High-Frequency Waveform Generation Using Optoelectronic Switching in Silicon

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Abstract—**Conversion of dc energy to RF pulses may be accomplished by fast optoelectronic switching in semiconductors. A particular device is described and demonstrated involving the simultaneous activation of an array of silicon switches by a laser pulse. The resultant traveling wave is a short RF pulse burst whose waveshape is determined by the static voltage profile established in the device. The possibility exists for generating megawatt-level pulses at frequencies extending into the higher microwave bands.**

Introduction

FAST-OPERATING switches may be employed in various schemes for converting dc energy to RF pulse sequences [1]–[3]. A particularly simple and efficient device is the frozen wave generator described in [1]. A schematic of a basic six-cycle frozen wave generator is illustrated in Fig. 1. In this case six elements of a transmission line which can support TEM mode propagation are initially charged to potentials $\pm V_0$ as shown. The result under static conditions is then the "frozen wave" shown in Fig. 1(b). When the switches *A* through *G* are simultaneously closed, the frozen wave is free to propagate. Two identical square waves of peak-to-peak amplitude V_0 will appear, one (the forward wave) leaving the system at switch *A*, and one (the regressive wave) at switch *G*. A transmission line short placed just beyond *G* reverses the latter which then joins the forward wave as illustrated, thereby creating a pulse having a width equal to twice the electrical length of the device. The wave period will equal two transit times of each segment of the system, i.e., the segments are one-half wavelength.

One of the difficulties encountered in achieving high dc-to-RF conversion efficiency is that associated with obtaining simultaneous and rapid closure of all of the switches of the system. Jitter in the initiation process produces random frequency modulation which removes energy from the fundamental. If jitter includes "missed closures," that is lag time variations exceeding one-half RF period, the device may not produce an output, or at least a useful one. The probability of the latter event increases with the number of switches, and is exacerbated by the nanosecond time scales encountered when working at VHF and beyond. Some of the spark gap switching techniques previously employed suffer from seemingly irreducible jitter on this time scale. In this note, we describe the successful application to this problem of a recently discovered mode of optoelectronic switching in high-resistivity silicon.

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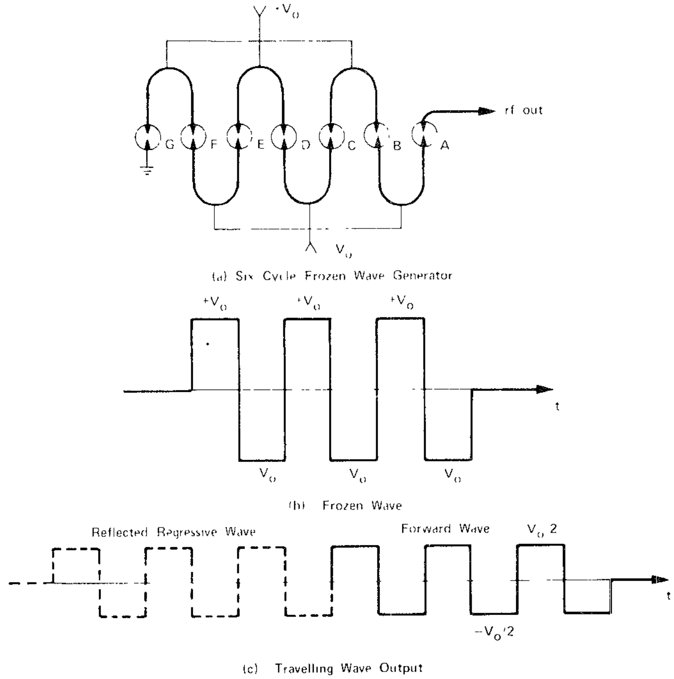


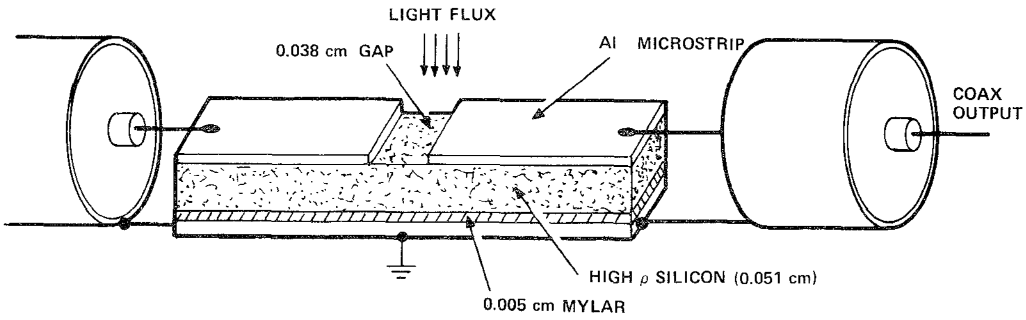
Fig 1. Frozen wave generator schematic.

