction is used. Although gases, liquids and solids are candidate switch materials, only semiconductors can be considered truly damage resistant to carrier generation due to the low relative ionization level. Therefore, the semiconductors silicon, gallium arsenide, indium phosphide, β-silicon carbide and diamond are the prime candidates. We shall discuss their various tradeoffs and respective abilities to maximize the parameter α. We also present life-testing results which confirm the ability of linear silicon switches to operate for many shots without damage or reduction in operation. Lastly, we analyze previously reported experimental results in light of the theory and show how the risetime of the UWB pulse and the parameter α compare.

2 Performance Parameter

As we described above, the most universal configuration is that of a switch bridging 2 identical TL's with the switch and the TL's all having the same width w, (see

Figure 1). Wrapping w around a cylinder corresponds to a coaxial geometry. The parameter α is defined as the switched power, P, per unit width, w, and per unit rise time t, i.e

$$\alpha = \frac{P}{wt} \quad (1)$$

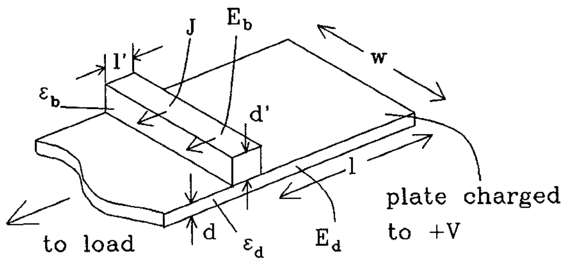

Figure 1 Schematic of switch and line in a planar geometry.

The parameter, α, is a measure of the gain-bandwidth of the system and it is essential that this be maximized for high performance UWB systems.

We recognize the following relations (see Figure 1 for the definition of the parameters):

the Poynting power relation:

$$\frac{E_d^2}{4Z} = \frac{P}{dw} \quad (2)$$

the voltage relation:

$$\frac{E_d}{E_b} = \frac{l'}{d} \quad (3)$$

the EM wave relation:

$$\frac{E_d}{2Jd'} = Z \quad (4)$$

where J is the switch current density when conducting (assumed uniform) and Z is the wave impedance (= $(\mu_0/\epsilon_d)^{1/2}$).

The substitution of these relations in (1) and rearranging yields:

$$\alpha = [\frac{E_b E_d}{4\mu_0}] \frac{l'}{vt} \quad (5)$$

Since the risetime, t, can never be smaller than l'/v, (v is the speed of the wave in the TL), the bracketed expression in (5) gives the largest possible α.

The risetime, t, is composed of a number of independent components which are added in quadrature. These are:

1. The dielectric relaxation; $\tau_0 = \epsilon_b E_b/J$. This is the time to discharge the charged switch capacitance with a current density J.
2. The electric field E_d decays along the switch length l'; thus $\tau_1 = l'/v$.
3. The switch inductance, L, limits the rise time by $\tau_2 = L/2Z$, where Z, the TL impedance, is given by: $Z = (d/w)(\mu_0/\epsilon)^{1/2}$. L is recognized as $\mu_0 l'd'/2w$, (the 2 resulting from the assumed uniform current density). Substituting and rearranging yields;

$$\tau_2 = \tau_0 (\frac{W_d}{8W_b}) = \tau_0 \beta \quad (6)$$

where $W_d = 0.5\, \epsilon_d E_d^2$, and $W_b = 0.5\, \epsilon_b E_b^2$, the electric energy density in the TL and the blocking switch respectively. β is the measure of the relative magnitude of the breakdown fields in the TL and the switch.
4. For photoconductive switches we have to include the transit time of the activating light through d' as $\tau_3 = d'/v_b$. We assume for simplicity's sake that the speed of light in the optical and the microwave frequency range are equal. Substitution and rearranging yields:

$$\tau_3 = \tau_0 \sqrt{\frac{\beta}{2}} \quad (7)$$

5. Lastly, we include the carrier generation process, τ_4, discussed in the introduction. This quantity can be ignored in linear light activation since it is of the order of a femtosecond. We cannot describe the avalanche time in a simple relationship since avalanche is a very strong function of the field[1] and the onset of current shifts the voltage from the switch to the load. Thus each circuit configuration results in a different avalanche time[1].

