Red Mountain Radio

www.RedMountainRadio.com

Thanks for your interest in my technical paper. If you find this work to be interesting, or have additional questions, please contact me at the address below. Red Mountain Radio LLC offers professional RF, optical, and microwave design services, and problem solving.

Regards,

Eric Funk, Ph. D.
Partner, Red Mountain Radio LLC
eric@redmountainradio.com
970-325-2158 ×12

The following IEEE paper is subject to copyright as noted below.

500 Hz Picosecond Inductive Energy Storage Pulsed Power System Using a High Tc Superconductor Opening Switch

Y. S. Lai, W. L. Cao, E. E. Funk, Chi H. Lee, S. N. Mao, X. X. Xi, and T. Venkatesan

***Abstract*—A high Tc superconductor opening switch controlled inductive energy storage pulsed power system (IESPPS) has been demonstrated. A 500 Hz pulse train of jitter-free 75–318 ps electrical pulses was produced. We also show that the IESPPS produces a pulse compression ratio of 6–10. Compared with previous results, we have reduced the pulse width by a factor of ten and increased the repetition rate by a factor of 500 while reducing the laser trigger energy from 1 mJ/pulse to 20 μJ/pulse.**

THE use of inductive energy storage is an important technique employed in the generation of short, high-power pulses. The inductive energy storage pulsed power system (IESPPS) stores energy as current in an inductor or short-circuited transmission line. By suddenly interrupting the charging current with an opening switch a large output voltage can be developed across the inductive element and delivered to a load. This output voltage pulse may be many times greater in amplitude and shorter in duration than the initial voltage used to charge the inductor. The practical development of the IESPPS relies on the availability of an ideal opening switch. Among the most important properties of the ideal opening switch are fast opening time, jitter-free operation, low on-resistance, and high repetition rate. The GaAs photoconductive opening switch has been explored extensively and found to satisfy many of these criteria [1]. However the GaAs photoconductive switch requires either a specially tailored long duration laser pulse [2] or special bandgap tailoring [3] to maintain the switch in a closed state for more than a few nanoseconds.

The high Tc superconductor (HTS) is superior to the photoconductive opening switch. In its superconducting state, the HTS is normally closed with zero resistance. The HTS can then be triggered into its normal, high resistance, open state, by a short laser pulse. The laser triggered HTS exhibits low optical reflection, picosecond rise time, and high switch-out efficiency [4]–[5]. The IESPPS with HTS opening switch was first demonstrated with a 1 mJ, 1 Hz laser pulse triggering a 500 μm gap Si closing switch and an HTS opening switch [6]. This system produced 1.6 ns electrical pulses at 1 Hz repetition rate. In this letter we have dramatically reduced the electrical pulse width by a factor of $\sim$10, improved the repetition rate to 500 Hz, and reduced the laser trigger energy to 20 μJ. This was accomplished by using a laser pulse train from a Nd:glass oscillator-regenerative amplifier system [7] and by improving the IESPPS design. Furthermore, the high repetition rate allows the picosecond electrical pulse train to be viewed with good temporal resolution on a commercial sampling oscilloscope.

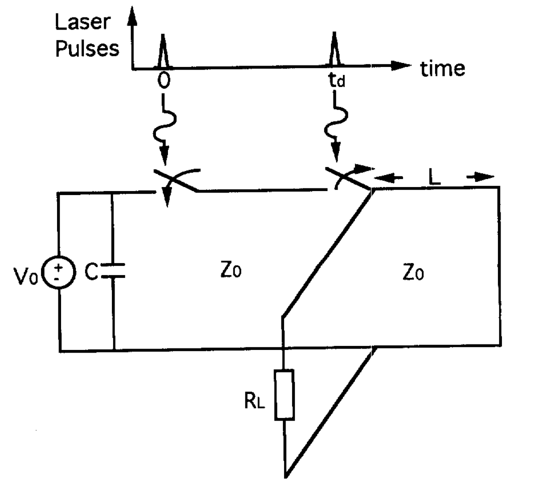

Fig. 1. Schematic diagram of the inductive energy storage pulsed power system (IESPPS). The incoming laser beam is equally split into two; the first beam triggers the closing switch at $t = 0$ and the second beam triggers the opening switch at $t = t_d$. R_L is the 50 Ω input impedance of the Tektronix 11802 sampling oscilloscope. We employed Si as a closing switch and HTS as an opening switch.

