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Development of a High Repetition Frequency Sub-Nanosecond Pulse Generator Based on Avalanche Transistors

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Abstract: The pulse source technology that can generate high repetition frequency pulse signals is being used in more and more fields, such as electromagnetic interference, biomedicine, precision instrument control, radar detection, etc. Developing pulse signals with high repetition frequency and narrow pulse width parameters is a challenging aspect of this technology. However, in this paper, using avalanche transistors as fast-switching devices helps to address this challenge. The authors have developed a pulse source based on the Marx circuit by optimizing various parameters of the circuit components, improving the circuit layout, and designing impedance matching. This pulse source can generate a negative pulse signal with specific characteristics of a falling edge of 140 ps, an amplitude of 620 V, and a half-peak pulse width of 170 ps when operating under a matched load of 50 Ω. To ensure stable operation and prolonged circuit life, a combination of water cooling and a semiconductor heat sink is utilized for heat dissipation. This allows the pulse source to work reliably at a repetition frequency of 300 kHz for more than 30 minutes.

Keywords. Avalanche Transistors Marx Circuit High Repetition Frequency

1. Introduction

In recent years, with the rapid development of ultra-wideband pulse source technology [1-3], pulse signals with sub-nanosecond pulse width and high repetition frequency characteristics are used in more and more fields, such as electromagnetic pulse attack weapons [4], pulse radar detection [5], pulse-induced cell fusion [6], discharge plasma [7], etc. The pulsed signals generated by applying ultra-wideband pulse source technology generally require high repetition frequency, narrow pulse width, fast-rising edge, high amplitude, high stability, and other characteristics. However, with the rapid development of various modern technologies, the pulse signal generated by the traditional Marx circuit with a maximum repetition frequency of one hundred kHz or less can no longer meet the requirements of its accuracy and performance. Therefore, optimizing the pulse signal parameters and improving the pulse source design become the focus of the next research.

This paper presents a comprehensive analysis of the factors that influence the performance metrics such as high repetition frequency and narrow pulse width of the ultra-wideband pulse source, takes a series of measures to improve the repetition

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frequency and reduce the leading edge[11], optimizes the technical parameters of the system, and conducts many experimental tests and carefully analyzes the experimental data. By utilizing a water-cooling cycle and a semiconductor heat sink as a form of heat dissipation control for the pulse source, it has been developed to stably output a repetition frequency of 300 kHz and a falling edge of 140 ps for the pulse signal.

2. Marx Circuit Analysis Based on Avalanche Transistors

This paper utilizes avalanche transistors as switching devices in Marx circuits due to their small size, stable operation, and fast response [8], which provide several advantages. Avalanche transistors are more prone to the multiplication effect of charge carriers. When a high power voltage is applied to the collector and transmitter ends of the transistor, a strong electric field is formed in the space charge region, and electrons and holes continuously gain higher energy[13], thus possessing great kinetic energy and colliding with each other under the influence of field strength, resulting in new electron hole pairs. These new electron hole pairs continue to move at high speeds under high kinetic energy, colliding with each other to produce new carriers. The field strength gradually accumulates, and the speed of the carriers rapidly increases, cycling back and forth. When the applied voltage exceeds the breakdown voltage of the transistor, the speed of the charge carrier rapidly increases like an avalanche effect. At this point, the avalanche current in the tube will also rapidly increase, and the avalanche transistor will be broken down. Gradually reducing the applied power voltage, the PN junction of the transistor will slowly return to its original state, so the breakdown of the avalanche transistor is reversible.

There are three common electrically triggered conduction methods of avalanche transistors, namely, triggered conduction, overvoltage breakdown conduction, and fast-rising edge conduction [9,12]. Figure 1 illustrates the pulse generation circuit using the avalanche transistor. The power supply VCC charges the energy storage capacitor C2, maintaining the avalanche transistor Q1 in a critical avalanche state. In this condition, a trigger pulse T is applied to the circuit, the transistor trigger conduction, and capacitor C2 release charge to provide avalanche current. Because the capacitor voltage cannot plunge eventually in the resistor, R3 will produce a downward-facing negative pulse signal.