Accordingly, we express the risetime, t, as:

$$t = (\tau_0^2 + \tau_1^2 + \tau_2^2 + \tau_3^2 + \tau_4^2)^{1/2} \quad (8)$$

Substituting (8) for τ_1 in (5) and neglecting τ_4 yields:

$$\alpha = C_1 \gamma \sqrt{(1 - \frac{(\beta + 1)^2}{4\sqrt{\beta}} [\frac{E_b}{J^2 t^2}] \gamma)} \quad (9)$$

where we define

$$\gamma = \sqrt{8 W_b W_d} \quad (10)$$

and C_1 is given by:

$$C_1 = \frac{v_b v_d}{4\sqrt{2}} \quad (11)$$

γ relates to the geometric mean of the respective energy density in the switch and the TL, and is thus a measure of the absolute value of E_b and E_d, in contrast to β (see above). The factor of 8 can be traced to the uniform current distribution in the conducting switch and the factor of

2 (twice) due to the circuit configuration of two TLs. v_b and v_d represent the velocity of the wave in the switch and the TL respectively.

Examination of (9) shows that α is maximized first when $\beta = 1$, and secondly when:

$$\gamma = \frac{2}{3} \frac{(Jt)^2}{\epsilon_b} \qquad (12)$$

which yield:

$$\alpha = \frac{C_1 \gamma}{\sqrt{3}} \qquad (13)$$

Studying (9), (12) and (13) yields substantial insight into the tradeoffs available. It is important to realize that all dimensions (except w which has no impact on α) are completely determined by the choice of variables in (9). Here we discuss only a few salient features and note the following.

Equations (9) and (13) show the optimum system is completely defined in dimensions and performance, given γ, β, and J. Once these parameters are set, one can measure how well a given design takes advantage of the inherent material limits.

Equation (9) shows that α is a constant for systems where t, the risetime, is long. In that regime, power can be exchanged directly for speed. As the speed increases, the term under the square root goes directly to zero unless it is compensated by the reduction in γ, which reduces α, or by an increase in the current density, J. From equations (9) and (12), we see that t and J only appear as a product. Thus high values of α can only be maintained at shorter risetimes by increasing the current density, which implies the use of low impedance structures. We conclude from this that the higher current density switches provide the highest performance UWB radar systems. Linear photoconductive switches have the highest current density, since the carrier generation process is independent of the temporal variation of the voltage.

3 Materials' Limits

The switch performance parameter, α, is limited by the properties of the switch material employed, particularly by E and J. Several semiconductors can be considered for use in high power switches, most obviously silicon which has been used for power switching for many years. Gallium arsenide has a fast recovery time and technology for the manufacture of GaAs is maturing, although efficient, high power lasers are not available at the GaAs band gap. Indium phosphide, β-silicon carbide, diamond and various II-VI semiconductors are not yet considered to be past the experimental stage for high power devices. Important material properties of silicon and gallium arsenide are summarized in Table I.

The theoretical switched power, P, is less than a factor of three lower for silicon than for gallium arsenide, due mainly to the higher mobility of carriers in gallium arsenide. However, contact metallurgy in GaAs is still immature relative to that for silicon, and GaAs is not yet able to sustain the high current densities at high power that silicon can.

Table I Electrical properties of silicon and gallium arsenide

	E_{max} V/cm 10^3	J_{max} A/cm^2 10^5	P W/cm^3 10^{10}	Band Gap eV	lifetime μs
Si	300	1.6	4.8	1.12	10-100
GaAs	400	3.2	12.8	1.43	.001-.01

However, other factors become important when considering an UWB system. For instance, the band gap of silicon, on the other hand is around 3/4 that of gallium arsenide and the carrier lifetime is considerably longer. The lifetime of the carriers becomes important when considering carrier conservation and switch recovery. If the required electrical pulse length is longer than the recombination time, as can be the case for UWB systems, then the optical energy required to keep the switch closed is increased since carriers continually have to be generated. The process of "lock-on" in gallium arsenide increases the effective carrier lifetime, but at a significant cost in terms of switch dissipation and damage.

As has been explained elsewhere[2], one can reduce the effective recovery time using a semiconductor diode junction. The result is that a silicon junction switch can be turned off in a few nanoseconds, simply by recharging the line. Additionally, the use of a junction switch reduces the heating by several orders of magnitude while the switch is blocking voltage due to the reduced leakage current[1].

Thus the properties of the available materials lead us to consider silicon junctions as the optimum photoconductive switch for generating high powers.

4 Light Sources

It has been shown, using simple arguments[3], that the use of solid state lasers gives a considerable advantage over the use of semiconductor lasers for activating photoconductive switches, especially for high power systems. Orders of magnitude advantages are gained in peak diode laser power, system volume and cost for the solid state laser, especially for high power systems: this is explained in more detail in Ref. 3

5 Experimental Results

LASS devices were tested at high power in low impedance configurations. Measurements were made by mounting a 50 Ω probe in parallel with the transmission line (typically less than 1 Ω). The large impedance mismatch between the line and the probe result in little perturbation on the propagating pulse. The signal was attenuated and measured on a Tektronics 7250 (6 GHz) transient digitizer. Various line configurations have been demonstrated where the switches have been operated in parallel (power combining) and series (multi-cycle waveform): these are described further in Ref. 2. Here we describe the operation of a single switch at high power and compare the results to the theory developed above. We also present the results of initial life-testing, which show that the linear silicon switch is capable of the long-life operation required of systems.