The IESPPS shown in Fig. 1 consists of a capacitor, a closing switch, an opening switch, and a short-circuited transmission line (TL), which together form a current charged transmission line (CCTL) [2]. The capacitor is initially charged to V_0 at $t = 0^-$. The incoming laser pulse train is split into two beams . The first beam triggers the closing switch at $t = 0$ and the second beam, delayed by t_d, then triggers the opening switch. When the closing switch is triggered,

Manuscript received May 23, 1994; revised July 13, 1994. This work was partially supported by the Army Research Laboratory.

Y. S. Lai, W. L. Cao, E. E. Funk, and C.H. Lee are with the Department of Electrical Engineering, University of Maryland, College Park, MD 20742 USA.

S. N. Mao, X. X. Xi, and T. Venkatesan are with the Center for Superconductivity Research, Physics Department, University of Maryland, College Park, MD 20742 USA.

IEEE Log Number 9404991.

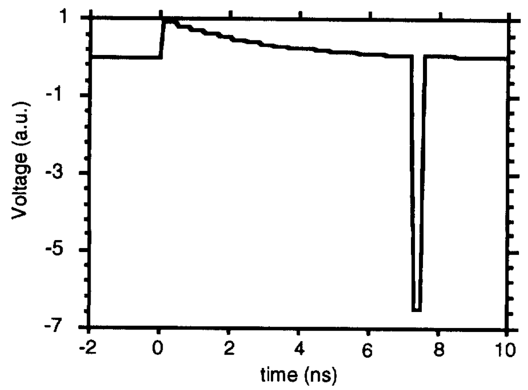

Fig. 2. The simulated load voltage waveform. We assume Ron = 4 Ω, $C = 0.1$ μF, $Z_0 = 50$ Ω, and a round trip time in the CCTL of 400 ps corresponding to the experimental conditions of Fig. 3(a).

current starts to flow in the CCTL . Two current waves are produced, a forward traveling wave, I^+, and a reverse traveling wave, I^-, both with equal amplitude. The current is reflected in phase at both ends, thus, current builds up in a staircase waveform which increases one step after each round trip. However the load voltage decreases in a staircase waveform due to both the discharge of the capacitor and the energy loss in the nonideal on-resistance. The HTS opening switch, triggered by the second beam, opens at time $t = t_d$. We can choose t_d corresponding to the time when the current in the transmission line has charged to its maximum value (or load voltage dropped to zero). A negative pulse with a duration corresponding to the round-trip transit time in the TL is delivered to the load. Ideally, all of the energy stored in the transmission line is delivered to the load. A simulated voltage waveform corresponding to the experimental conditions of Fig. 3(a) is shown in Fig. 2.

In the experiment, we employed Si as a closing switch and an HTS as an opening switch. All the elements, the 0.1 μF capacitor, the Si-switch, the HTS switch, and the TL were put on a single mount which was fastened to a cold finger in a vacuum cryogenic chamber. This was done in order to reduce the round trip time of the CCTL. An $f = 15$ cm cylindrical lens was employed to focus the laser beam. The Si-switch [8] for this experiment, had two parallel 500 μm wide, 3000 Å thick, Al electrodes separated by a 50 μm gap. It was fabricated on a 0.25 mm thick Si substrate with ohmic contact achieved using a standard ion implantation process. The dark resistance was about 1 M Ω at liquid nitrogen temperature, ensuring no thermal runaway problems. After optically triggering the Si-switch, the resistance changed from 1 MΩ to a few ohms in ~300 ps and remained constant for 50 ns at liquid nitrogen temperature. The opening switch was a 500 Å or 1000 Å thick YBCO microstrip line, with T_c equal to 90 K and critical current density of $\sim 10^6$ amp/cm^2 grown on a 0.5 mm $LaAlO_3$ substrate by laser ablation. Its optical response has a rise time shorter than the resolution of Tektronix 11802 sampling oscilloscope and the laser pulse

