Photoconductive Impulse Generation and Radiation

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***Abstract*—The generation of extremely narrow, high peak power pulses using an optically activated impulse generator has been demonstrated. Radiative measurements at 1 Hz PRF have been conducted at pulse bias levels up to 15 kV, using an optical pulse from a Nd:YAG laser to trigger the device. The measured pulse from a wide-band antenna had a pulsewidth of 1.5 ns with a risetime of 900 ps. The frequency spectrum of this radiated waveform ranged from 50 MHz to 1 GHz.**

I. Introduction

The DEMONSTRATION of photoconductive switches operating at large bias voltages and generating multi-megawatt powers has stimulated the research of optically activated semiconductor switches in the pulsed power community [1]. Initially, research emphasis was devoted to the generation of high peak power pulses with risetimes in the multi-nanosecond regime. However, in recent years there has been an increased interest in the generation of sub-nanosecond risetime pulses with high peak powers and with very short durations. Research efforts have resulted in substantial progress in the reduction of risetime and pulsewidth. The generation of megawatt pulses with sub-nanosecond rise times has been reported by Pocha *et al.* [2] and Zutavern *et al.* [3].

The generation of high peak power pulses with sub-nanosecond risetimes and very short durations using an optically activated semiconductor switch is a difficult design problem. One way to control the pulse width of the output pulse is to decrease the dimensions of the pulse forming line (PFL) used for the energy storage medium. The output pulse width is approximately equal to the round-trip traveling time of the wave in the PFL. However, as the physical dimensions of the PFL approach the values necessary to achieve the narrow pulsewidth (<1 ns), the diminished energy storage capability of the PFL and the large stray inductance between the PFL and switch electrode pose a serious problem.

Manuscript received April 3, 1991; revised July 3, 1991.

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IEEE Log Number 9102783.

Utilization of the radial transmission line structures as the PFL has several advantages when compared to the typical microstrip or coaxial transmission line structure. The geometrical effect of this radial transmission line creates a large electrode area, so that a relatively large electrostatic energy may be stored. In addition, the impedance transformation, caused by the impedance variation in the radial line, results in a voltage gain [4]. Kim *et al.* [5] have experimentally demonstrated the generation of nanosecond pulses with voltage gain using an optically activated device housed in a radial transmission line.

The generation and characterization of the switch waveforms, using a dummy load, represent only part of work needed to obtain an understanding of this emerging technology. The incorporation of a wide band antenna with the switch and the measurement of the actual radiated waveforms are also needed to complement this effort. Toward this goal, this paper investigates the radiated waveforms obtained by driving a wide band antenna with an optically activated impulse generator, comprising a radial transmission line. The radiated waveforms were generated, measured, and characterized for several switch voltages. These measurements should benefit impulse technology [6], i.e., the radiation of short pulses having a very high peak power level and a broad frequency spectrum that extends from near dc to several gigahertz.

II. Optically Activated Impulse Generator Utilizing a Radial Transmission Line

A. Device Structure

The optically activated nanosecond impulse generator consists of a discrete photoconductive GaAs switch and a radial transmission line (hybrid design). Utilization of the radial transmission line structure as the energy storage medium enables one to enhance the energy storage capability, while producing a narrow pulsewidth and output voltage gain in a compact structure. Both diode and Nd:YAG lasers were used to optically activate the GaAs switch.

The schematic diagram of this impulse generator is given in Fig. 1. The optically activated GaAs switch was located at the center of the radial transmission line structure. The radial transmission line, in which the electro-

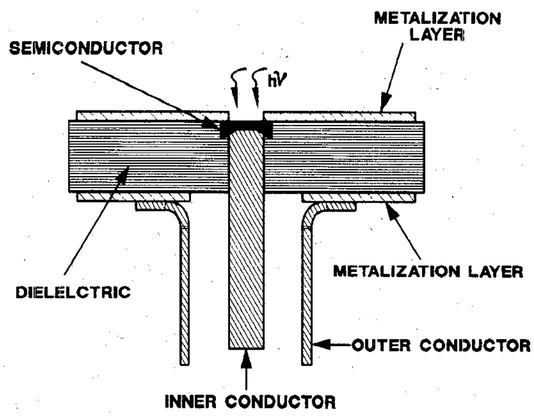

Fig. 1. Side view of the optically activated impulse generator (not to scale).

