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GENERATION OF AN 80 KW PULSE IN A PHOTOCONDUCTIVE SEMICONDUCTOR SWITCH CONTROLLED INDUCTIVE ENERGY STORAGE PULSED POWER SYSTEM

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Abstract

An 80 kW, 2.1 kV pulse has been generated with an inductive energy storage pulsed power system controlled by a GaAs photoconductive semiconductor switch. Power gain is achieved by discharging a capacitor through the switch into a current charged transmission line where current rapidly builds up. When the switch opens, the energy stored by the current is delivered to a matched 50 Ω load in parallel with the transmission line, producing a pulse of greater voltage than that to which the capacitor was initially charged. This results in both voltage and power gain. A power gain of 49 is demonstrated in this work.

I. Introduction

The development of the photoconductive semiconductor switch (PCSS) has been encouraged by the recent need for high performance switches for use in pulsed power applications [1]. This work focuses on the development of an inductive energy storage pulsed power system (IESPPS) of which the key element is an opening PCSS. Such systems are capable of achieving power gain, and a voltage greater than the charging voltage is delivered to the load.

In order to achieve power gain, the PCSS design, laser pulse characteristics, and circuit design must be carefully matched.

II. Circuit Design

In an IESPPS, energy is stored as magnetic field energy in an inductive circuit element. That is in contrast to capacitive energy storage pulsed power systems (CESPPS) where energy is stored as electric field energy in a capacitor. The IESPPS offers several advantages over the CESPPS including high energy storage density and inherent voltage step-up [2].

The experimental IESPPS is shown in Fig. 1. A current charged transmission line (CCTL) [3] is the inductive element in the circuit. The CCTL is a 2.0 m long transmission line with characteristic impedance $Z_o = 50\ \Omega$, which is matched to the load resistor. The 0.1 Ω current viewing resistor (CVR) provides a nearly short circuit at the end of the CCTL as well as a means of monitoring the current. The switch is a laser activated PCSS with on-resistance, R_{sw}.

The capacitor is initially charged to the voltage V_o. For analysis, assume the ideal case where $R_{sw} = 0\ \Omega$ and the capacitor has a large enough capacitance to be treated as a voltage source. Then, when the switch is closed, the capacitor is the source of a current traveling wave of amplitude $I = V_o/Z_o$ which travels down the transmission line and is reflected repeatedly from both ends of the CCTL. As illustrated in Fig. 2, the current will build up in steps of amplitude $2V_o/Z_o$ and length τ, where τ is the round trip transit time in the CCTL. Suppose the switch is closed for a period, t_{ch}, and then opened. Upon opening of the switch, the current stored in the CCTL is delivered into the matched load producing a pulse of length τ and amplitude,

$$V_l = V_o t_{ch}/\tau \qquad (1).$$

In this model, voltage gain is achieved whenever the charging time, t_{ch}, exceeds the round-trip transit time, τ. Hence, the CCTL should be kept short, and t_{ch} should be long. In the practical implementation, the switch opening time imposes a design limit on the CCTL length. The CCTL must be short enough to ensure that the switch opening time is much faster than τ.

The circuit of Fig. 1 may also be analyzed by treating the CCTL as a lumped inductance. We take the inductance of the CCTL as $L = Z_o l/v$ where l is the CCTL length and v is the traveling wave velocity. We may then solve for the current in the CCTL as a function of time. This lumped analysis does not predict the step-like charging of current described

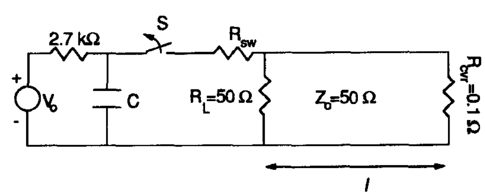

Fig. 1. Experimental inductive energy storage pulsed power system. R_{sw}–closed switch resistance; Z_o–transmission line characteristic impedance; R_{cvr}–current viewing resistor; R_L–load resistor; C–capacitor; S–switch; V_o–charging voltage; l–transmission line length.