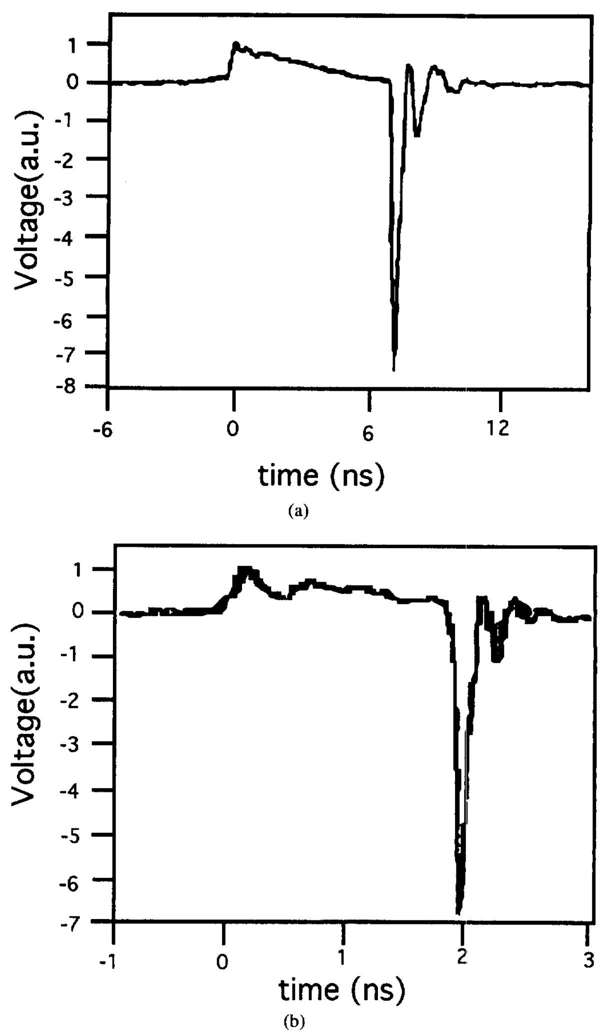

Fig. 3. Output pulse from IESPPS with a transmission line length, L, of (a) 2.5 cm and (b) 0.3 cm.

[9], recovery time on the order of 10 ns, and 80% switching efficiency at 79 K. The optical response is dependent on the first time derivative of the kinetic inductance which is inversely proportional to the Cooper pair density [10]. The fast rise time was attributed to a reduction in the Cooper pair density in an ultrashort time due to the breaking of Cooper pairs by photons and the electron-electron interaction cascading effect [10]. The long recovery time was attributed to a slower reduction in Cooper pair density due to quasiparticle generation by electron- phonon interactions, followed by an increase of the Cooper pair density due to a net quasiparticle recombination [10].

In this experiment, the TL length was varied from 0.3 cm to 2.5 cm corresponding to switched out electric pulses of 30 to 250 ps. The measured pulses varied from 75 ps to 318 ps which agreed with the predicted values within the resolution of the delay line mode of the sampling oscilloscope.

Fig. 3 shows the load voltage waveforms associated with the $L = 2.5$ cm and $L = 0.3$ cm cases. The switched out pulse widths are 318 ps and 75 ps respectively. The additional peak following the switched out pulse in Fig. 3 is a result of mismatch. The experimental results of the $L = 2.5$ cm case agreed with the simulated result which is shown in Fig. 2. The pulse compression ratio, the ratio of the switched out voltage to the pre-pulse voltage, is about 7 for both cases. The power gain, the ratio of peak power delivered to the load from the IESPPS to the peak power which would be delivered to the same load directly from the capacitor, is 10 for the case shown in Fig. 3(a) and 2 for the case shown in Fig. 3(b).