static energy is stored, was realized by fabricating a disc-shaped conductive layer on both sides of the teflon dielectric. The radius of the inner edge of the radial transmission line was selected to have a characteristic impedance of 50 Ω. The diameter of the outer edge of the radial line, 25 cm, was determined by the design criterion of about 1 ns pulsewidth.

B. Analysis of Radial Transmission Line

At least three techniques are available for analyzing the pulse output from a radial transmission line, used as the energy storage medium. The first technique considers the radial transmission line as the equivalent of a perfect step-up transformer [7]. In this case the voltage is stepped up by virtue of the impedance transformation in the radial line. This approach is somewhat crude, but under certain conditions in which the impedance transformation is less than 2 or so it does allow one to make reasonably good estimates of the peak pulse output. The mathematical expression of the expected output voltage from the radial line (with both the switch and load impedance at the center) is [5]

$$V = [V_o Z_o / (Z_{ir} + Z_o + R_{on})] \times [Z_{ir}/Z_{or}]^{1/2} \quad (1)$$

where the Z_{ir}, Z_{or} are the characteristic impedance values at the inner and outer edges, respectively, V_o is the bias voltage, Z_o is the load impedance, and R_{on} is the on-state semiconductor resistance. The first term is identical to that of a uniform PFL. The square root term expresses the voltage transformation of the radial line and is referred to as the voltage gain factor.

In order to use (1), we make use of the expression for the characteristic impedance of a wide microstrip line [8], as applied to a radial transmission line:

$$Z_o(r) = (377/\sqrt{k})(d/2\pi r) \text{ for } 2\pi r \gg d \quad (2)$$

where r is the radius, $Z_o(r)$ is the characteristic impedance (ohm) at r, d is the thickness, and k is the dielectric constant of the radial line. Substitution of $k = 2.07$, $d = 3$ cm, and the radii of the inner and outer edges of the radial line (diameters of 5 cm and 25 cm, respectively) into (2) results in the characteristic impedances at the inner and outer edges of approximately 50 Ω and 10 Ω, respectively. The impedance transformation is therefore a factor of 5. As will be noted in the following discussion, this is too large for the simple transformer model to provide an accurate estimate of output voltage.

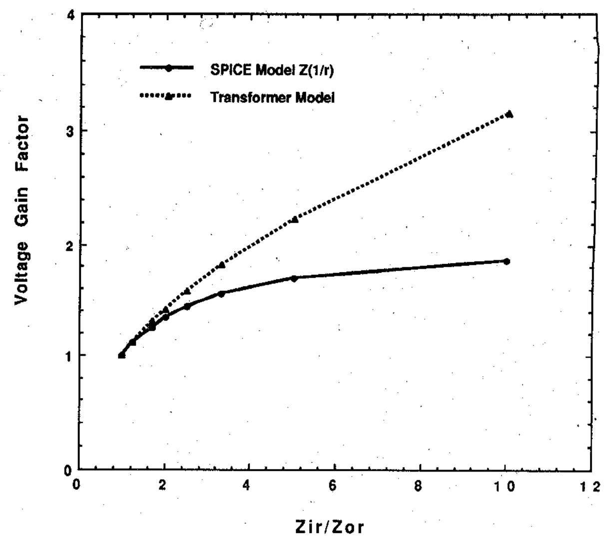

Fig. 2. Voltage gain factor versus impedance ratio for the transformer and transient SPICE model.

The problem is that the given pulsewidth determines the length of the device, which combines the transforming and PFL functions into a single structure. Consequently the transformer cannot be made arbitrarily long, so as to accomodate all frequency components. As a result, internal reflections and some pulse spreading are bound to occur, and they are more noticeable when the transformation ratio is large. In the case of the radial line, the reflections are particularly intense near the central region. For impedance transformations greater than 2, an alternate modelling approach must be employed.

