Generation and Shaping of Megawatt High-Voltage Pulses by Optoelectronic Technique

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Abstract —**A composite miniature structure is used to generate megawatt electrical pulses. Two photoconductive switches (one GaAs and the other Si) are used, along with voltage multiplication and pulse forming lines, to generate over 14 kV pulses from a dc bias of only 9 kV. These megawatt pulses have picosecond synchronization and can vary in width from nanoseconds to picoseconds.**

I. Introduction

THE SCOPE of optoelectronic and electro-optic applications of photoconductive switching has increased at a fast rate. Soon after Cr:GaAs was used to observe nanosecond/picosecond laser pulses [1], Si was used to switch, gate, and sample voltage pulses in a microstrip line [2]. Picosecond photoconductive switching and its applications have become important tools in research laboratories and industry [3], [4]. The following is a list of some of the applications of photoconductive switches (PS's): (i) ultrashort electrical pulse generation, (ii) high-voltage pulse generation and shaping, (iii) temporal measurements of electrical and optical pulses, (iv) jitter-free timing of multiple tasks, e.g., the operation of streak camera, (v) microwave generation and modulation, (vi) optical and particle detection, and (vii) optical control of millimeter waves. These applications utilize the unique characteristics of PS's, namely, their extremely high speed and jitter-free response, in addition to their scalability and large dynamic range.

In the area of coherent microwave generation Mourou *et al.* used a PS to drive various antennas [5]. Heidemann *et al.* demonstrated the generation of microwave pulses by triggering a PS holding dc voltage across a tapered slot-line antenna [6]. DeFonzo *et al.* have used a similar scheme to generate and detect millimeter waves [7]. Mooradian generated microwave radiation by spatial time-division multiplication of the repetition rate of mode-locked laser pulses [8]. In our laboratory, Chang *et al.* demonstrated the generation of high-voltage sequential waveforms, using the concept of frozen wave generation [9]. Also, Sayadian *et al.* demonstrated the optoelectronic generation of over 7 kW, with peak-to-peak voltage of over 1.2 kV, of a variety of microwave pulse forms with picosecond synchronization [10]. This was realized by pulse exciting a microwave cavity.

There is significant interest in using PS-based high-voltage (HV) pulse generators, because of the advantages afforded by the PS [11], [12]. Zucker *et al.* demonstrated high-power switching in silicon thyristors [13]. One of the authors demonstrated PS switching in bulk GaAs [14]. Si PS's for high-voltage applications were investigated by Mourou [15] and by Koo *et al.* [16]. Nunnally and Hammond reported on the photoconductive generation of megawatt electrical pulses [17]. In our laboratory, Mathur *et al.* demonstrated HV PS operation of $CdS_{0.5}Se_{0.5}$ [18].

For a given PS application, a specific switch material is chosen depending on its intrinsic advantageous characteristics while avoiding its intrinsic disadvantages. The two most widely used materials are GaAs and Si. The intrinsic carrier lifetimes, for undoped high-quality materials, are ~1–5 ns and 10–1000 μs, respectively, whereas their resistivities are $\geqslant 10^8$ $\Omega\cdot$cm and $\leqslant 10^5$ $\Omega\cdot$cm respectively. Consequently, Si is ideal for pulse modulation and shaping functions requiring long "on" times; however, the bulk Si suffers from thermal runaway and cannot hold dc high voltage. Recently Rosen *et al.* have eliminated the problem by using p-i-n structure with a wide intrinsic region [19]. On the other hand, GaAs is ideal for high-voltage applications, as it does not suffer from thermal runaway. However, GaAs cannot be used for modulating and shaping electrical pulses, since it has a short carrier lifetime in the absence of continuous illumination.

In this paper we report on a "miniature" and "integrated" composite device that combines the advantages of GaAs and Si PS's to generate, multiply, and continuously shape high-voltage pulses. The device has generated pulses of over 13.5 kV, with output peak power of over 1 MW in 150 Ω load. Voltage enhancement by a factor of 1.5 over the dc HV bias is achieved. Furthermore, the

Manuscript received July 17, 1989; revised November 16, 1989. This work was supported in part by AFOSR

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IEEE Log Number 8934037

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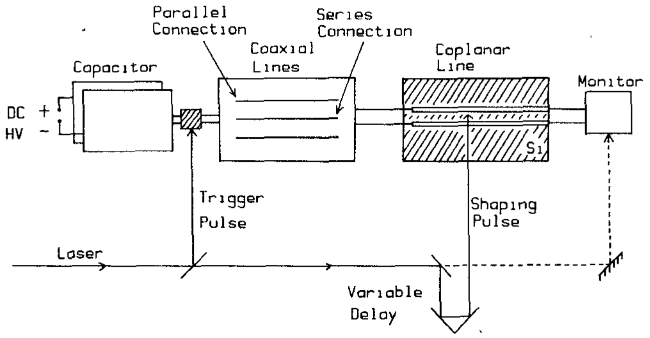


Fig 1 Schematic of the composite device that generates, multiplies, and shapes pulses of tens of kilovolts in magnitude and megawatts of peak power. See text for details

generated HV pulses may be continuously varied in width from 5 ns down to 100 ps (width of the optical trigger.)