Since the limiting temporal resolution of our sampling oscilloscope is $\sim$70 ps, we believe that the actual pulse is much shorter than what is shown in Fig. 3(b). There is the potential of getting an even shorter pulse by shortening the TL. An autocorrelation technique may be applied to view these shorter pulses. The TL and the HTS opening switch can be combined into a microstrip line to avoid the contact and mismatch problems. It is possible to further integrate a Si-switch, an HTS switch, and a TL monolithically since YBCO films can be fabricated on a silicon wafer [11]. Finally, the jitter free and optically controllable pulses could be fed to a radiating antenna which is either external or monolithically integrated. This technique can be applied to ultra-wideband (UWB) impulse radar or as a transmitter for an UWB communication system [12]. In summary, we have demonstrated the operation of a high repetition rate (500 Hz) IESPPS controlled by an optically triggered HTS opening switch. The IESPPS produced fast (75–318 ps) jitter free electrical pulses. We believe that shorter pulses can be obtained with a few modifications.

Acknowledgment

We would like to acknowledge Dr. Y. Liu for his technical assistance and Dr. S. E. Saddow of Army Research Laboratory for producing the Si closing switch.

References

[1] A. Rosen and F. Zutavern, eds., *High-Power Optically Activated Solid-State Switches*. Boston: Artech, 1993.

[2] E. E. Funk, E. A. Chauchard, M. J. Rhee, and Chi H. Lee, "80-kW inductive pulsed power system with a photoconductive semiconductor switch," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 576–577, 1991.

[3] K. H. Schoenbach, V. K. Lakdawala, D. C. Stoudt, T. F. Smith, and R. P. Brinkmann, "An optically controlled closing and opening semiconductor switch," *J. Appl. Phys.*, vol. 63, pp. 2460–2462, 1988.

[4] A. Frenkel, *et al.*, "Optical response of nongranular high-Tc $YBa_2Cu_3O_{7-x}$ superconducting films," *J. Appl. Phys.*, vol. 67, pp. 3054–3068, 1990.

[5] W. R. Donaldson, A. M. Kadin, P. H. Ballentine, and R. Sobolewski, "Interaction of picosecond optical pulses with high Tc superconductor films," *Appl. Phys. Lett.*, vol. 54, pp. 2470–2473, 1989.

[6] Wei-Lou Cao, *et al.*, "Nanosecond inductive energy storage pulsed power system using YBCO superconductor opening switches," *Photon. Technol. Lett.*, vol. 5, pp. 109–111, 1993.

[7] Li Yan, P-T. Ho, Chi H. Lee, and G. L. Burdge, "Generation of ultrashort pulses from a neodymium glass laser system," *IEEE J. Quantum Electron.*, vol. 25, pp. 2431–2440, 1989.

[8] S. E. Saddow, B. J. Thedrez, and Chi H. Lee, "An optoelectronic attenuator for the control of microwave circuits," *IEEE. Microwave Guided Wave Lett.*, vol. 3, pp. 361–362, 1993.

[9] L. Shi, G. L. Huang, C. Lehane, J. Zheng, and H. S. Kwok, "Generation and measurement of picosecond voltage pulses in $YBa_2Cu_3O_7$ thin films," *Appl. Phys. Lett.*, vol. 61, pp. 489–491, 1992.

[10] Nathan Bluzer, "Temporal relaxation measurement of photoinduced non-quilibrium in superconductors," *J. Appl. Phys.*, vol. 71, pp. 1336–1347, 1992.

[11] Th. Matthee, *et al.*, "Orientation relationship of epitaxial oxide buffer layers on silicon (100) for high-temperature superconducting $YBa_2Cu_3O_{7-x}$ films," *Appl. Phys. Lett.*, vol. 61, pp. 1240–1242, 1992.

[12] Y. S. Lai, *et al.*, "Ultra-wideband pulse generation and radiation using high Tc superconductor opening switch," *Appl. Phys. Lett.*, vol. 65, pp. 1048–1050, 1994.