The second more accurate technique relies on the use of a SPICE simulation, in which the radial line is replaced with small sections of transmission line connected in series. The impedance of each section is allowed to vary inversely with radial length, which is characteristic of a radial line. This technique is usually adequate provided the sections are chosen small enough to maintain accuracy. In this simulation a minimum of ten sections were employed in order to achieve the necessary accuracy. The comparison of these results with the transformer model is shown in Fig. 2. As shown the outputs for both results are identical up until the impedance ratio of about 2. Beyond this point, the two models diverge, with the SPICE simulation predicting much smaller gains compared to the perfect transformer model.

Problems, however, even with the SPICE simulation, will arise in the transition region, where the conditions no

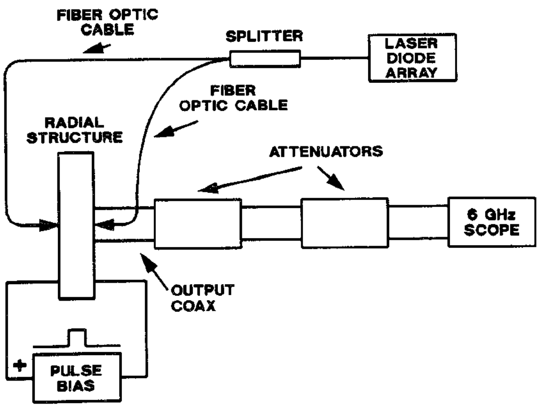

Fig. 3. Experimental set-up for testing the optically activated impulse generator utilizing a resistive dummy load.

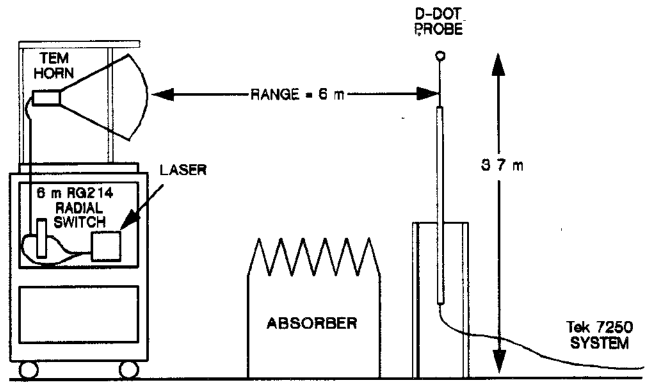

Fig. 4. Experimental set-up for the measurement of radiated waveforms from a wide-band antenna.

longer conform to a simple transmission line and where the boundary conditions become more complicated. In order to overcome these complications, a third technique must be employed, in which a transient electromagnetic field mapping is employed. This technique will be the subject of a forthcoming study.

C. Device Characterization

Initial research efforts were devoted to the investigation of the switching mechanisms and the behavior of the radial transmission line using a dummy load. In an effort to facilitate the understanding of this device, new experimental procedures were devised. Acquisition of the experimental data, which is crucial to the understanding of the switching mechanisms and the voltage gain, were conducted using a 50 Ω resistor as a dummy load and a laser diode as a triggering optical source. The schematic diagram of the experimental set-up is given in Fig. 3. A 50 Ω coaxial structure was pressure fitted to the ground side electrode of the impulse generator. An SCR-transformer circuit was used as the charging pulser. After charging the radial transmission line with the charging pulser, optical light pulses from the laser diode array triggered the device. The voltage waveforms were measured using an oscilloscope as the terminating load, with wide bandwidth Barth attenuators connected directly to the Tektronix 6 GHz transient digitizing oscilloscope.

A laser diode, which generated optical pulses with a pulsewidth of 40 ns, was used to trigger a 2 mm gap photoconductive GaAs switch. The switch was mounted into a radial transmission line. Although the output power of this laser diode was about 100 W, the actual optical energy delivered to the switch was much less than 1 uJ (only a small portion of the laser pulse was utilized). The waveform measurements of the output pulses were conducted at field strengths up to 60 kV/cm. The obtained output pulse parameters such as the risetime, pulsewidth and voltage amplitude of the output pulse provided critical information for the understanding of the switching modes (in the case, the avalanche mode) and the transformation behavior of the radial line (output voltage gain).

