DEMONSTRATION OF A FREQUENCY-AGILE RF SOURCE CONFIGURATION USING BISTABLE OPTICALLY CONTROLLED SEMICONDUCTOR SWITCHES (BOSS)[a]

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ABSTRACT

The processes of persistent photoconductivity followed by photo-quenching have been demonstrated at megawatt power levels in copper-compensated, silicon-doped, semi-insulating gallium arsenide. These processes allow a switch to be developed that can be closed by the application of one laser pulse (λ=1.06 µm) and opened by the application of a second laser pulse with a wavelength equal to twice that of the first laser (λ=2.13 µm). The opening phase requires a sufficient concentration of recombination centers (RC) in the material for opening to occur in the subnanosecond regime. These RC's are generated in the bulk GaAs material by fast-neutron irradiation (~1-MeV). Neutron-irradiated BOSS devices have been opened against a rising average electric field of about 36 kV/cm (18 kV) in a time less than one nanosecond while operating at a repetition rate, within a two-pulse burst, of about 1 Ghz. The ability to modify the frequency content of the electrical pulses, by varying the time separation, is demonstrated. Results demonstrating the operation of BOSS devices in a frequency-agile RF source configuration are also discussed.

1. INTRODUCTION

Almost all photoconductive switches are closed either by direct excitation across the bandgap, the so called *linear mode*, or by a very low energy trigger pulse from a laser diode, the so called *gain*, *lock-on*, or *avalanche mode*. An alternative switching mechanism was proposed by Schoenbach, et al.(1988).[1] This concept, called the Bistable (or bulk) Optically controlled Semiconductor Switch (BOSS), relies on persistent photoconductivity followed by photo-quenching to provide both switch closing and opening, respectively. Persistent photoconductivity results from the excitation of electrons from the deep copper centers found in copper-compensated, silicon-doped, semi-insulating GaAs (GaAs:Si:Cu). The small cross-section for electron capture back into the Cu centers allows long conduction times after the first laser pulse is terminated. Photo-quenching is accomplished by the application of a second laser pulse of longer wavelength which elevates electrons from the valence band back into the copper levels. This laser pulse floods the valence band with free holes which rapidly recombine with free electrons to quench the photocurrent over a time scale given by the electron-hole lifetime of the material. These processes allow a switch to be developed which can be *closed* by the application of one laser pulse ($\lambda \approx 1$ µm) and *opened* by the application of a second laser pulse with a wavelength about twice that of the turn-on laser.

Preliminary experimental results showed that the current through a BOSS switch could not be fully quenched by the application of a 140-ps (FWHM) 2.13-µm laser pulse. A numerical solution of the semiconductor rate equations for copper-doped GaAs showed that the primary cause for incomplete photo-quenching was that the concentration of the recombination centers (RC) was too low (Stoudt, et al., 1993).[2] As stated above, the opening transient is the result of a two-step process. The second step is controlled by the electron-hole recombination lifetime in the bulk material. If there is an insufficient RC concentration, the holes that were generated by the 2-µm laser pulse would be retrapped into the copper centers before they could recombine with electrons in the conduction band. This would result in the switch remaining closed after the second laser pulse. Recently, work concentrating on the reduction of the minority-carrier lifetime, by increasing the RC concentration in GaAs, through fast-neutron irradiation was reported by Wang, et al. (1989).[3] This work directed us towards the investigation of neutron damage for the purpose of RC enhancement in BOSS devices (Stoudt, et al., 1994).[4] The neutron source that was used in this work is Sandia National Laboratory's (SNL) SPR-III reactor with an energy spectrum that was peaked at about 1 MeV.

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14. ABSTRACT

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2. SAMPLE PREPARATION

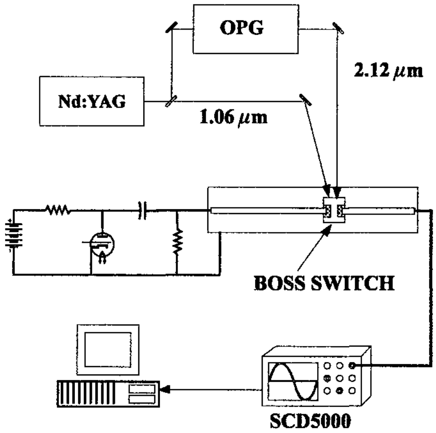

Fig. 1 Schematic diagram of the experimental setup.