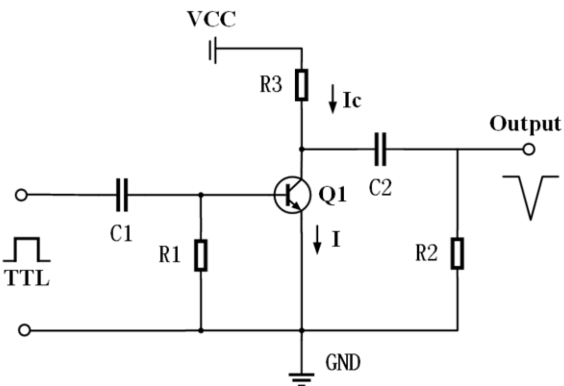

Figure 1. Avalanche Transistor Pulse Generation Circuit

3. Circuit Design

Conventional Marx circuits generate signals with limited amplitude and repetition frequency. When operating at high repetition frequencies, issues such as avalanche transistor power consumption and charging of energy storage capacitors directly impact the waveform. As the repetition frequency increases, so does the load on the avalanche transistor and the overall power consumption of the circuit. The RC value should be reduced to ensure complete charging of the capacitor within each cycle due to the shorter pulse interval. However, this creates a contradiction between the high repetition frequency and the narrow pulse width of the signal. Therefore, the RC value must be carefully selected to achieve a high repetition frequency and narrow pulse width. This paper proposes using parallel-connected avalanche transistors to prolong the circuit life at high repetition frequencies. The traditional parallel method has been improved by gradually increasing the number of parallel transistors as the number of circuit stages increases, aiming to mitigate the impact of avalanche current on a single transistor. Experiments prove that this improves the circuit lifetime and optimizes the pulse signal fronts.

At the same time, when the circuit is operating in a state of high repetition frequency, the effect of its spurious parameters cannot be neglected. Therefore, in this paper, the impedance matching of the microstrip line is considered in the PCB design so that the impedance of the Marx circuit increases in a gradient manner from the first stage and finally matches the output impedance. The design minimizes the wiring length to compact the structure and reach the purpose of miniaturizing the pulse source.

A twenty-four-stage Marx circuit is shown in Figure 2, which is charged in parallel by an energy storage capacitor and discharged in series by an avalanche transistor as a fast-switching device. Theoretically, a voltage of nVcc can be obtained at the load RL. However, the final voltage obtained is generally lower than the theoretical value due to losses such as avalanche transistors and circuit other parameters at high re-frequencies.

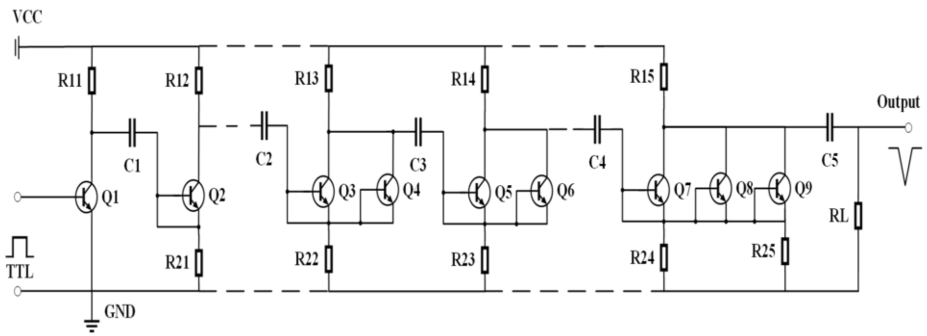

Figure 2. Twenty-four stages Marx circuit based on avalanche transistors

The energy storage capacitance mainly affects the speed of the falling edge. Hence, the capacitance parameters selected for high re-frequency operation are needed to ensure that the energy storage capacitor is fully charged under the premise of trying to select a smaller capacitance. The formula for the lower capacitance limit [10] can be expressed as Eq. (1).

$$k\,R_{ij}C_i \le \frac{1}{f_0} \quad (1)$$

f_0 indicates the repetition frequency of the pulse signal, and to ensure that the capacitor providing energy can be fully charged, the k value is generally taken as 6. The upper limit of the energy storage capacitor is mainly affected by the peak power of the pulse signal, which can be expressed as Eq. (2).

$$C_i \geq \frac{\sqrt{\pi}}{\sqrt{2\ln(2)}} \frac{T_e U_e^2}{R_l n U_0^2} \quad (2)$$

The charging resistance is determined by the rated current of the power supply and the repetition frequency of the pulse source, which is expressed as Eq. (3).

$$\frac{nU_0}{I_0} \leq R_{ij} \leq \frac{1}{C_i k f_e} \quad (3)$$

Considering the energy loss of the circuit during high repetition frequency operation, the energy storage capacitor should be selected as a high-frequency capacitor. During experimental tests, it is necessary to adjust the energy storage capacitor and charging resistance based on the repetition frequency. This ensures that the energy storage capacitor can fully charge without impacting the pulse amplitude.