III. Measurement of the Radiated Waveforms

After characterizing this device using a dummy load, the optically activated impulse generator was connected into the wideband antenna and further investigations were conducted on the radiated waveforms. The radiative measurements were performed in the anechoic chamber at MICOM. The schematic diagram for the measurements of the radiative waveforms is given in Fig. 4. The radiated waveforms were measured using a Prodyne 3 GHz D-dot probe and a Textronix 7250. The overall diagnostic bandwidth was estimated to be slightly less than 3 GHz. The derivative field was measured for several switch voltages at a range of 6 m.

The switch wave forms were radiated using a large TEM horn antenna. The antenna was well characterized, having a flat gain across a half-beamwidth of 45° and capable of supporting pulse rise times of less than 200 ps. The 1.6 m plates, with a 90° spread angle and 80° divergence angle, had a quarter-wave ring frequency of 50 MHz.

The switch assembly was first configured in the laboratory and tested to verify its operation using a Q-switched Litton P-3 Nd:YAG laser system. Although the laser pulse risetime was slow, about 10 ns, this apparently did not slow down the risetime of the switch, which was operating in an avalanche mode. The laser output was attenuated to produce a total output through the fiber optic of 10 uJ. After verifying the operation of the switch, the optically activated impulse generator was moved into the anechoic chamber and attached to the horn antenna, which was elevated to a height of 3.5 m. Connections at the antenna and at the switch were made using HN cable connectors. For the radiation measurements, the switch was operated at voltages ranging from 6 kV to 15 kV. The derivative waveforms were then integrated and scaled to determine the peak fields and the risetime for each voltage.

IV. Experimental Results and Discussion

The summarized experimental results using a dummy load and a laser diode are given in Table I. At below 6 kV bias voltage, there was no switching action. At 8 kV bias

TABLE I
MEASURED PULSE PARAMETERS USING A RESISTIVE 50 Ω DUMMY LOAD

Bias Voltage (kV)	Peak Voltage (kV)	Risetime (ps)
8	5.2	850
10	6.9	740
11	8.1	580
12	9.5	480

TABLE II
MEASURED RADIATED WAVEFORM PARAMETERS

Bias Voltage (kV)	Peak Field (V/m)	Risetime (ps)
9	410	1100
10	475	1100
12	650	1000
13	690	950
15	860	900

voltage, the output voltage amplitude was about 5.2 kV. At 12 kV bias voltage, the output voltage amplitude was about 9.5 kV. Thus, the voltage gain factors at 8 kV and 12 kV bias voltages amount to 1.30 and 1.58, respectively. This was indicative of the general trend in which, as the bias voltage increased, the magnitude of the voltage gain increased while the risetime diminished. The extremely fast pulse risetimes (sub-nanosecond risetime), compared to the risetime of the triggering optical pulses (several nanoseconds risetime), suggest an avalanche-like switching mechanism. The substantial improvement in the voltage gain factor at high bias voltages is attributed to the constant, "lock-on [3]" voltage drop across the device. The result is that at higher bias voltages, the voltage gain factor will behigher. Experimental results of the radiative measurements using a Nd:YAG laser are summarized in Table II. Representative waveforms are shown in Fig. 5(a) and (b) for bias voltages of 9 kV and 15 kV, respectively. It should be noted that the pulse waveform was very repeatable for all bias voltages. The first observation to be made is the fact that the field risetimes, which were avalanche initiated, were much less than the optical pulse risetime of several nanoseconds. Also, as shown in Table II, the risetime of the generated pulses again decreased as the bias voltage increased, caused possibly by a hastening of the avalanche process. Because the inductive cable interface to the radial line was not optimized, the actual risetimes in the switch are estimated to be on the order of 500 ps or lower at the higher bias voltages. The radiated field strengths were observed to increase rapidly with bias voltage. This result stems from two effects: 1) lower voltage drop in the semiconductor, and 2) enhanced radiation efficiency of the antenna, resulting from the fast risetime pulses produced by the higher bias voltages.