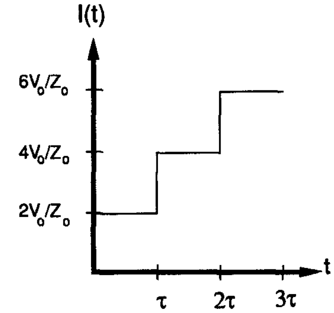

Fig. 2. Theoretical step-like charging of the current charged transmission line. τ–round-trip traveling wave transit time; V_o–charging voltage, Z_o–transmission line characteristic impedance.

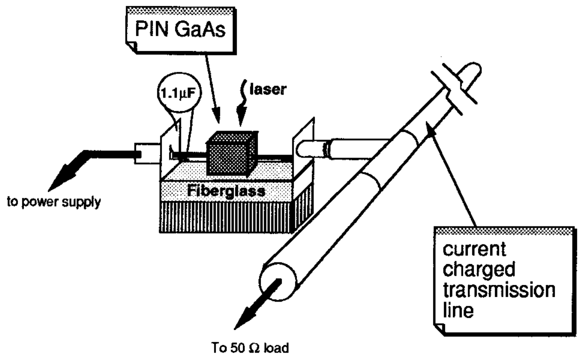

Fig. 3. Experimental setup of the PIN GaAs switch and current charged transmission line.

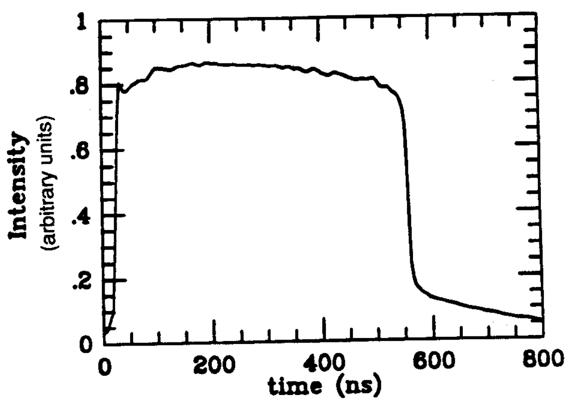

Fig. 4. Square, 540 ns, optical pulse from Nd:Glass laser system.

previously, however it does provide an accurate prediction of the charging current envelope. The current through the CCTL is given by:

$$I(t) = I_o[exp(s_1 t) - exp(s_2 t)], \quad (2)$$

where $s_{1,2} = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$, $I_o = \frac{V_o R_l}{L(R_l+R_{sw})(s_1-s_2)}$, $a = LC\,(R_{sw} + R_l)\,, b = R_{sw}R_lC + L$, and $c = R_l$.

Given a constant R_{sw} and charging time, (2) is used to choose the CCTL length and capacitor in order to maximize the charging current and output voltage.

III. Switch and Laser Setup

According to the requirements of the circuit, a GaAs PCSS was chosen. The several nanosecond carrier recombination time in GaAs allowed the use of a CCTL with a round trip transit time as short as 20 ns. Hence, with a 540 ns square laser pulse, a voltage gain was achieved.

The PCSS was assembled from a 5 mm cube GaAs p-i-n diode [4] provided by A. Rosen at the David Sarnoff Research Center. The PCSS was mounted on a rectangular aluminum mount above a fiberglass insulator. Contacts to the GaAs samples were made by connecting a thin strip of copper foil to each of the side surfaces with silver paint. Care was taken to connect these leads so that the p-i-n diode was operated under reverse bias. The setup is shown in Fig. 3. The CCTL was a

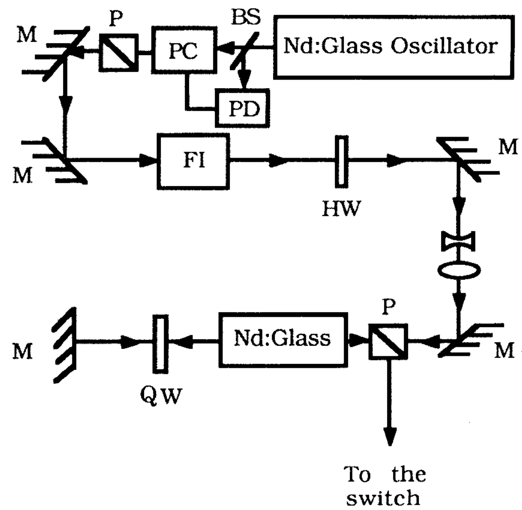

Fig. 5. Nd: Glass laser system setup. BS–beam splitter; PD–photodetector; PC–Pockels Cell; P–polarizer; M–mirror; FI–Faraday isolator; HW–half wave plate; QW–quarter wave plate.

