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OPTOELECTRONIC TECHNIQUES FOR MICROWAVE AND MILLIMETER-WAVE APPLICATIONS

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ABSTRACT

Three different experiments using optoelectronic techniques are reported. They are: (1) kilovolt sequential waveform generation by picosecond optoelectronic switching, (2) Direct DC to RF conversion by impulse excitations of a resonant cavity, and (3) high speed optoelectronic modulation of millimeter-waves in a silicon-on-sapphire waveguide.

INTRODUCTION

A high dark resistivity semiconductor can be transformed from semi-insulating state to quasi-metallic state almost instantaneously when it is illuminated by picosecond or fermtosecond optical pulse. A semiconductor can thus be used as an optically activated switch. Some unique features of these picosecond photoconductors are: extremely high speed, large dynamic range, scalability and jitter-free switching. Using this optoelectronic technique, one can now produce electric impulse in complete synchronization with optical pulse with extremely fast rise time. Such type of electrical pulse generation technique has many applications in microwaves and millimeter-waves. In this paper we report three different experiments all involving generation or control of RF waves by optoelectronic means.

KILOVOLT SEQUENTIAL WAVEFORM GENERATION BY PICOSECOND OPTOELECTRONIC SWITCHING IN SILICON

Sequential RF waveform generation has been reported (1,2) using a frozen-wave generator which consists of many segments of transmission lines connected by semiconductor switches in series. When the switches in the generator are closed simultaneously without jitter, the "frozen-waves" which are charged inside the segments of the transmission line will be brought out sequentially. We have reported previously (2) the generation, using three silicon switches, of a sequential pulse of two and one-half cycles (250 MHz) having a risetime in the picosecond range. The early experiment was performed with low charging voltage. However, due to the limited high voltage handling capability of the earlier switches, the previous experiment could not be extended to the kilovolt range.

The schematic diagram of the frozen wave generator used in this work is shown in Fig. 1. It is composed of three charged line segments and three silicon switches. The three charged line segments have lengths of 42cm, and 21cm, which correspond to pulse lengths of 2ns, 2ns, and 1ns respectively. This frozen wave generator produced a pulse of two and one half cycles with a period of 4ns. Three switches of 0.25mm gap were fabricated on a silicon wafer, and they were separated to prevent coupling between them. To prevent surface breakdown under high bias voltage, the surfaces of the switches were coated with a thin layer of clear epoxy. To prevent the thermal runaway in silicon, the switches were pulse biased. The bias pulse was generated by a pulsed power supply consisting of a high voltage charging capacitor, a krytron switch, and an output transformer. The transformer had two secondary windings to produce both positive and negative polarity outputs. The output pulse had a pulse duration of 200 nanoseconds and an amplitude of 500 to 3000 volts. It was triggered and synchronized by the optical pulse from a mode-locked Nd:YAG laser. A single optical pulse of 30 picosecond duration with an energy of 50 μJ was used to activate three switches simultaneously. The result output waveform is shown in Fig. 2. It has a pulse of two and one-half cycles (250 MHz), a period of 4ns and a peak-to-peak amplitude of 850 volts.

This experiment demonstrates a method to generate a kilovolt sequential waveform pulse by applying a pulse bias to the frozen wave generator. This method could possibly generate sequential waveform pulse of even higher voltage if the surfaces of the silicon switches were properly protected. However, the pulse bias which applied to the silicon switches can extend only to the intrinsic bulk breakdown region ($E \sim 3x10^5 v/cm$). Therefore, it appears that in future experiements a design utilizing wider gaps in the switches will be necessary for the generation of a multikilovolt sequential waveform pulse.

DIRECT DC TO RF CONVERSION BY IMPULSE EXCITATION OF A RESONANT CAVITY

The frozen-wave is an ideal device to generate special waveform including a periodic pulse train. For applications requiring the generations of a large number of pulses in a train the following

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method is more suitable. It involves the use of only single optoelectronic switch and a coaxial resonant cavity. The basic principle of operation is described as follows. (Fig. 3) The electrical impulse generated by an optoelectronic switch is coupled via an antenna to a coaxial structure cavity. This pulse will reflect back and forth inside the resonant cavity which is shorted at one end and opened at the other end. At the shorted end of the cavity, the resultant electrical field has to be zero to meet the boundary condition. Thus the reflected electrical field must have the same amplitude but opposite polarity of the incident pulse. At the open end, the total current must be zero. Thus the reflected current pulse has opposite polarity. The pulse bounding back and forth inside the coaxial cavity forms a series of pulses of alternative polarities. If one uses another antenna inside the cavity to couple these pulses out, the output signal will consist of a damped periodic pulse train. The frequency of this oscillation equals to the cavity resonant frequency. The damping rate depends on the coupling coefficiency of the cavity or the loaded quality factor (Q). The higher the quality factor (Q), the slower the damping rate.

