Design of Nanosecond Pulse Driver Circuit

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Abstract. The laser can achieve high peak power pulse output by electro-optic Q-switch technology. Aiming at the problem of how to achieve Q-switch output with ns level front and kV level amplitude on 100kΩ large load, a method of pulse output by using avalanche conduction state of triode is proposed. By using the 11 stages pulse forming circuit, the DC power supply voltage can be greatly reduced, and the selected devices can work normally under the condition of meeting the first stage derating standard, in order to improve the stability. The key factors affecting the parameters of the output pulse, such as amplitude, pulse width, frequency, leading edge and trailing edge, are analyzed and verified by experiments. Using +150V DC power supply, the experimental results show that the pulse driving source circuit designed in this paper can output a half height width of 12.6ns and an amplitude of 1500V Q-switch regulating signal on a 100kΩ load.

1. Preface

Solid-state lasers can output lasers with large energy and power, and at the same time has the advantages of high physical and mechanical strength, long band coverage, stable performance and long usage time. It has been widely used in the space field, such as space laser communication, laser etching, laser ranging, laser guidance technology. However, the pulse output of general solid-state lasers is a series of peak oscillations. Lasers operate near the threshold and exhibit relaxation oscillation characteristics. Therefore, Q-switching technology is used to achieve single-pulse energy output, high peak power and narrower pulse width.

Q-switching technology is to compress the continuous output of general laser energy into extremely narrow pulses for emission, so that the peak power of the light source can be increased by several orders of magnitude. Electro-optic Q-switching technology is a commonly used Q-switch adjustment technology at present. Speeding up the Q-switching speed can greatly reduce the loss in the resonant cavity during the Q-switching process and shorten the forming time of the laser pulse, which can effectively shorten the pulse width and increase the peak power of the pulse [1]. As a commonly used high-speed and high-power semiconductor device, the avalanche transistor has a high single-tube breakdown voltage and can still work normally when the first-level derating is met. It can also provide extremely high switching speed. Using the avalanche effect of the triode can obtain large peak power pulses with fast response time. Therefore, the pulse source based on the avalanche state of the triode is widely used in electro-optical Q-switching technology.

This article combines specific application conditions and uses a pulse shaping circuit designed based on the avalanche state of a transistor to obtain a large peak power pulse output with short rise
time and narrow pulse width at a large load of 100kΩ, and combined with experiments to analyze the key factors affecting the output pulse parameters.

2. Avalanche characteristics of triode and nanosecond pulse forming circuit

2.1. Avalanche characteristics analysis

The output characteristics of the transistor usually have three regions, namely the saturation region, the amplification region, and the cut-off region, and the avalanche state of the transistor works in a specific avalanche region. Its working region is shown in Fig.1. When the base current $i_B<0$, the area where the collector-emitter voltage $U_{CE}$ changes will cause the collector current $i_C$ to change sharply is called the avalanche area.

The range of the avalanche area is determined by the collector-emitter breakdown voltages $V_{CEO}$ and $V_{CBO}$. When the collector-emitter voltage $U_{CE}$ is located in this area, if an appropriate trigger signal is applied externally, the carriers will be strong. Under the action of an electric field, a "multiplication effect" appears, and the collector current $I_C$ rises rapidly, and the transistor will undergo one and two breakdowns in succession, thereby achieving rapid conduction. After the conduction, the collector-emitter resistance $R_{CE}$ reaches the minimum value, $U_{CE}$ decreases, and the output terminal can get higher voltage amplitude, so the avalanche state of the transistor is an ideal high-voltage fast switching state [2]. When the transistor works in the avalanche state, although the instantaneous power is very high, but because the avalanche process is very short (ns level), as long as the operating frequency is not very high, its average power consumption does not exceed its rated power consumption, and it will not cause permanent damage to the transistor [3]. At the same time, the junction heating effect It is small, which avoids the problem of difficult heat dissipation in some special applications. You can shorten the lead length, fill the thermal conductive material between the transistor and the printed board, and increase the area of copper near the pins. In order to achieve the purpose of speeding up heat dissipation.