The expected voltage gain factor of this impulse generator, based on the SPICE simulation was about 1.72 (due to the impedance transformation); the experimental gain factor of the obtained waveform at 12 kV bias voltage was about 1.58. As mentioned previously, part of this discrepancy may result from the voltage drop in the semiconductor and the simplified assumptions made for the central transition region.

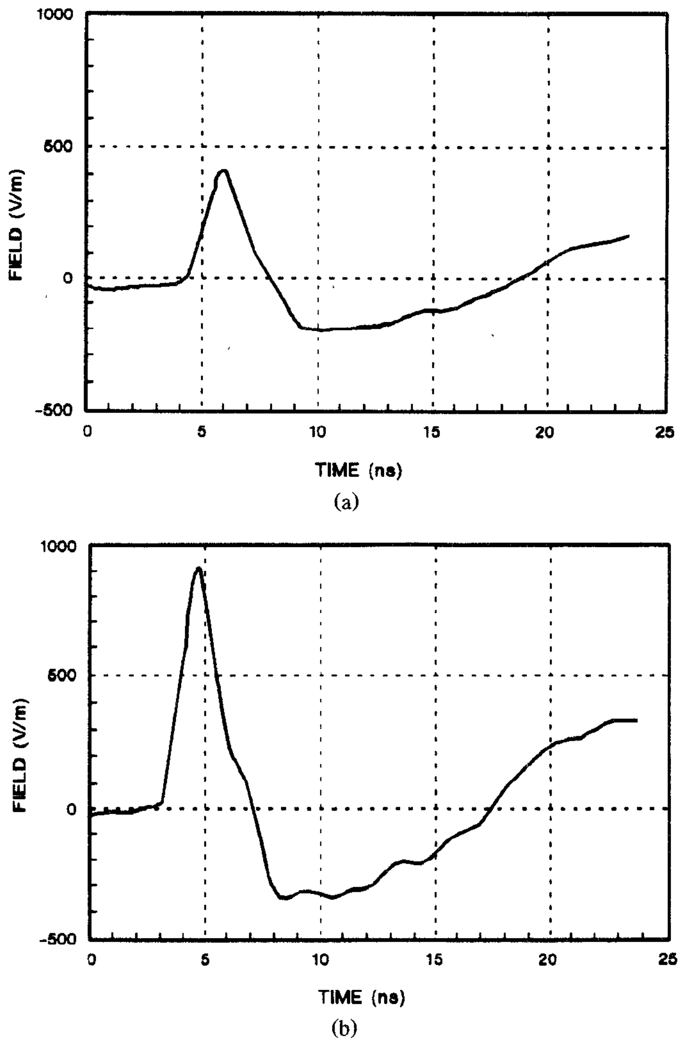

Fig. 5. Radiated pulse waveforms (V/m) for bias voltages of (a) 9 kV and (b) 15 kV.

V. CONCLUSION

Radiative measurements from an optically activated radial line, impulse generator, using a wide-band horn antenna have been conducted at various voltages ranging from 6 kV to 15 kV. The voltage gain results agree reasonably well with a transient SPICE model applied to a radial transmission line. The peak field improved rapidly as the bias voltage was increased from 9 kV to 15 kV. This may be attributed to the higher switching efficiency of the semiconductor at higher bias voltage levels, as well as to the faster pulse risetimes at the higher voltages, which radiate more efficiently from the antenna. The range of the frequency spectrum from this 1.5 ns wide pulse extended from 50 MHz to 1 GHz. Similar radiative measurements will be conducted for the linear switching mode in GaAs, employing a high power mode-locked Nd:YAG laser.

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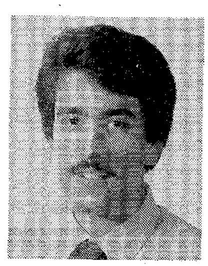

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