II. Electrical Circuit

The high speed and jitter-free response of PS, in addition to their scalability and large dynamic range, make them ideal for many pulse power applications and for high-power microwave effect simulation. The advantages of PS-based systems over others derive from the nature of the switching. The optical triggering of the PS allows for the electrical isolations of the controlled and controlling systems. The whole switch changes states on command as the optical trigger arrives and does so very rapidly and with no inherent jitter. The level of conduction can be controlled by design.

With an ideal switch, the simple charged line circuit [3] generates output pulses with voltage equal to half of the dc charge voltage. For very high voltage applications it is often advantageous to use circuits or pulse forming networks (PFN's) which generate a higher output voltage for a given dc charge voltage. Marx, Blumlein, and stacked line generators can be used for this purpose [20]. The Marx and stacked line generators require a switch per stage for dc bias multiplication. The Blumlein is a generator with output pulse voltage equal to dc bias and it requires a single switch. To keep the fidelity of the PFN operation, nanosecond (or shorter) pulse generators should be designed as distributed circuits.

In Fig. 1 we show a schematic of our composite device that is capable of generating pulses of over 13.5 kV from a dc bias of 9 kV with pulse durations of 5 ns down to 100 ps (laser pulse width). Two PS's, one GaAs and the other Si, are used in a configuration that retains their intrinsic desirable characteristics and avoids the undesirable characteristics. The first stage is a parallel-plane capacitor that is dc biased to high voltages. The parallel-plane capacitor is also a microstrip transmission line designed to have a low characteristic impedance, $Z_0 \simeq 1\ \Omega$. A GaAs PS is used to hold the dc HV. The PS connects the first stage to the second. The second stage is composed of three transmission lines of higher characteristic impedance, $Z_0 \simeq 50\ \Omega$. These transmission lines are connected so as to be electrically parallel at the GaAs PS and in series at the third stage. The third stage is composed of a coplanar strip [21], [22] on a Si PS bulk substrate designed to have a characteristic impedance equal to the sum of the second stage line impedances (150 Ω). The third stage connects to the "outside" world. A single optical pulse is divided into two, the triggering and shaping pulses. The triggering pulse turns the GaAs PS on. This generates a voltage pulse of approximately the same amplitude as the dc charge voltage. This generated pulse is transmitted through the parallel connected transmission lines. The propagating pulses are added in series at the other end of the second stage, and transmitted to the third stage with a transmission coefficient of $\simeq 1$ (impedance matched transmission). Theoretically, this scheme yields an output voltage pulse that is three times the dc bias voltage into an impedance matched load. The length of the output pulse can be controlled by the timing of the optical pulse, which is incident on the Si PS and overlaps the coplanar transmission line. The width of the generated HV pulse can be fine-tuned because of the precise timing between the triggering and shaping laser pulses (realized by "dialing" the optical path length difference between them).

This approach to high-voltage multiplication has an advantage over the use of multiple switches in the Marx and stacked line generators. The limitation is that the "on" resistance of the switch must be significantly less than the impedance of the second stage.

It is important to note that the GaAs and Si PS operations are complementary. The GaAs PS is used to hold the HV dc bias, because of its immunity to thermal runaway, and trigger the pulse forming operation on command. On the other hand, the long carrier lifetime of Si allows for the clean shaping of the generated HV pulses. Since the HV pulse will be across the coplanar line for several nanoseconds at most, the Si PS does not have enough time to undergo thermal runaway.

III. Experimental Setup

An active–passive mode-locked Nd:YAG laser was used to generate ~1 mJ of 1.06 μm radiation of 100 ps width at 1 Hz. Using second harmonic generation in KD*P, 0.53 μm radiation was generated from the 1.06 μm pulses. The 1.06 μm pulses are used to optically trigger the PS. The 0.53 μm pulses are used to measure the temporal width of the electrical pulses when shorter than a nanosecond. In Fig. 2 we show a schematic of the pump and probe technique used to monitor the generated subnanosecond high-voltage pulses. The miniature Pockels cell is made of $5 \times 5 \times 2\ \mathrm{mm}^3$ KD*P in the longitudinal geometry with a 50 Ω microstrip line. Fig. 3 shows the integration of the Pockels cell with a test microstrip high voltage pulse generator, with an effective round-trip length of ~100 ps. Fig 4 shows the monitored pulse shape. Note the presence of a reflected pulse when the terminating resistance is removed. The resolution of the Pockels cell is ~20 ps when not limited by probing pulse duration.