![Figure 1. Volt-ampere characteristic curve of avalanche transistor.](image)

2.2. Nanosecond pulse forming circuit

Although the triode has a high voltage resistance and flow capacity, and has a fast switching speed when working in an avalanche state (the leading edge is only a few nanoseconds), the output pulse amplitude of a single transistor is limited, causing its application to be limited. Multiple avalanche transistors are connected in series or constitute a Marx circuit, which can effectively increase the amplitude of its output pulse.

The Marx type circuit has a simple structure and requires a low supply voltage, which can meet the first-level derating standard, and the number of stages can be very high, which can generate the amplitude is much higher than the pulse of the power supply voltage. Therefore, a Marx-type circuit as
shown in Fig.2 is used in this article, in order to obtain a shorter rise time and a higher amplitude output pulse on a large load under the condition of providing a lower power supply voltage.

![Multi-level Marx circuit](image)

**Figure 2. Multi-level Marx circuit**

2.3. Marx circuit works

In the Marx-type circuit shown in Fig.2, $V_{CC}$ is the DC supply voltage. To prevent the overvoltage breakdown of the transistor, $V_{CC}$ should be slightly smaller than $V_{CBO}$. When the trigger signal is not added, charge $C_n$ to $V_{CC}$ through the isolation resistors $R_{Cn}$ and $R_n$ of each stage; after the trigger signal is added, $Q_1$ has avalanche conduction, and the potential at the left end of $C_1$ is pulled to the zero potential due to instantaneous grounding. Because the voltage across the capacitor cannot be abruptly changed, the potential at the right end of $C_1$ jumps to $-V_{CC}$; at this time, $Q_2$ has overvoltage conduction, the potential at the left end of $C_2$ is pulled to $-V_{CC}$ by $C_1$, and the potential at the right end jumps to $-2V_{CC}$; and so on, $Q_3 \sim Q_n$ sequentially enter the avalanche breakdown state and turn on, and finally turn on at $C_n$ [4].

The right end generates an instantaneous high-voltage pulse with an amplitude of $-nV_{CC}$. At the same time, attention should be paid to the influence of the rising edge slope of the trigger signal on the pulse stability. Fast rising edge trigger signal obtained by the differential circuit is obtained, the necessary condition for the stable output of the pulse source [5]. Its system structure is shown in Fig.3.

![Structure diagram of Marx pulse forming circuit system](image)

**Figure 3. Structure diagram of Marx pulse forming circuit system**

Therefore, the Marx circuit can be understood as: when not triggered, the energy storage capacitors at various levels are connected in parallel; after the trigger signal arrives, the energy storage capacitors at various levels discharge the load $R_L$ through the triode in series, and the equivalent circuit of discharge is shown in Fig.4. Negative pulses with fast front and high amplitude are generated at both ends of $R_L$. 
3. circuit design and experiment

3.1. Influence of equivalent impedance on the circuit

The transistor selected in this article is 3DK105. In order to enable it to work safely in the avalanche region, the DC power supply voltage $V_{CC}$ is selected to be 150V, and to output a 1500V high-voltage pulse on a 100kΩ resistive load, the number of circuit stages is 11. The output pulse voltage waveform on the resistive load is shown in Fig.5.

It can be known from the working principle that the voltage amplitude $-nV_{CC}$ generated on the load will increase with the increase of the number of stages $n$. The 11-stage pulse forming circuit should theoretically output a voltage of 1650V, but the actual output will be less than the theoretical value. That’s because the utilization of the power supply actually decreases with the number of circuit stages, that is, the superimposed effect of series discharge of energy storage capacitors at various levels is getting worse and worse. The reasons for this analysis are mainly as follows:
First, as the number of stages increases, the equivalent internal resistance $r_n$ of the pulse forming circuit increases, and the output voltage divided by the load will decrease. The equivalent circuit is shown in Figure 6. If $V_o$ is the output voltage on the load; $R_L$ is the load resistance; $r_n$ is the equivalent internal resistance when the circuit is discharged; $n$ is the number of Marx circuit stages, and the equivalent internal resistance is

$$r_n = \frac{nR_l}{V_o} - R_L$$  \hspace{1cm} (1)