Low resistivity, silicon-doped (n-type) GaAs can be made semi-insulating by the introduction of copper acceptor levels through a thermal-diffusion process (Roush, et al., 1993).[5] The GaAs material used in this investigation was originally doped with a silicon concentration of ~2x10^{16} cm^{-3} which yielded a resistivity of about 7x10^{-2} Ω-cm.. After the thermal diffusion step, at ~575° C for 6 hours, the samples were polished on both sides to a mirror finish. The sample dimensions were roughly 10 mm by 5 mm by 0.5 mm thick. The p^{+}-i-n^{+} devices were manufactured by depositing a Au-Ge based metalization for the n-type contact and a Au-Zn based metalization for the p-type contact. The contacts resulted in switch geometry that was 5 mm wide and separated by a 5-mm gap on the same side of the sample. After deposition, the contacts were annealed at 450° C for 5 minutes in N_2 at atmospheric pressure. Following the contact anneal, the samples were irradiated with fast neutrons to increase the RC concentration. Two sets of BOSS devices were neutron irradiated at two different fluences. The lower fluence was measured at 2.45x10^{15} cm^{-2} (Sample A) while the higher fluence was measured at 3.93x10^{15} cm^{-2} (Sample B) 1-MeV-GaAs Equivalent damage (Griffin, et al, 1991).[6] The DC I-V characteristics of the samples indicated an increase in the switch resistance from about 3.2 MΩ to about 55 MΩ for the lower fluence, and an increase from about 4.3 MΩ to about 273 MΩ for the higher fluence.

3. SWITCHING EXPERIMENTS

The BOSS-switching experiments were conducted with a mode-locked Nd:YAG laser system (1.06 μm), manufactured by Continuum Inc., that was equipped with a optical parametric generator (OPG) that served to double the wavelength (2.13 μm). The laser system produced a Gaussian pulse with a FWHM of about 140 ps. A simple optical delay was then used to adjust the time between switch closure and when the switch was opened. Photoconductivity measurements were performed to evaluate the operation of the neutron irradiated BOSS devices. The BOSS switches were embedded in a 50-Ω transmission line (two-way transit time ≈ 8 ns) that was pulse charged with roughly a 40-ns FWHM voltage pulse generated by a Krytron switch as shown in Fig. 1. The maximum voltage applied to the BOSS devices was about 18 kV. The current through the device was measured by a 50-Ω current-viewing resistor (CVR) placed after the switch in the 50-Ω line. The current waveform was recorded by a Tektronix SCD5000 digitizer with a 3.0 GHz analog/digital bandwidth.

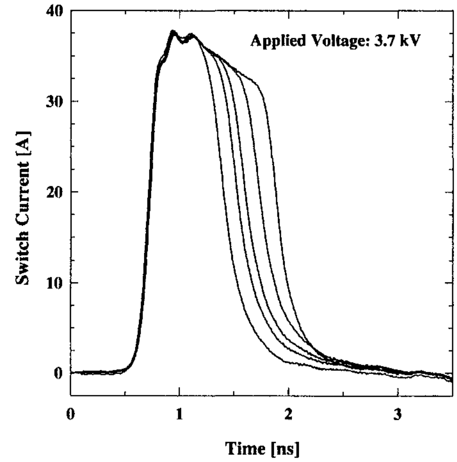

Fig. 2 Demonstration of pulse-width agility by varying the time delay between laser pulses.

3.1 Lower-fluence switching results

Switching results illustrating the photocurrent for Sample A are shown in Fig. 2 for an applied voltage of 3.7 kV. The maximum voltage that was switched with this device was about 18 kV which was bias-voltage modulator limited. The switching behavior of Sample A did not change as the applied voltage was increased. Figure 2 shows several current waveforms superimposed to demonstrate the ability to control the pulse width of the electrical pulse delivered to the 50-Ω CVR. The laser pulse energy for both the 1-μm and the 2-μm wavelengths was set at 4.5 mJ. The minimum switch resistance during the transient was measured to be ≤1 Ω. The minimum pulse width achieved with this device was measured to be about 650 ps FWHM. A curve fit to the switch conductance during the opening phase, after it was extracted from the circuit load line, indicated a recombination time constant of 100 ps. Figure 2 illustrates that as the time between the two laser pulses is increased, the switch conductivity decreases with time prior to the turn-off laser pulse as a result of the enhanced RC density. This effect will ultimately limit the switch *on-time* of neutron-irradiated BOSS devices. Therefore, there appears to be a trade-off between the maximum time that the switch will remain closed after the 1-μm laser pulse, and the RC density in the material. It should be noted that BOSS devices that were not irradiated with neutrons had demonstrated on-times of several hundred nanoseconds (Stoudt, et al., 1991).[7]