The PS materials were intrinsic GaAs and Si. The GaAs took the form of $4.5 \times 4.5 \times 4.5\ \mathrm{mm}^3$ cubes, and the Si PS

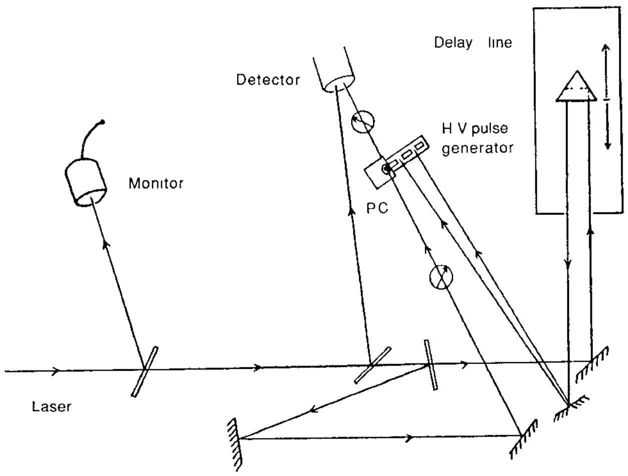


Fig. 2. Schematic of the pulse-probe scheme used, along with a miniature KD*P Pockels cell, to measure the duration of electrical pulses that are less than a nanosecond

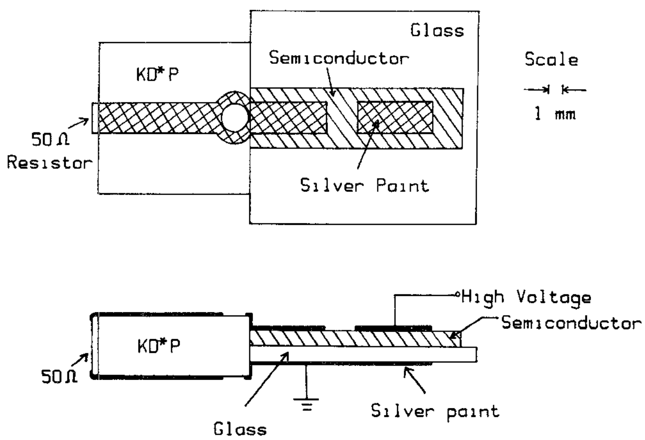


Fig. 3. Schematic of the microstrip HV pulse generator and the Pockels cell monitor.

was a disk 5 cm in diameter and 1 cm thick. The faces to be illuminated by the 1.06 μm laser were polished.

Two versions were made of the parallel charge, series discharge pulse generator. The microstrip parallel-plane capacitor, in the first version of our device, was a $90 \times 12 \times 0.07$ cm^3 G-10 filter glass epoxy board with a thin foil of copper (with dimensions of 87.5×9.75 cm^2) attached to each surface. The parallel-plane capacitor dimensions were chosen so as to give a 1 Ω transmission line of 5 ns round-trip length [22]. The second stage transmission lines were 50 Ω coaxial rigid lines of 92 cm length (corresponding to $\simeq 7.5$ ns round-trip length). The width, separation, and thickness of the line were chosen so as to give a coplanar strip with a characteristic impedance of $\simeq 150$ Ω. A 100 Ω Allen–Bradley resistor with short leads, with one end connected to the high-voltage electrode of the coplanar line and the other to a 50 Ω RG-174 coaxial cable, provides a connection to the "outside" world. The 50 Ω coaxial cable is connected to the oscilloscope through the π attenuator.