The equivalent internal resistance of each stage of the discharge circuit includes the conduction loss of a single tube, the stray capacitance and stray inductance of the circuit itself, etc. The single tube conduction resistance $r_o$ can be calculated from equation (2), where $U_{CE}$ is transistor CE inter-electrode voltage, when the output voltage pulse $V_o$ reaches its peak, that is, when the transistor is fully avalanche on, the CE inter-electrode resistance $r_o$ reaches the minimum.

$$r_o = -\frac{U_{CE}R_l}{V_o}$$  \hspace{1cm} (2)

When making PCB, the capacitance and resistance adopt chip components and compact design, which can reduce the circuit volume and reduce the impact of stray parameters, in order to improve the peak output, which is an important work in the design of Marx circuit [6].

The second is that when the circuit is discharged, the voltage difference between the charging isolation resistors $R_{Cn}$ and $R_n$ will form a leakage current on the resistance, which will cause losses. Therefore, the charging isolation resistance should not be too small, the larger the resistance is, the smaller the leakage current is, the smaller the loss will be, and the higher the output peak voltage will be. If the voltage across the energy storage capacitor is $u_c$, the loss on the resistor will be [7]

$$P_{R_{Cn}} = f \cdot \int_0^{\tau_1} \frac{(V_{CC} - u_c)^2}{R_{Cn}} dt$$  \hspace{1cm} (3)

$$P_{R_n} = f \cdot \int_0^{\tau_1} \frac{u_c^2}{R_n} dt$$  \hspace{1cm} (4)

3.2. Influence of capacitor resistance on circuit

When the transistor is not turned on, the charging isolation resistors $R_{Cn}$ and $R_n$ provide a charging circuit for the energy storage capacitor. The charging speed depends on the maximum time constant of each circuit. If $R_{Cn} = R_n = R$, each stage is charged time constant $\tau_1 = 2RC$, so when the circuit's
working frequency is high, in order to make the energy storage capacitor be fully charged every
 discharge gap, that is, the charging time should be less than the repetition period 1/f, the charging
 isolation resistance should not be too large.

During the discharge, the charging isolation resistors $R_{Cn}$ and $R_n$ isolate the high-voltage potential
 from the ground, so the resistance cannot be too small; at the same time, the larger the resistance, the
 smaller the loss caused by leakage current. In the case of frequency requirements, the larger the
 resistance of $R_{Cn}$ and $R_n$ is the better [8].

![Capacitance voltage variation waveform](image)

**Figure 7.** Capacitance voltage variation waveform

During discharge, the storage capacitors at various levels discharge the load in series. It can be seen
 from the waveform in Figure 7 that when the transistor is not turned on, the storage capacitor is
 charged to Vcc. After the conduction is triggered, the storage capacitors at all levels are connected to
 the load in series. Discharge, after the discharge, the DC power supply will replenish the voltage
 across the capacitor to Vcc and wait for the next signal. Therefore, the larger the energy storage
 capacitor, the longer the corresponding capacitor charging time, and the more stored energy, the
 output voltage amplitude is also larger, and the pulse width is wider [9]. Therefore, the selection of the
 energy storage capacitor is still limited by the frequency. The capacitance of the capacitors $c$ at all
 levels is the same. The equivalent capacitance of the circuit during series discharge is

$$C_n = \frac{C}{n}$$  \hspace{1cm} (5)

When the charging isolation resistances $R_{Cn}$ and $R_n$ are unchanged, the larger the capacitance value
 $C$, the longer the charging time, and the smaller the range of the operating frequency. Take the output
 pulse rise time as $t_r$ and the fall time as $t_f$, the full bottom pulse width $t$ of the output voltage pulse is

$$t = t_r + t_f$$  \hspace{1cm} (6)