3.2 Higher-fluence switching results

Photoconductivity experiments were also conducted on Sample B, which was irradiated at a fluence of $3.93\text{x}10^{15}$ cm^{-2}. One drawback of an increased RC concentration is that the on-state conductivity will be reduced because electrons in the conduction band will recombine with holes in the valence band before those holes can be trapped in the Cu_B center. This process reduces the number of holes that are trapped in the Cu_B center which, in turn, reduces the available sites to receive electrons from the valence band during the turn-off laser pulse. However, a benefit can be derived if the RC concentration in the bulk material is made high enough to cause the switch to open without the need of the turn-off laser pulse. This effect is shown in Fig. 3 where two 1-μm laser pulses were used to *close* Sample B at a high repetition rate. For these experiments, the switch was *only* illuminated by two 1-μm laser pulses with a variable time delay between them. The reason why Sample B opened without the turn-off laser pulse was because it was irradiated at a higher neutron fluence than Sample A. Therefore, there was a higher RC density in the bulk material of Sample B. The purpose of this experiment was twofold, first we wanted to see how the switch responded to the turn-on laser pulse, and secondly, we wanted to test the repetition rate capability of Sample B. The applied voltage for the waveform shown in Fig. 3 was about 16 kV. The minimum on-state resistance that was measured for Sample B was about 15 Ω. The average pulse width was measured to be about 340 ps. The maximum voltage that was switched with this device was 18 kV, yielding an average electric field of 36 kV/cm. It is important to note that there was no indication of the device collapsing into a filamentary-current mode of conduction at any point in the switching cycle. This is significant since almost all previously reported photoconductive switch experiments exhibit a transition into filamentary conduction, or lock-on, at average electric fields of ≥10 kV/cm (Rosen and Zutavern, eds., 1993).[8] The most striking attribute of the current pulses in Fig. 3 is that the switch completely opens *without* the need of the 2-μm laser pulse. Figure 3 also demonstrates the ability of the device to be operated at a repetition rate of 290 Mhz within a two-pulse burst. Two-pulse experiments were conducted with a pulse separation of less than 1 ns which demonstrate a repetition-rate capability of greater than 1 Ghz.

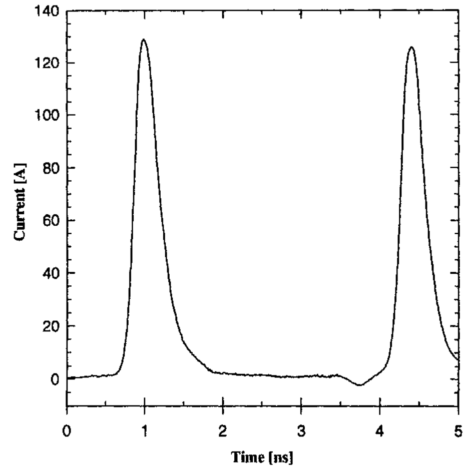

Fig. 3 Demonstration of a 290-MHz repetition rate in a two-pulse burst using the 1-μm laser only (sample B).

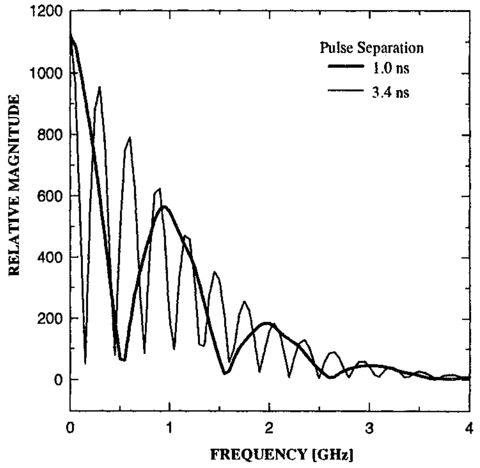

Fig. 4 Fourier spectra for Fig. 5 (thin line) and for a pulse separation of about 1 ns (thick line).