The second version of our device was designed to be significantly smaller in overall size than the first version

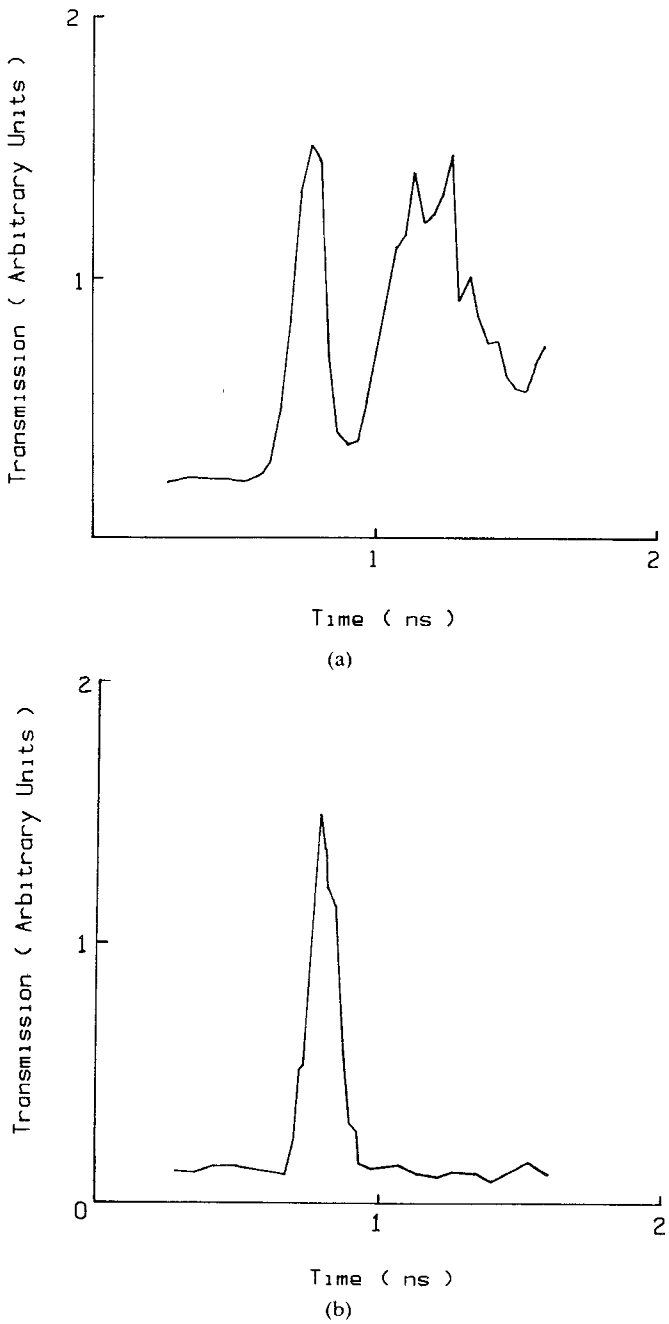


Fig. 4. Picosecond HV pulses generated and monitored by the device shown in Fig. 3. (a) 50 Ω terminating resistance is absent. (b) 50 Ω terminating resistance is present.

and to perform as well. The reduction in size was realized by replacing the G-10 based microstrip ($\epsilon_r \simeq 2.5$) with a ceramic-based microstrip ($\epsilon_r \cong 93$).[1] This allowed the construction of a 1 Ω, 5 ns microstrip line with dimensions of 8×3.8 cm^2 with a dielectric thickness of 2.5 mm. Furthermore, we have replaced the coaxial transmission lines, in the second stage, with coplanar strips. Each coplanar strip has dimensions of 1.5 mm width and 2.5 mm separation. Also, each coplanar strip was laid on a ceramic bar of (7×7 mm^2 cross section). These parameters yield a characteristic impedance of $\simeq 50$ Ω and an effective dielectric

[1]Obtained from Trans Tech Inc. Adamstown, MD.