The rising edge is mainly determined by the conduction speed of the transistor, that is, the time
 required to enter the avalanche state, so the time is almost unchanged after the transistor is selected.
When the circuit is discharged, the trailing edge of the pulse is mainly determined by the discharge time constant $\tau_2$. After the charging isolation resistance and energy storage capacitor are determined, the discharge time constant can be obtained

$$\tau_2 = \left( r_n + R_L \right) \cdot \frac{C}{n}$$  \hspace{1cm} (7)

To reduce the width of the output voltage pulse on the load $R_L$, one is to choose a transistor with a fast on-state and a small on-resistance between C-E; the second is a compact layout that reduces the inherent stray parameters between the circuits and thus reduces Small equivalent resistance; third, the energy storage capacitor capacity can be appropriately reduced and the number of stages [10] can be increased.

3.3. Triode selection
Due to the avalanche effect of the triode, the high amplitude and high speed of the output pulse can be guaranteed, so the performance of the triode is important for the design of the circuit. The output pulse performance of the circuit designed in this paper is mainly measured by the pulse width and amplitude, so the focus is on the triode. $BV_{CBO}$ and $BV_{CEO}$ parameters. Can refer to the following requirements to select a suitable transistor: (1) $BV_{CBO}$ and $BV_{CEO}$ have larger values; (2) the avalanche area is wider ($\beta$ should be larger) (3) The characteristic frequency of itself is higher.

At the same time, the basic parameters such as the current and power of the circuit need to be calculated to avoid damage to the transistor beyond the working range of the transistor. The power loss of the transistor can be expressed as:

$$P = \frac{1}{2} CV_o^2 f$$  \hspace{1cm} (8)

When the circuit is working, the actual calculated power $p$ should be smaller than the maximum power dissipation allowed by the transistor itself. Although the instantaneous power of the circuit designed in this article is high, because the effective working time is short, as long as the operating frequency is not very high, the average power consumption will not exceed its rated power consumption [11].

4. Experimental analysis
This article uses a digital oscilloscope MDO4104C with a sampling bandwidth of 1GHz and a sampling frequency of 5GHz to observe the waveform. The DC power supply voltage VCC is 150V, and the charging isolation resistors $R_{Cn}$ and $R_n$ at all levels are 12kΩ. And the energy storage capacitor adopts 1NF high-voltage ceramic chip capacitor. In order to meet the first-level derating standard, the capacitor model is CT41L-300V.
Figure 8. Single capacitor voltage and output pulse voltage waveform

The output pulse voltage varies with the storage capacitor voltage as shown in Figure 8. When no trigger signal is added, the DC power supplies charge the voltage at both ends of the energy storage capacitor to $V_{CC}$, and the output voltage is 0 at this time; the triode avalanche is triggered after the trigger signal arrives. Turn on, the energy storage capacitors at all levels discharge the load resistor in series, and instantly output a 1500V voltage pulse. After the discharge is completed, the triode is turned off and the output voltage drops to 0. The DC power supply replenishes the voltage across the capacitor to $V_{CC}$ and waits for the next signal to arrive.

Figure 9. Single output pulse voltage waveform
During the storage capacitor discharge, a voltage pulse with an amplitude of 1500V and a rising edge of 9.2ns can be obtained on the load. The output voltage waveform is shown in Figure 9. It can be seen that the rising edge of the output pulse is fast, because the action of the triode entering into the avalanche conduction state is very fast, and the speed of the rising edge mainly depends on the conduction speed of the transistor; the trailing time of the output pulse is longer, mainly because this article is aimed at a large resistance load of 100kΩ, and the discharge time constant is too large. As a result, the falling time is relatively slow; at the same time, the resistance too large causes the circuit to be nearly open circuit, and the energy stored in the energy storage capacitor cannot be discharged quickly and effectively through the load during the discharge, so the falling edge will oscillate.