Since one of the potential applications of a BOSS device is in an impulse or ultra-wide-band (UWB) radar, we wanted to examine the Fourier spectra of the waveform in Fig. 3, as well as the effect of varying the pulse separation on the frequency content. The results of performing a 4096-point FFT on the data in Fig. 3, as well as for the case of a pulse separation of about 1 ns, are shown in Fig. 4. Figure 4 shows significant frequency content up to about 3 Ghz which was the bandwidth limit of the SCD5000 digitizer. The result of adjusting the delay between the two pulses can be seen as a change in the number, and location, of the *nulls* in the spectra. This capability could be very useful in UWB radar applications, particularly if certain frequency bands are to be avoided.

3.3 BOSS-based RF source

The primary goal of this research is to produce a wide-band, frequency-agile source that can *radiate* the RF energy with a broadband antenna. In order to maximize the radiative efficiency of the source, it is necessary to produce AC power, thereby reducing the DC component of the waveform which cannot be radiated. The ability of the BOSS switch to open, as well as close, in the subnanosecond regime allows a new type of RF source to be developed that is capable of generating repetitive high-power microwave cycles of varying duration, depending on the relative delay between the turn-on and turn-off laser pulses. A source configuration that is capable of generating AC power with real-time frequency agility is shown in Fig. 5 and is called the pulse-switch-out (PSO) generator. This source uses two BOSS switches that are embedded in oppositely charged 50-Ω transmission lines which can generate single positive and negative half-cycles by first closing and opening each switch. Both switches then feed into a single 50-Ω transmission line that leads to a matched load.

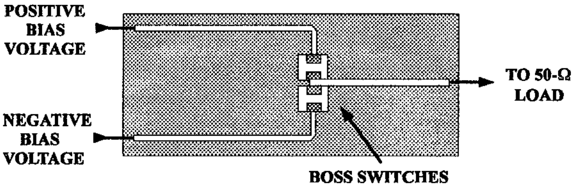

Fig. 5 Diagram of the 50-Ω PSO microstrip circuit.

Experiments were conducted with the circuit shown in Fig. 5, at a bias voltage of about 9.5 kV, and with BOSS devices that were irradiated at the higher neutron fluence, and therefore, only illuminated with 1-μm laser pulses. Experiments will be conducted shortly with devices that require both of the laser pulses. The time-domain waveforms for a time delay of about 500 ps and about 2 ns are shown in Fig. 6. We found that the pulse width of the positive half-cycle could be reduced, at the expense of the negative half-cycle peak voltage, by closing the second BOSS switch before the first one was completely open. The Fourier spectra for these two waveforms differ significantly as shown in Fig. 7. As expected, the bipolar pulses significantly reduced the DC component in the spectra. In addition, the generation of nulls in the spectra increased the power spectral density at some of the lower frequencies. As before, the number and location of these nulls can be adjusted by varying the time delay between the two laser pulses.

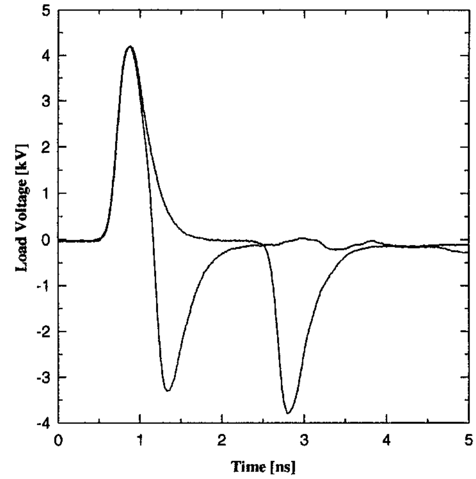

Fig. 6 Demonstration of two bipolar pulses produced by a PSO generator for a 500-ps and 2-ns delay between 1-μm laser pulses.

3.4 Potential RF Waveforms

The laser system that is required to test the operation of the PSO generator at high repetition rates is not presently available. However, since the operation of the switch has been demonstrated at about 1 GHz, in a burst mode, and since the operation of two BOSS devices in a PSO generator has also been demonstrated, it is reasonable to examine the effect of generating a short burst of RF cycles at megahertz repetition rates. To accomplish this, a potential RF output from a PSO generator was simulated by replicating data similar to that shown in Fig. 6 for a laser pulse separation of 500 ps, and a time separation between RF cycles of 10 ns. The result of this data manipulation is shown below in Fig. 8 where four RF cycles, at a 100-MHz repetition rate, are given with the total time window set at 80 ns. Figure 8 is an illustration of the type of waveform that is expected to be generated by a PSO RF source once the laser system, which is currently being developed, becomes available.