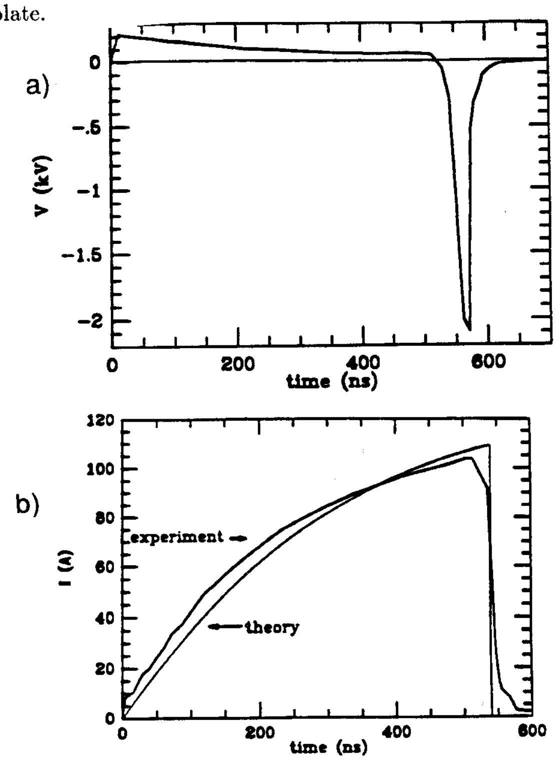

Fig. 6. a) Voltage across the load resistor showing 2.1 kV output pulse. b) Current through the current viewing resistor, and theoretical prediction with switch on-resistance set to $R_{sw} = 1.2\ \Omega$.

2.0 m long RG-213U, 50 Ω transmission line. It was shorted at one end with the 0.1 Ω CVR, and the other end was connected to the switch. The 50 Ω load resistance was provided by the 50 Ω input impedance of an oscilloscope connected to the circuit through two 10 × attenuators.

The switch is illuminated with a specially tailored Nd:Glass laser pulse [5]. The laser system is designed to provide a long, square pulse with fast rise and fall times.

The $\sim$ 10 mJ, 540 ns laser pulse is shown in Fig 4. The customized laser system consists of a free-running flashlamp-pumped, Nd:glass oscillator, and a two-stage double-pass amplifier. The oscillator output is chopped into a square pulse with a Pockels Cell and polarizers. The laser system setup is shown in Fig. 5.

IV. Results

The output pulse produced with a charging voltage of $V_o = 300$ V is shown in Fig. 6. When the switch is closed, a positive voltage appears across the load resistor; the voltage slowly drops as the capacitor discharges into the CCTL. The switch is then opened by the extinction of the optical pulse. As soon as the switch is opened, the stored current in the CCTL passes through the load, producing the large negative output pulse.

The amplitude of the output pulse is 2.1 kV corresponding to a power of 80 kW into the 50 Ω load. With an initial charging voltage of $V_o = 300$ V, this corresponds to a voltage gain of 7 and a power gain of 49. The power gain is defined as the ratio of the peak power delivered to the load with the pulsed power system to the peak power which would be delivered to the same load without the pulsed power system but with a 0 Ω switch on-resistance. Thus, the power gain, G_p is,

$$G_p = [V_l(max)/V_o]^2, \tag{3}$$

where $V_l(max)$ is the maximum value of $|V_l|$, the voltge across the load.

A trace of the current, $I(t)$, through the CVR is also shown. A theoretical prediction of $I(t)$ is available from (2). The theoretical curve is also shown. The best fit of theory to experiment occurs when we set $R_{sw} = 1.2$ Ω in the theoretical model, suggesting that the switch on-resistance may be as low as 1.2 Ω. The step-like buildup of current is not visible on this time-scale, however, if we use a longer, 3.5 m CCTL and a smaller time scale, the steps are clearly visible as in Fig 7.