In our experiment, a piece of Cr doped GaAs was used as a single pulse switch. GaAs switch is essential since it will generate an electrical impulse with duration much shorter than the period of the RF signals. It can also withstand higher DC bias voltage than Si switch. Fig. 4 shows the output waveform from such a device. More than one hundred cycles of 300 MHz oscillation was generated by a single pulse of green light produced by a frequency doubled mode-locked Nd:YAG laser (30 ps, 20 μj). One can also use the whole mode-locked optical pulse train as the light source to activate the semiconductor switch. As a matter of fact, one generally obtains at the output of the device an RF pulse train with higher amplitude and more total energy provided that the electrical length of the coaxial resonator is tuned to a sub-multiple of the optical cavity length. Fig. 5 shows the resultant RF pulse train when the semiconductor switch was illuminated by the mode-locked pulse train (lower trace). The RF frequency for the signal shown in Fig. 5 is 600 MHz, doubling the frequency of the RF oscillation shown in Fig. 4. Here the same coaxial cavity was shortened at both ends. The entire cavity length equals to a half-wave length instead of a quarter-wave as before.

HIGH SPEED OPTOELECTRONIC MODULATION OF MILLIMETER-WAVES IN A SILICON-ON-SAPPHIRE WAVEGUIDE

Recently we have reported a new family of optoelectronic devices at the millimeter-wave spectral region which have picosecond speed capability(3,4). For example, the gating of millimeter-wave pulse with variable pulse duration ranging from a few nanoseconds to subnanoseconds has been reported. When the device is operated as a phase shifter, the phase shift as large as 1500°/cm has been observed(4). In these previous studies, we have found that, in general, the carrier diffusion will cause large loss and less phase shift for the millimeter-waves. In this work, we will report on the performance of dielectric waveguide made of silicon-on-sapphire (SOS). It is expected that the optically induced electron-hole plasma will be confined in a thin layer of epitaxially grown silicon and thus a high density but thin plasma layer may be maintained, resulting in a small dynamic insertion loss.

Fig. 6 shows the modulation of a CW millimeter-wave signal by a frequency doubled mode-locked pulse train from a Nd:YAG laser. The experimental arrangement for generating such a signal has been discussed elsewhere(4). It is clear that the millimeter-wave output (b) mimicking the incident optical pulse train (a). The rapid decay of the millimeter-wave is attributed to the short lifetime of free carriers in the silicon expitaxial layer. Strong surface recombination at the silicon-air and silicon-sapphire interfaces may also contribute to the rapid decay. This result shows that the modulation bandwidth of 1 GHz with a repetition rate greater than 200 MHz is achieved. Using a single picosecond optical pulse, we can also generate a single millimeter-wave pulse. The temperal profile of such a millimeter-wave pulse has to be measured by the standard excite-and-probe technique. The measurement confirms that the duration of the millimeter-wave pulse is about 1ns.

In conclusion, we have shown three different applications of picosecond optoelectronic techniques for microwaves and millimeter-waves. With the advent of ultrashort lasers, temperal manipulation of microwave or millimeter-wave signals with picosecond time precision is quite possible. This capability may lead to the development of a whole new series of RF optoelectronic devices. This work was supported in part by the Air Force Office of Scientific Research, the Army Research Office and the National Science Foundation.

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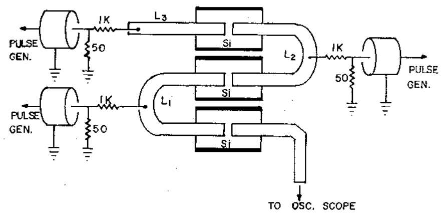


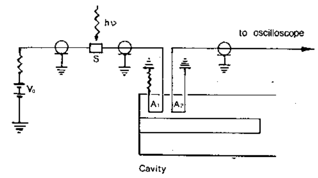


FIG 3 EXPERIMENTAL ARRANGEMENT, S IS THE SEMICONDUCTOR SWITCH, A_1 AND A_2 ARE LOOP ANTENNAS AND THE CAVITY IS A COAXIAL STRUCTURE.

Fig. 1. The schematic of a frozen-wave generator. The structure consists of three silicon switches which can be activated by a pico-second laser pulse.

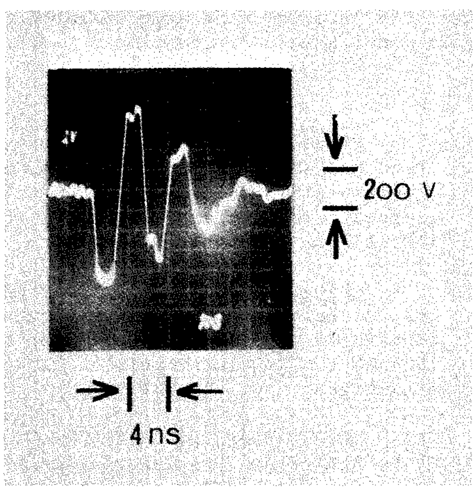


Fig. 2. The oscillogram of the RF waveform. The peak-to-peak voltage is 850 volts.