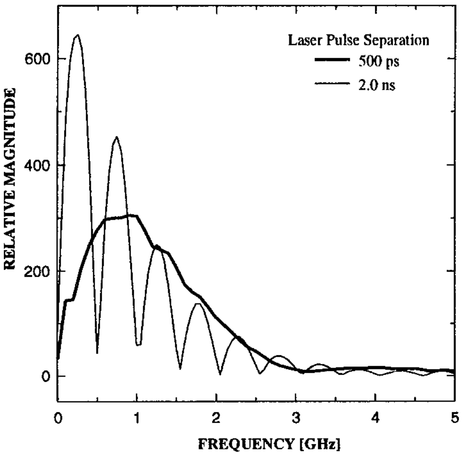

Fig. 7 Fourier spectra for data in Fig. 6.

The power spectra of a single monocycle as well as the waveform shown in Fig. 8, corrected for a burst repetition rate of 1 kHz, are illustrated in Figures 9 and 10, respectively. The method by which the power spectrum is calculated is as follows. An FFT is performed on the time-domain waveform of the voltage on the 50-Ω load. The data is *padded* with zeros out to a total time window of 80 ns which corresponds to a 12.5-MHz burst-repetition rate, as far as the FFT is concerned. The amplitude of the resulting frequency-domain data is in units of volts. To obtain the power spectrum in the 50-Ω load, the amplitude is squared and subsequently divided by 50. The resulting spectral amplitude is now in units of watts, however, this amplitude corresponds to the 12.5-MHz repetition rate. To scale the data for a 1-kHz repetition rate, the data must be multiplied by the square of the ratio of 1 kHz over 12.5 MHz, or a factor of $6.4\text{x}10^{-9}$.

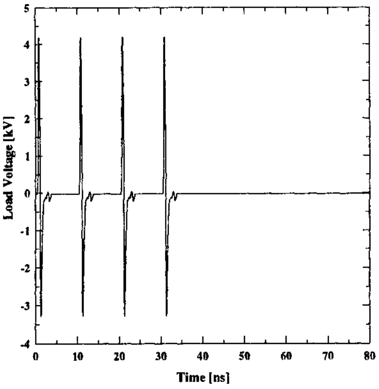

Fig. 8 Potential output of a PSO generator constructed by replicating data similar to that shown in Fig. 6 for a laser pulse separation of 2.0 ns.

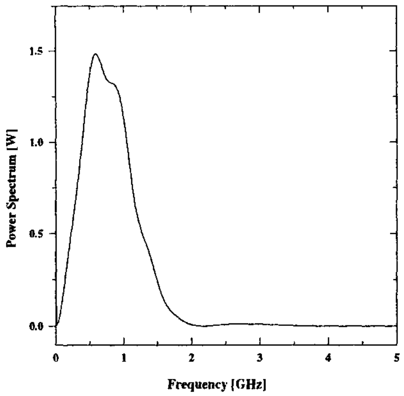

Fig. 9 Power spectrum of the single monocycle, for a repetition rate of 1 kHz, that was used to create the four-pulse burst shown in Fig. 8.

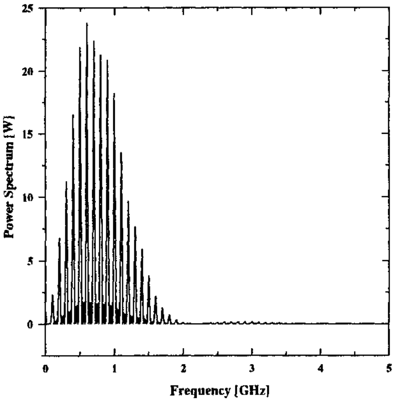

Fig. 10 Power spectrum of the waveform shown in Fig. 8 for a 1-kHz burst-repetition rate.