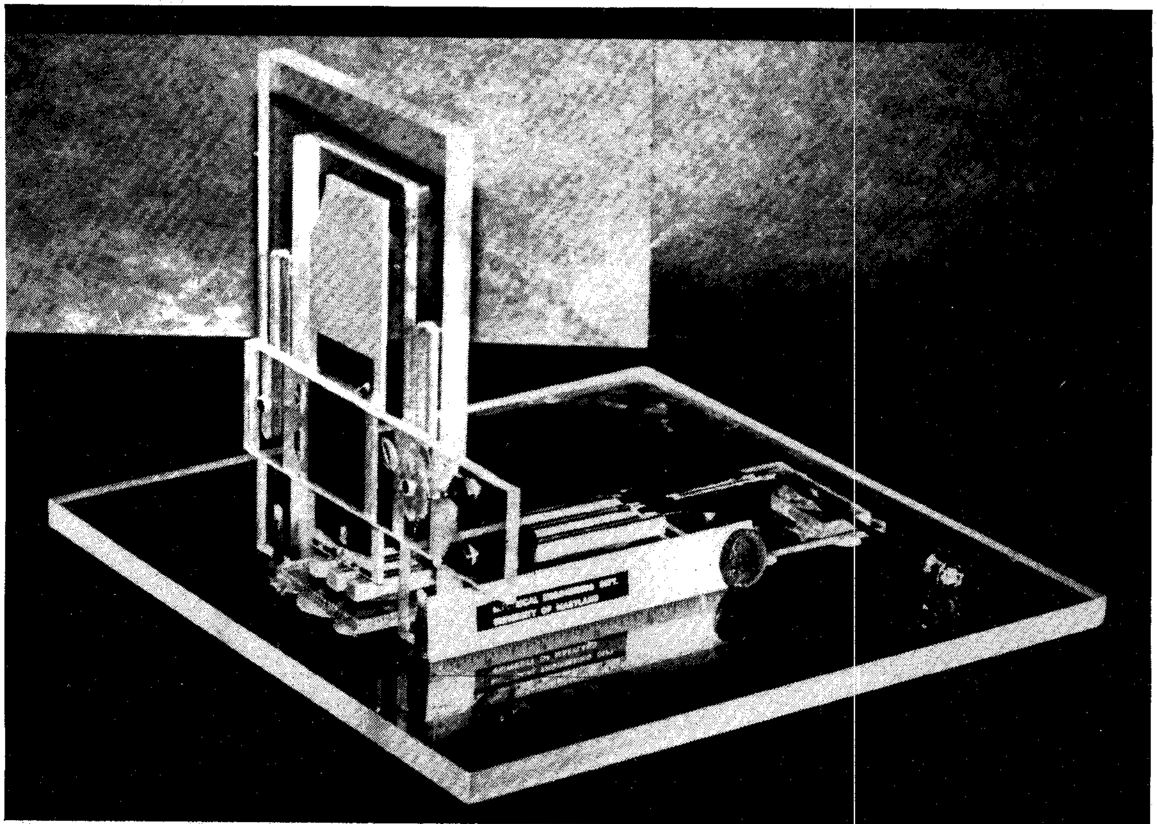


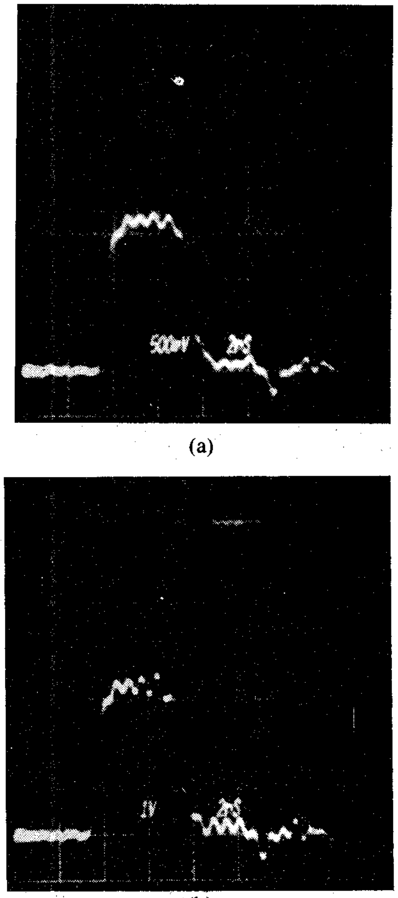
Fig. 5. Photograph of the "miniature" parallel charge, series discharge HV pulse generator.

constant of $\simeq 42$. Consequently, we have used 13.5-cm-long (round-trip length of 5.8 ns) coplanar strips as the second stage. The third stage is same as before. Fig. 5 is a photograph of the actual second version of the pulse generator.

Our 4.5 mm cube GaAs switches have a dark resistance (across opposite faces) of over 200 MΩ. Consequently, initially the full dc bias will appear on the GaAs. As time progresses and thermal runaway commences, the bias voltage will begin to drop. At a dc bias of 10 kV the voltage across the GaAs held for about 10 s. We then repeated the experiment with the GaAs cooled, by the flow of nitrogen gas at 1 atm, and obtained holding times of over 30 s for the same bias voltage. These results were reproduced by different GaAs switches. At these high dc fields we have observed occasional electrical flashover and sparks. We have reduced this limitation and enhanced the mechanical strength of the electrode contact to the GaAs PS by the following procedure: i) a square Plexiglas piece is machined to have the cross section of the GaAs PS and a thickness of $\simeq 3$ mm with a circular hole at its center; ii) this is "glued" to the surface of the GaAs switch with electrically insulating gel, making sure that the hole in the Plexiglas is over an uninsulated GaAs surface; iii) the hole is filled with conducting epoxy and a wire is introduced into the hole; iv) finally, the conducting epoxy is cured with the wire in place. This technique produces mechanically strong electrical contact to the GaAs PS, in addition to reducing the field strength in the air. The resistance of the GaAs PS was monitored under dynamic conditions. We estimate the on-resistance of the GaAs PS, along with the contacts, to be less than 0.5 Ω when triggered by ~ 100 μJ of 1.06 μm radiation. In Fig. 6 we show the HV pulse output when the GaAs PS (gap length = 4.5 mm) is optically triggered. Note that over a quarter of a megawatt of peak power is delivered to a 50 Ω load when the bias voltage is 7200 V. Our GaAs PS's have operated under moderately high dc bias fields (~ 15 kV/cm) for hundreds of thousands of shots without degradation, whereas operation of the PS under pulse biased HV has been limited only by air breakdown.