When the load resistance is 100Ω, 500Ω, 10kΩ, 100kΩ, the output voltage pulse waveform is shown in Figure 10. The smaller the load resistance value is, the shorter the trailing edge time of the output pulse is and the smaller the tail oscillation is. The experimental waveform is consistent with the analysis. Increasing the load resistance can increase the amplitude of the output voltage, but the increment of the voltage amplitude will become smaller and smaller. This is because when the resistance of the load resistance is much larger than the equivalent impedance of the discharge circuit, the ratio of the divided voltage is small, and the effect of increasing the output voltage amplitude by increasing the load resistance is no longer significant.

5. Conclusion
This article is oriented to practical engineering applications. Based on the working principle of the triode Marx circuit, the role of each parameter in the circuit in the working process and its impact on the circuit are analyzed in detail. The 11 level Marx circuit is used to stably output the instantaneous voltage pulse with the amplitude of 1500V and the half height width of 12.6ns on the 100kΩ load. A compact PCB is produced to verify the theory, and the experimental results meet the design requirements through parameter design, which has a certain reference significance for the design of related circuits in the future.

References
[1] Chen Wei, Sun Feng, Liu Zaizhou. Experimental research on electro-optic q-switched driver based on ordinary triode [j]. Optics and Optoelectronic Technology, 2011 (06): 80-83.
[2] Li Jiangtao, Zhong Xu, Xue Jing, et al. All-solid-state modular MARX circuit and pulse synchronous superposition design [J]. High Power Laser and Particle Beams.

[3] Xu Le, Jiang Weihua. Research on fast front pulse power source based on avalanche transistor [j]. High Power Laser and Particle Beams, 2016, 28: 015001.

[4] Li Zi, Li Pan, Rao Junfeng. Improvement of Triode Switching Marx Pulse Shaping Circuit [J]. Journal of University of Shanghai for Science and Technology, 2016, 37 (5).

[5] Yuan Xuelin, Zhang Hongde, Xu Zhefeng, et al. Research on high repetition rate and high stability pulse source based on avalanche transistor [J]. Research and Progress of Solid State Electronics, 2010 (01): 68-72.

[6] Zhao Zheng, Zhong Xu, Li Zheng, et al. Overview of high repetition frequency and high voltage nanosecond pulse generation methods based on avalanche transistors [J]. Journal of Electrical Engineering and Technology, 2017 (08): 39-53.

[7] Li Z, Li P, Rao J, et al. Theoretical Analysis and Improvement on Pulse Generator Using BJTs as Switches[J]. IEEE Transactions on Plasma Science, 2016, PP(99):2053-2059.

[8] Rao Junfeng, Zhang Wei, Li Zi, et al. Nanosecond pulse generator with avalanche triode in series [J]. High Power Laser and Particle Beams, 2018 (9): 71-77.

[9] Zhang Yadong, Liang Buge, He Ji'ai, et al. Experimental research and implementation of enhanced MARX nanosecond pulse source based on avalanche tube [J]. Ship Electronic Engineering, 2017 (4).

[10] Jiang Weihua. High repetition frequency pulse power technology and its application: (1) Overview [j]. High power laser and particle beam (1): 16-21.

[11] Wang Ying. Research on transient electromagnetic pulse transmission characteristics and marx signal source of avalanche transistor [d]. Beijing University of Chemical Technology, 2012.

[12] Yuan Xuelin, Zhu Sitao, Fan Yajun. Study on the stability of all-solid-state pulse source based on avalanche transistors [c]. National Microwave and Millimeter Wave Conference, 2009.

[13] Wang Ji. On the Reasonable Selection of Avalanche Operation State of Avalanche Transistors [j]. Fire Control Radar Technology, 1999 (03): 20-22.

[14] Yuan Xuelin, Ding Zhenjie, Yu Jianguo, et al. High stability pulse technology based on avalanche tube Marx circuit [J]. High Power Laser and Particle Beams, 2010 (04): 63-66.