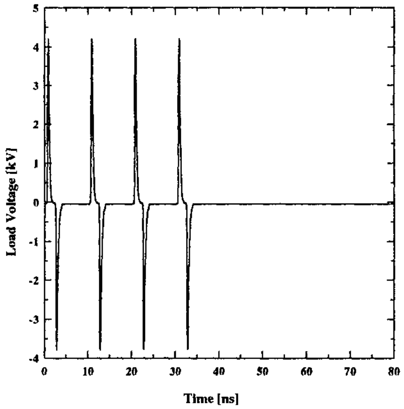

Fig. 11 Potential output of a PSO generator constructed by replicating the data shown in Fig. 6 for a laser pulse separation of 2.0 ns.

The spectrum for the single monocycle, shown in Fig. 9, has a maximum amplitude of about 1.5 W. However, as a result of the 10-ns spacing between the RF cycles, the spectrum for the four-pulse burst, shown in Fig. 10, is further subdivided into peaks which occur every 100 MHz. As a result of the increased number of nulls in the spectrum, the power spectrum at each one of the peaks is increased considerably. In fact, the peak power increased from 1.5 W to about 24 W, or a factor of 16. There are basically two reasons for this increase in the power spectrum. First, since the power spectrum for both the monocycle and the four-pulse burst were calculated for a 1-kHz repetition rate, the total energy in the burst is a factor of four higher. The other factor of four comes from the subdivision of the spectrum into discrete peaks at every 100 MHz. In a similar manner, if ten pulses were generated within a single burst, the peak of the power spectrum would be increased by a factor of 100. A higher number if cycles in the burst would also have the effect of reducing the width of each one of the 100-MHz peaks.

The same type of results are obtained when using the waveform distorted by separating the positive and negative half cycles, as shown in Fig. 11, to fabricate the four-pulse burst. Note that this distortion results in an additional increase in the peak of the power spectrum, at lower frequencies, as shown in Fig. 12. These results indicate that the time delay between the positive and negative half-cycles dictates the shape of the envelope of the spectrum, while the cycle repetition rate within the burst dictates the placement of the various spectral peaks. The type of waveforms shown in Figs. 8 and 11, with their associated spectra shown in Figs. 10 and 12, respectively, may have considerable advantages for use in UWB-radar and other high-power-microwave applications.

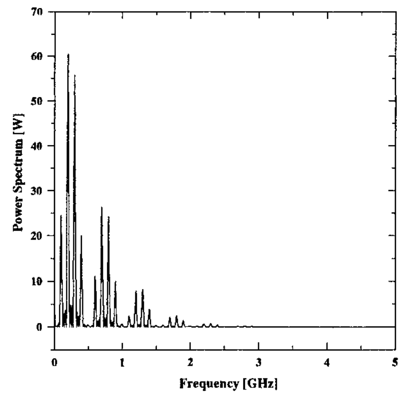

Fig. 12 Power spectrum of the waveform shown in Fig. 11 for a 1-kHz burst-repetition rate.

4. CONCLUSION

Experiments were performed to determine the effect of irradiating BOSS material with two different 1-MeV neutron fluences. For the lower fluence of $2.45\text{x}10^{15}$ cm^{-2}, the optically induced closing and opening effects were demonstrated at voltages up to 18 kV. Experimental data was presented which demonstrated the pulse-width agility of the BOSS switch in the subnanosecond range. Results were also presented for the operation of BOSS devices that were irradiated at a fluence level of $3.93\text{x}10^{15}$ cm^{-2}. These devices exhibited an ability to open, at voltages of up to 18 kV, *without* the need for the 2-µm laser pulse. It was determined that this effect was due to the electron-hole recombination time being much faster than the time for hole trapping into the Cu_B level. Two-pulse bursts were generated which demonstrated their ability to operate at repetition rates ranging from the hundreds of megahertz to one gigahertz. A BOSS switch that exhibits a self-opening effect may have substantial advantages over other irradiated photoconductive switches because the switching mechanism is a true bulk-conductivity effect. Most other short-lifetime photoconductive switches rely on lasers with photon energies *greater* than the bandgap of the semiconductor. These type of devices inherently operate using surface conduction rather than bulk conduction.

A PSO generator, operating at high power levels, has been demonstrated for the first time. True frequency agility has now been made possible through the use of simple time-delay techniques. An added advantage of the PSO generator is that by using a single mode-locked laser, the RF source will maintain phase coherence between the pulses within the burst *and* between the bursts themselves.

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