Experimental Results

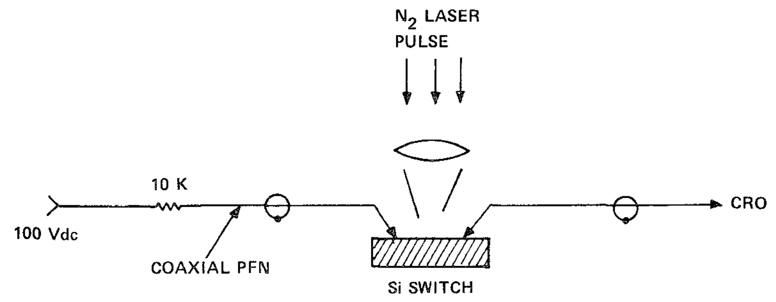
Auston [4] has shown that illumination by a pulsed laser can produce quasimetallic photoconduction in silicon with a corresponding change in conductance, e.g., from 10^{-4} $(\Omega \cdot cm)^{-1}$ to 10^3 $(\Omega \cdot cm)^{-1}$. The switching speed is limited only by the optical pulse since the dielectric relaxation time is less than 1 ps. Auston demonstrated pulse widths of 15 ps at power levels of the order of 100 W, while Zucker *et al.* [5] reported nanosecond-risetime switching with multi-megawatt peak power in light-activated multilayer silicon devices. The absorptivity spectrum of silicon governs the optical penetration depth and hence the interplay between laser wavelength and device geometry.

In the present investigation, we demonstrated the feasibility of this technique in multiswitch arrays making up the frozen wave generator. Working with high-resistivity silicon and a gas laser, we were able to achieve quasimetallic conduction and virtually exact synchronism of multiple switches in this generator.

Initial experimentation was performed using an 0.051-cm wafer of 5×10^4-$\Omega \cdot$ cm silicon upon which was placed a metallized microstrip transmission line as shown in Fig. 2. A gap in the microstrip line, ranging between 0.013 and 0.064



(a) Construction of Optoelectronic Switch



(b) Single Switch Circuit

Fig. 2. Single switch construction and test circuit.

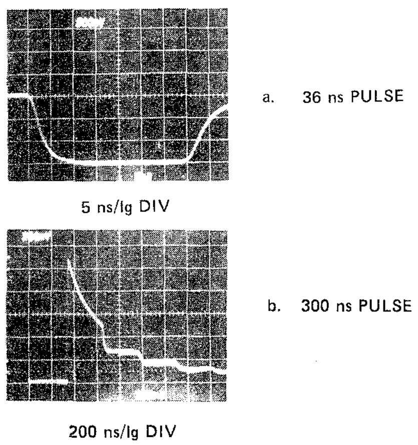


Fig. 3. Pulses launched by single channel optoelectronic switch.

cm in length and 0.10 cm in width for various experiments, permitted the light pulse from the laser to penetrate the silicon surface. Thus, a conducting sheet was formed in the gap region having the areal dimensions of the illuminated gap and a depth approximately equal to the reciprocal of the absorption coefficient. We used an N_2 laser (Avco Model C950), which produced 10-ns 1-mJ pulses at 0.337 μm, where the absorption coefficient is approximately 10^6 cm^{-1}. Assuming an illuminated resistivity in Si of 10^{-3} $\Omega \cdot$ cm, the switch should exhibit a resistance on the order of 100 Ω when closed. The use of 0.53-μm pulses (as per [4]) would have resulted in a penetration depth and switch conductance about 100 times greater.

The switch circuit for initial testing is as shown in Fig. 2(b). A coaxial pulse forming network was used to form a rectangular pulse upon activation of the switch. Experiments were normally performed in the 50- to 100-V range. Higher potentials, perhaps as high as 10^3 V, could have been used if a final dielectric coating had been used over the gap region.