IV. Results and Discussion

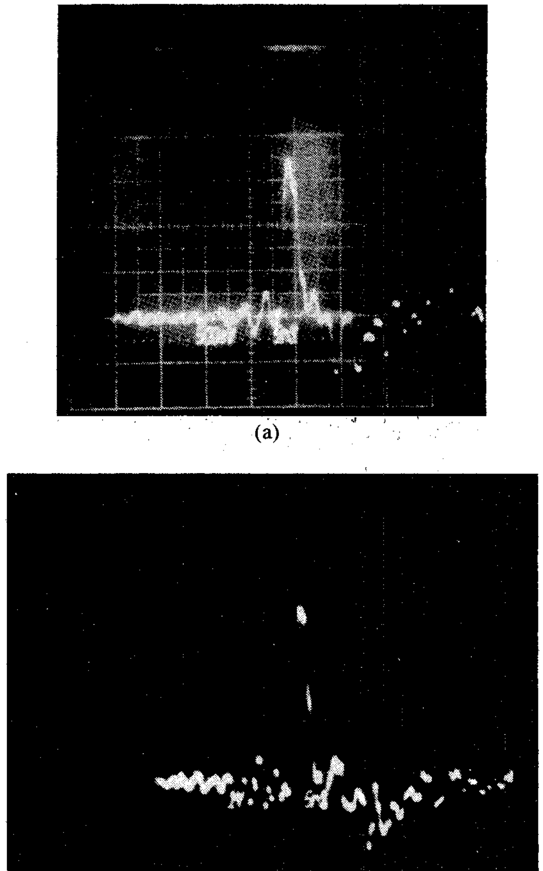
The miniature composite pulse generator has produced pulses of over 13.5 kV when dc biased to only 9 kV. In Fig. 7 we show the generated HV pulses from two different dc bias voltages in the absence of shaping optical pulse. The outputs correspond to a voltage multiplication factor of 1.5. The output pulse resulting from the 9 kV dc is nearly 14 kV and delivers a peak power of $\cong 1.25$ MW into a 150 Ω load. In Fig. 8 we show the effect of the optical shaping pulse. The large composite pulse generator was biased to 2.5 kV. In the absence of the shaping pulse, the device produces a 4 kV pulse, with a full width at half maximum (FWHM) of 5 ns (Fig. 8(a)). The optical shaping pulse reduces the width of the generated HV pulse to 3



(a)

(b)

Fig. 6. HV pulse output of GaAs PS when optically triggered: (a) dc bias = 3600 V; (b) dc bias = 7200 V.



(a)

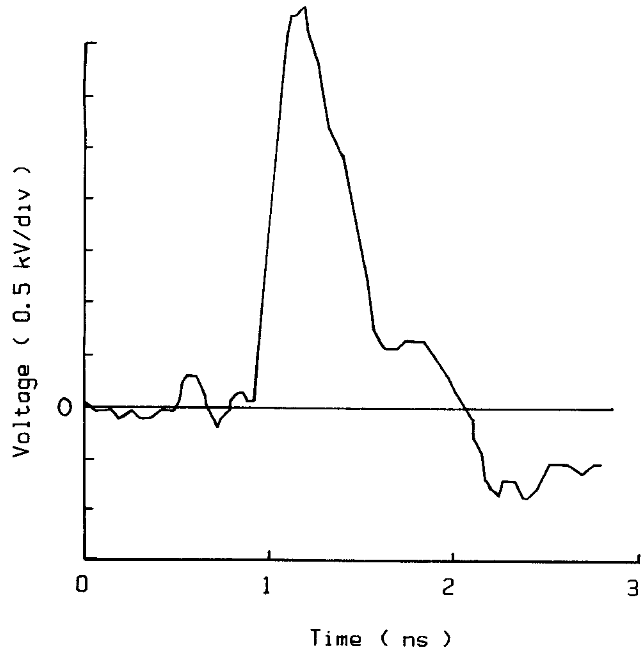
(b)

Fig. 7. HV pulse generated by the "miniature" composite structure, in the absence of optical shaping pulse: (a) dc bias = 4 kV: (b) dc bias = 9 kV.