In the high power, single switch test, two 4 cm wide switches were mounted in parallel on a 0.128 Ω (8 cm wide) line and activated by a 35 psec light pulse: the generated signal is shown in Figure 2. The peak power measured was

118 MW, with a risetime of around 32 psec. The source operated at 5 Hz. The rate of current rise was 9.5×10^{14} A s^{-1}, a record for this class of switch. The Poynting vector was 3 GW/cm^2 and the power per unit width across the transmission line was 14.75 MW/cm. This high peak power was generated with a source volume of less than 1/4 cm^3. This experiment demonstrates the unique power and speed capability of this type of switch compared to other photoconductive switches.

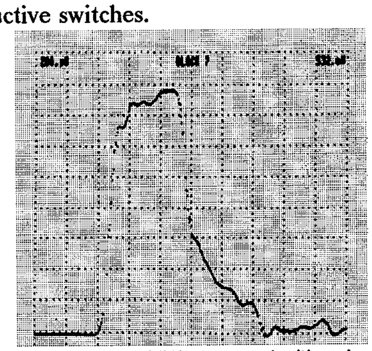

Figure 2 Signal at 118 MW generated with a risetime of 30 psec.

It is useful to make a comparison of the performance of this switch with that predicted by the theory described in Section 2. In this case, we use the values:

$d = 50\ \mu m$
$d' = 6.4\quad 10^{-2}$ cm
$l' = 0.125$ cm
$V = 7.8$ kV
$\epsilon_b = 3.5\, \epsilon_0$
$\epsilon_d = 11.4\, \epsilon_0$

Substituting these values into (8), we obtain a theoretical value for the risetime to be 28 psec, the majority of this risetime being attributable to the inductive component. This is very close to the measured risetime of 32 psec, and shows that the switch was operating close to the risetime limit, despite the fact that the optical pulse was not instantaneous, as is assumed in the theory, but had a minimum width of 35 psec. The fact that the risetime was shorter than the optical pulse indicates that there was sufficient optical energy in the early portion of the pulse to activate the switch completely, and that the latter portion of the optical pulse did not affect the risetime.

The experimental value of α is 4.6×10^{19} W m^{-1} s^{-1}, whereas the theoretical value is 5.3×10^{19} W m^{-1} s^{-1}. The (low speed) theoretical maximum, $C1\,\gamma$, is 2.04×10^{20} W m^{-1} s^{-1}. Here the reduction from the low speed maximum was a factor of 0.294, rather than the theoretical optimum of $1/\sqrt{3} = 0.57$. This was due to the inductive risetime, $\tau_2 = \beta\, \tau_0 = 23.7 \times 1.1$ ps, which dominated the risetime. This was a design choice given the material limits which was made to maximize γ at the expense of β, since both the laser and the measuring system were limited in speed to around 30 ps.

In order to examine the longevity of the linear silicon switches, life testing was performed at power levels reduced form those just described. In the first test, an 8 cm wide line (two 4 cm switches operating in parallel) was repetitively operated at 10 Hz. The line operated at 30 MW peak power with a pulse risetime in the region of 100 psec for around 1.8 million shots. The energy of the activating optical pulse was 2.5 mJ, giving an optical requirement of 83 μJ/MW. The test ended after the transmission line material (not the switch) failed. A second lifetime test was performed on another 8 cm line operating at 60 MW peak power (42 μJ/MW). This line operated at 10 Hz for over 150,000 shots, again with a pulse risetime of around 100 psec. This line also failed due to the transmission line material and not the switch: we are currently investigating the quality control process of the transmission line material.

These preliminary results show that the approach of using linear silicon junction switches in a low impedance configuration will provide a reliable method for the generation of UWB signals.

6 Summary

We have presented a general theoretical analysis of switching in a matched system and applied it to the case of linear photoconductive switches. The analysis presents us with a performance parameter, α, which is related to the power produced per unit width of the system and the pulse risetime. The parameter shows us that in the high speed regime, there is no simple trade-off for power and speed, and that high performance operation necessitates high switch current density, i.e. low impedance and linear operation. A comparison of a previous experimental result, which had the highest known value of α for a photoconductive switch, and the theory developed herein shows good agreement. Preliminary lifetime testing also shows that the linear silicon junction switch is capable of the long lifetimes required of these systems.

7 Acknowledgements

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8 References

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