Typical switched pulses are shown in Fig. 3. The upper trace was obtained using a 3.66-m coaxial cable PFN. The observed risetime, about 3 ns, closely tracks the risetime of the integrated light pulse. The carriers persist after the light pulse for a time determined by the shorter of the recombination time or the drift time in the field. In an experiment performed to determine this characteristic time, a 30.5-m line was used to generate a 300-ns pulse. The observed droop

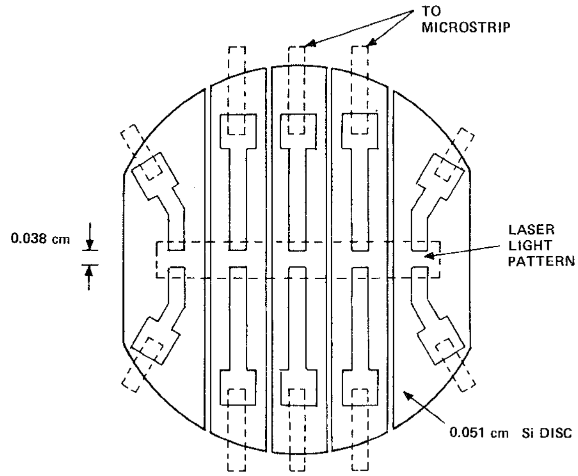


Fig. 4. Five element optoelectronic array.

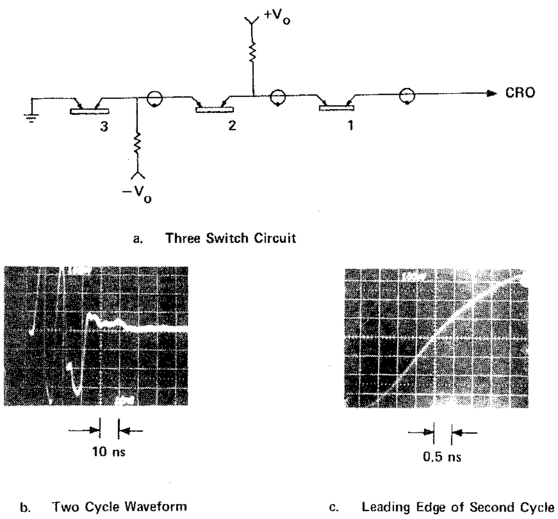


Fig. 5. Three-switch array and waveform.

in the launched pulseshape shown in Fig. 3(b) is due to the loss of carriers with a characteristic time of about 200 ns. Various experiments indicated that this corresponds to the rate at which carriers are swept from the illuminated region of the switch. This relatively slow loss of carriers presents little limitation of the technique when applied to Hertzian arrays, except that the recovery time sets a limit on the maximum repetition rate which can be achieved.

The general success of the single-switch experiment led us to fabricate small arrays of similar switches with provisions for variation in the pulse forming circuitry. An array of five elements was arranged in the pattern shown in Fig. 4. The five, 50-Ω microstrip lines were laid out on a 2-cm diameter disk which was subsequently sliced as indicated and mounted in a microstrip holder. The latter contained microstrip-coax BNC adaptors for each line, making for considerable flexibility in the traveling wave circuitry. The laser light was focused into a slit pattern (0.1×2 cm) which equally illuminated the switches of the array. The laser delivered an estimated 10^{-6} J to each switch element. Approximately 2×10^{-7} J was deposited during the first 2–3 ns of the pulse.

Three elements of the array were arranged in the circuit shown in Fig. 5(a). In this case a two cycle waveform was observed as seen in Fig. 5(b). The beginning of the second cycle corresponds to closure of switch element 3. Its timing under repetitive operation, relative to the first cycle which triggered the CRO, is shown in Fig. 5(c). The jitter, if any, is less than about 50 ps.

Further experiments with this array sought to activate all five elements simultaneously. This objective was realized, although distortions as seen in the second cycle of Fig. 5(b) became more pronounced and detracted from the otherwise graphic demonstration of simultaneity. Such distortion probably arose from the failure of the UV laser to produce a truly high conductance state upon switch activation.

Summary

The significance of these results, in conjunction with those of Auston and of Zucker, lies in the possibility of generating megawatt pulses in the higher microwave bands by solid semiconducting devices. This performance is far beyond that of known junction devices. In view of the phase stability of the switches composing an array, even more power could be achieved by coherent addition of multiple sources. Ultimately, the power might exceed the reasonable expectations of spark gap devices. In addition, aperiodic or coded pulse trains might be generated by appropriately varying the transit time between elements of an array.

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