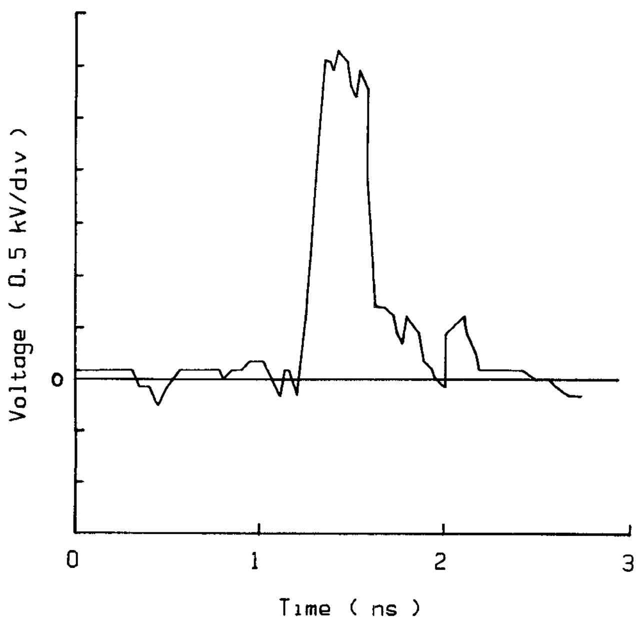
ns (Fig. 8(b)). The prepulse energy in the optical shaping pulse causes a reduction in the resistivity of the Si PS, thus reducing the magnitude of the HV pulse transmitted by the coplanar line into the load. The rise times of shown HV pulses are limited by the 1 ns response of the scope.

The actual voltage multiplication factor ($\times 1.5$) is lower than the theoretically desired one ($\times 3$) because of discontinuities between the consecutive stages. Since the pulses are rather short, the sizes of the electrical connections (three transmission lines in series or parallel) appear as parasitic distributed elements that load the circuit (through RF and microwave generation) and reduce the output voltage. Furthermore, the transmission lines in the second stage may couple to each other. For example, in the miniaturized device, the nearest electrodes of neighboring coplanar lines form stray coplanar lines with effective impedances of $\simeq$150–200 Ω. In addition, since coplanar transmission lines are not true TEM lines, dispersion effects may be important. This will be more pronounced for the coplanar lines on the ceramic, since it has a high dielectric constant. Dispersion effects will be important for subnanosecond pulses. Since both the miniature and large pulse generators have similar voltage multiplication factors, we believe that the discontinuities between the stages are the most relevant cause.

The third stage of our composite devices is subjected to the high fields ($\sim$ 50 kV/cm). The dark resistance between the coplanar electrodes is about 2 kΩ (over ten times the characteristic impedance of the coplanar transmission line). The time necessary for thermal runaway is about 50 μs, four orders of magnitude longer than the actual duration of the electric field. This fact allows for the active modulation of the generated pulse shape. Consider introducing a gap in the "hot" electrode at the output of the coplanar transmission line of the third stage. As the pulse generator is optically triggered, the HV pulse charges the third stage coplanar line in one round-trip length of the coplanar line (0.76 ns). The optical shaping pulse is divided into two pulses, with no delay between them. These two optical pulses are then directed at the Si PS, where one illuminates the gap in the "hot" electrode and the other illuminates the gap between the coplanar electrodes. The output HV pulse will be dipolar, with significantly more power in higher frequency components than that for a monopolar (i.e., flat-top) pulse [10]. The width of the dipolar pulse can be varied by changing the position of the illumination between the coplanar electrodes; the closer this is to the gap in the "hot" electrode, the shorter the pulse (the longest pulse being 0.76 ns). A separate structure (Fig. 9)



(a)



(b)

Fig. 8. HV pulses generated by the long composite structure when dc biased to 2.5 kV (a) in the absence of the optical shaping pulse and (b) in the presence of the optical shaping pulse.