Since traces of both the current and the voltage were taken simultaneously, the dynamic switch resistance may be calculated by computer according to the equation,

$$R_{sw}(t) = \frac{V_o - \frac{1}{C}\int I(t)\ dt - V_l}{I(t)}. \tag{4}$$

The result is plotted in Fig. 8. Notice that the switch resistance, R_{sw}, drops to nearly 2 Ω when the switch is closed by the laser pulse. When the pulse is extinguished, there is a rapid rise in R_{sw} until it reaches $\sim$ 300 Ω; then the switch resistance begins to fall. This unexpected behavior may be caused by the lockon effect which has been observed by other experimenters in closing switch experiments [6]. This is further evidenced by a plot of the voltage across the switch which is also shown in Fig 8. The unexpected reduction in R_{sw} occurs when the voltage across the switch reaches $\sim$ 3 kV, corresponding to a field of 6 kV/cm across the 5mm gap of the switch. We notice that this is just above the reported range of threshold fields for the onset of lockon [6].

As the charging voltage was increased above 300 V the output voltage pulse was found to drop below 2.1 kV due to lockon; subsequently, the voltage gain and power gain were reduced.

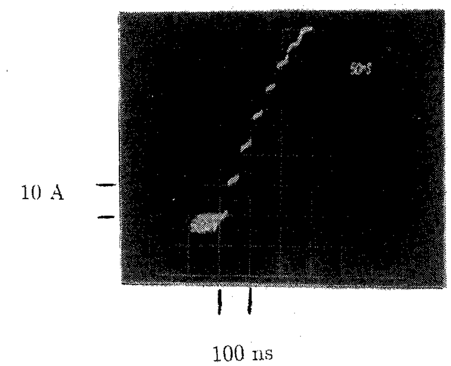

Fig. 7. Staircase-like buildup of current in a 3.5 m long current charged transmission line.

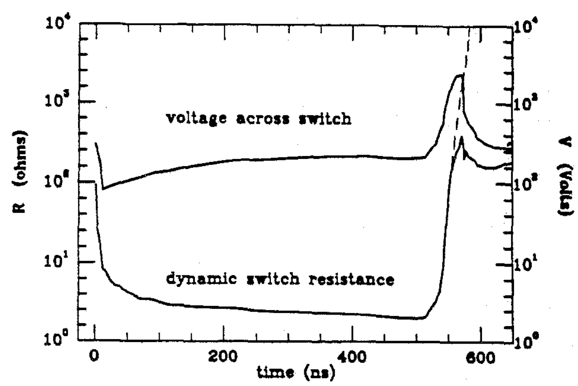

Fig. 8. Dynamic switch resistance, $R_{sw}(t)$, and voltage across the switch, $V_{sw}(t)$. The drop in switch resistance after the extinction of the optical pulse is evidence of lockon. Without lockon the switch resistance would rise toward infinity (dotted line).

V. Conclusions

The GaAs photoconductive semiconductor switch is an effective closing and opening switch in an inductive energy storage pulsed power system . The CCTL inductive element, and GaAs switch provide the fast response time necessary to obtain a power gain of 49 within the limits of switch on-resistance and charging time. A specially tailored square Nd:Glass laser pulse was developed to provide long charging time and fast rise and fall times. The laser pulse was effective in lowering the switch resistance below 2 Ω.

The power gain of 49 was achieved with a charging voltage of 300 V producing an output pulse of 2.1 kV, or 80 kW. In order to achieve higher output voltages when using a GaAs PCSS, it is necessary to increase the critical lockon voltage. This may be done by using either a longer GaAs PCSS or a Cr:GaAs PCSS. The critical lockon field in Cr:GaAs is $\sim$ 8.5 kV/cm which is much higher than the 3.2 kV/cm critical field in GaAs [6]. Experiments with 5 mm cube Cr:GaAs switches indicate that the 10 mJ of laser energy is not sufficient to lower the PCSS resistance below 7 Ω. The carrier recombination time in Cr:GaAs may be up to an order of magnitude less than in GaAs requiring an order of magnitude more optical energy to maintain the same switch resistance as in GaAs.

The subject of lockon is currently being investigated in greater detail as we seek to understand the fundamentals of this mechanism. The observation of lockon in the CCTL configuration rather than the CESPPS configuration may provide some valuable insights.

Acknowledgment

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