4. Simulation and Experimental Results

The circuit diagram of Figure 2 is simulated using Pspice simulation software. The simulation results are shown in Figure 3. Figure 4 shows the experimental setup, Figure 5 shows the actual pulse waveform during the experimental test, and Figure 6 shows the pulse signal repetition frequency. Comparing the simulated output waveform and the actual output waveform, we can see that the output amplitude of the simulated waveform is 850 V. In contrast, the test waveform is only 620 V. This is because the simulation software cannot truly simulate the effect of the overall circuit temperature increase when the circuit is operated at a high repetition frequency for a long time. Another reason are the spurious parameters generated by the energy storage capacitor, charging resistance and circuit substrate on the pulse output amplitude.

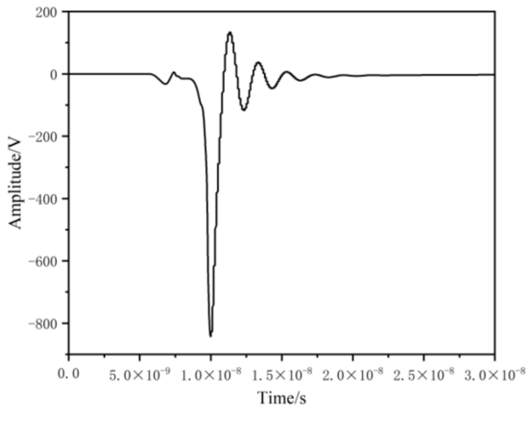

Figure 3. Simulation output waveform

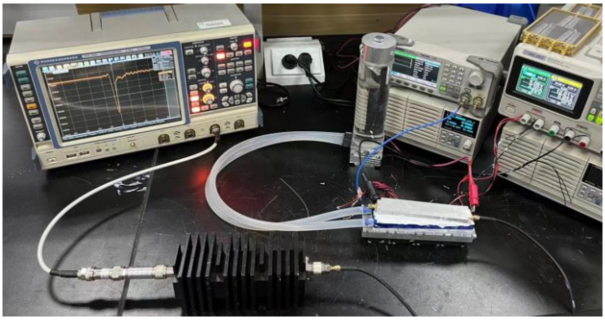

Figure 4. Experimental setup

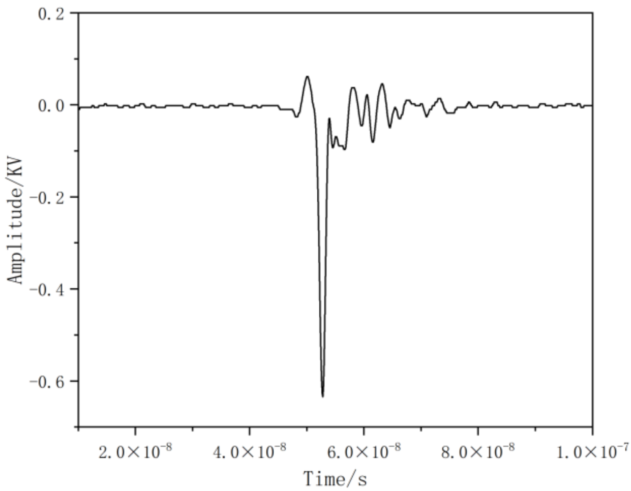

Figure 5. Experimental test output waveform

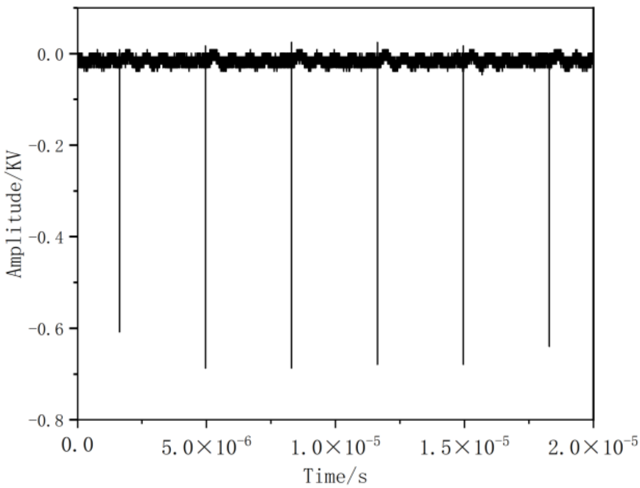

Figure 6. Pulse signal repetition frequency

5. Conclusion

In this paper, an avalanche transistor is used as a fast-switching device in the Marx circuit to improve the re-frequency by improving various parameters in the circuit components, designing a circuit structure to increase the number of parallel transistors step by step to extend the operating life, and making impedance matching in the PCB design. The developed pulse source can output a negative pulse signal with a repetition frequency of 300 kHz, an amplitude of 620 V, a pulse width of 170 s, and a falling edge of 140 ps. The stable output of the pulse source is achieved by using a combination of a water-cooling cycle and a semiconductor heat sink. And the pulse source has a compact structure and beautiful appearance, which can be better used in military, biomedical, precision instrument control, and other fields.

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