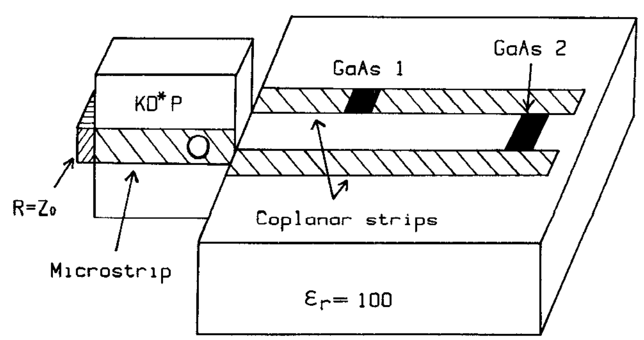
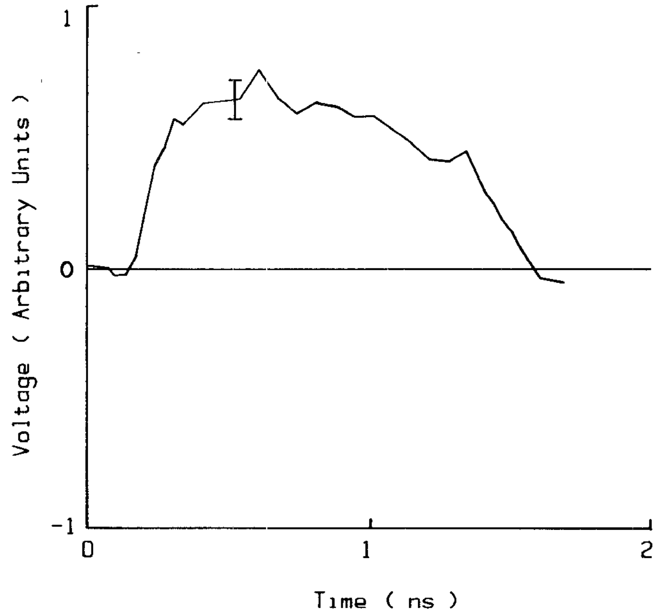
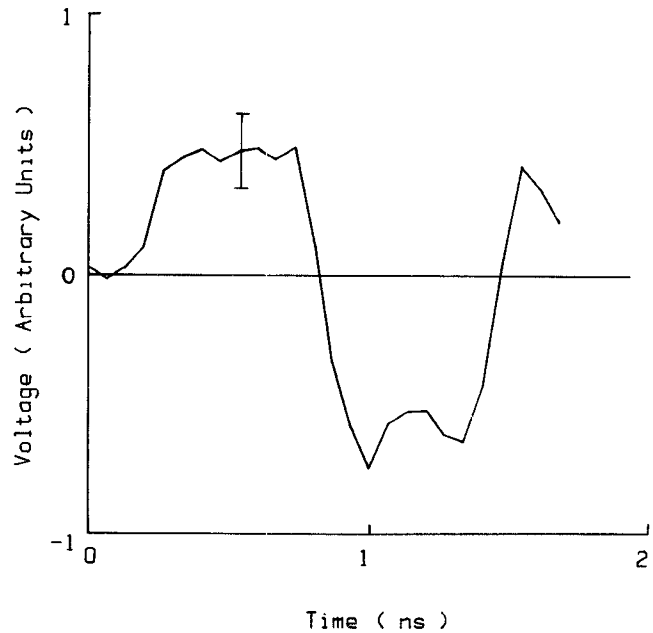


Fig. 9. Schematic of the coplanar HV pulse shaping structure and the Pockels cell monitor



(a)



(b)

Fig. 10 HV pulse generated by the device in Fig. 9. (a) Monopolar (flat-top) pulse generated by triggering GaAs PS 1 (b) Dipolar pulse generated by triggering GaAs PS 1 and 2 simultaneously.

was used to demonstrate this concept. In Fig. 10 we show the generated HV pulse when (a) only the gap on the "hot" electrode is illuminated and (b) both the gap on the electrode and that between the electrodes are illuminated simultaneously.

Finally, we mention the "gain" achieved in controlling the HV systems with the optical energy. The parallel-plane capacitor stores 40 mJ of electrical energy when biased to 9 kV. About 0.1 mJ is used to trigger the GaAs PS and generate the HV pulses. Less than 0.5 mJ would be necessary to trigger a HV PS and dump the stored energy into a matched load. Hence, we can use 1 unit of optical energy in controlling 100 units of electrical energy.

V. Conclusion

We have presented a composite structure composed of a GaAs and Si PS's and pulse forming networks that generates HV pulses of 1.5 times the magnitude of the dc bias. The devices are capable of generating over 1 MW of peak power at a 150 Ω load. These optoelectronically generated HV pulses have picosecond synchronization and may vary in width from 5 ns down to picoseconds.

Acknowledgment

The authors are grateful to M/A COM for providing the bulk GaAs material.

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