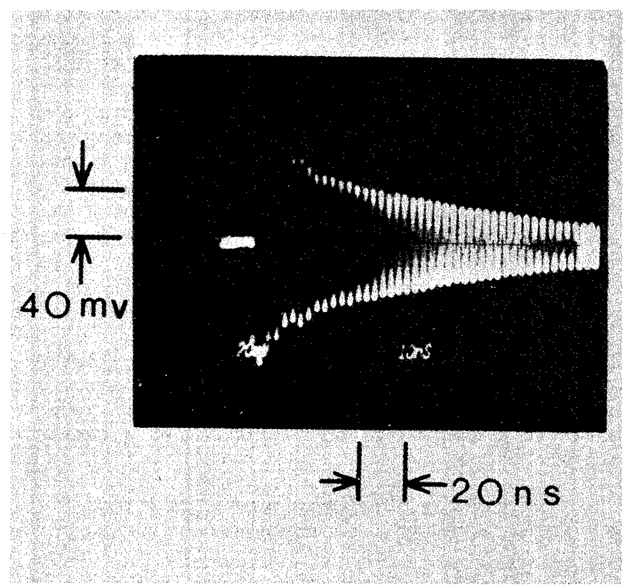


Fig. 4. The oscillogram of the RF output pulse train excited by a single electric impulse from a Cr:GaAs switch.

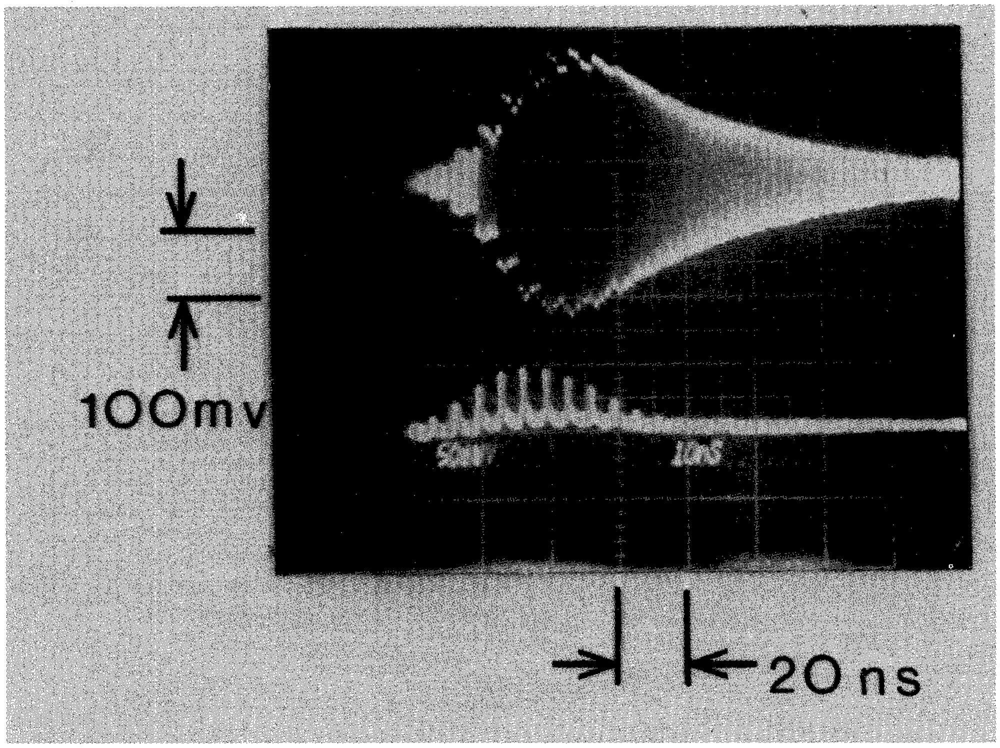
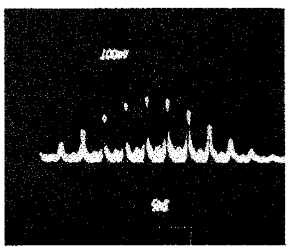


Fig. 5. The oscilloscope traces of (a) lower trace, electric pulse train at the output of the Cr:GaAs switch minicking the laser pulse train; (b) upper trace, the RF pulse train excited by the electric pulse train shown in (a).

a



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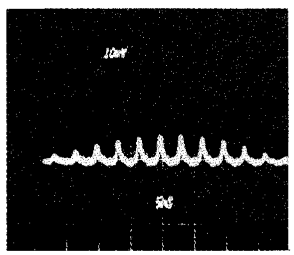

Fig. 6. Millimeter-wave pulse train (b) mimicking the incident optical pulse train (a) from a Q-switched mode-locked laser. The wave-guide material is SOS. The traces shown here are bandwidth limited.