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Design of Pulse Power Supply for High-Power Semiconductor Laser Diode Arrays

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ABSTRACT This paper mainly introduces a design circuit and control method of pulse power supply for high-power semiconductor laser diode arrays. According to the high voltage and large current operating characteristics of semiconductor laser, the control strategy of multi-module cascade topology combined with multiple MOSFET connected in parallel is adopted. The topology of multi-module cascade is presented to meet the requirement of wide output voltage range. The multiple MOSFET connected in parallel in the grounding module is proposed to increase output current of the pulse power supply, and each MOSFET has exclusive closed-loop regulator. The pulse current is controlled by the gate driving voltage of the MOSFET which operates in the linear zone, which can ensure the pulse current to be smooth and stable without overshoot. Digital control and analog control are combined to make the control of the pulse power supply more flexible. An experimental platform with a pulse power of 132.3 kW is built. The parameters of pulse power supply are exhibited: pulse current 210 A, pulse voltage 630 V, pulse width 200μs, and repetition frequency 100 Hz.

INDEX TERMS Semiconductor laser, pulse power supply, multi-module cascade, linear zone.

I. INTRODUCTION

With the development of materials and technological advances, semiconductor laser has become more and more popular [1]–[3]. Semiconductor laser is mainly composed of P-N junctions, which is an ideal photon source device that converts injected electrons into photons. Semiconductor laser has many advantages, such as small size, light weight and wide light-emitting band, and has been widely used in communication, medicine, military, industry and other fields [4]–[7]. According to the output pulse power of semiconductor laser, its applications are summarized in the following aspects, as shown in Fig. 1.

High-power semiconductor laser is widely used in military defense and industrial production, especially in the laser weapons and manufacturing [8], [9]. However, the general disadvantage of high-power semiconductor laser is very expensive and fragile, and the quality of the emitted laser is greatly affected by the pulse power supply [10]–[13]. Therefore, a stable pulse power supply is extremely important for the development of high-power semiconductor laser.

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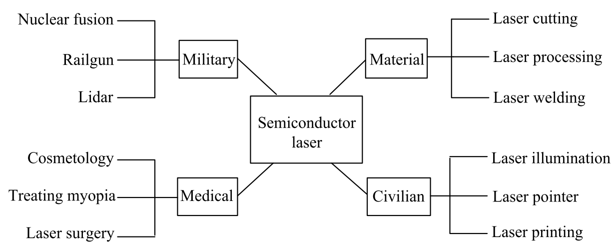

FIGURE 1. Application of semiconductor laser.

There are two operating modes of semiconductor laser: one is a continuous wave (CW), which requires the output of the semiconductor laser to be a constant current; another is a quasi-continuous wave (QCW), which is at lower duty cycle, typically 100-300μs pulse length, 1-1000Hz pulse repetition frequency, and the pulse current is smooth and stable without overshoot [14]–[16]. In this paper, the design of pulse power supply for semiconductor laser which operates in quasi-continuous wave (QCW) mode is introduced. Section II introduce the topology of the pulse power supply. In Section III the control method of pulse power supply is analyzed. Section IV show the experimental results of single

FIGURE 2. ARR179P200 feature.

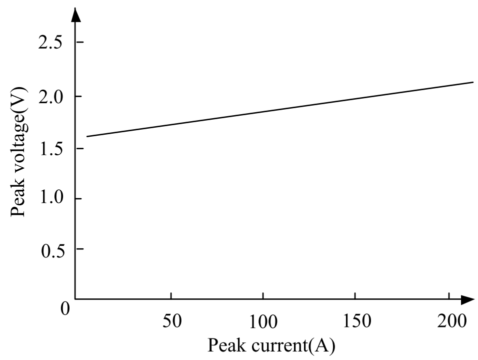

FIGURE 3. V-I characteristic curve of ARR179P200.

module and multiple-module cascade. And Section V is the summary of this paper.

II. TOPOLOGY DESIGN OF PULSE POWER SUPPLY

A. SEMICONDUCTOR LASER

Semiconductor laser is made of laser diode arrays, which has similar properties to diodes in essence. Therefore, the semiconductor laser will operate when the applied voltage exceeds its threshold voltage [17]. In this paper, a single BAR is chosen to describe the V-I characteristics of the semiconductor laser. The model number is ARR179P200 produced by Northrop Grumman corporation, and the single BAR is shown in Fig. 2 [18].

The V-I characteristic curve is shown in Fig. 3. When the applied voltage of single BAR is less than the threshold voltage of 1.6V, the single BAR does not work. When the applied voltage of the single BAR exceeds its threshold voltage of 1.6V, its input current increases rapidly.

The resistance of a single BAR is 0.002Ω. If a pulse current of 210A is generated, the amplitude of the output pulse voltage is $210 * 0.002 + 1.6 = 2.02$V. At this time, the single BAR works normally and emits laser. This experiment parameters: a 315-BAR in series is used in this design as the load of the pulsed power system and then the amplitude of output pulse voltage is over 630V; the amplitude of pulse current is 210A.

B. DESIGN OF PULSE POWER SUPPLY

According to the characteristics and requirements of semiconductor laser, a pulse power supply for high-power semiconductor laser is designed in this paper. The principle block diagram is shown in Fig. 4.

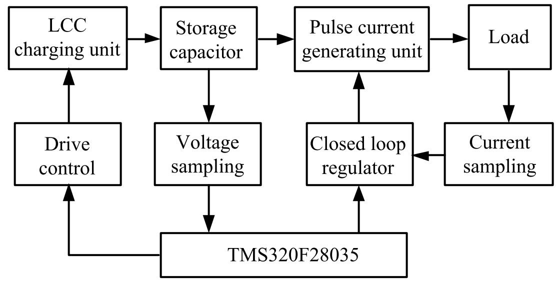

FIGURE 4. System block diagram of pulse power supply.

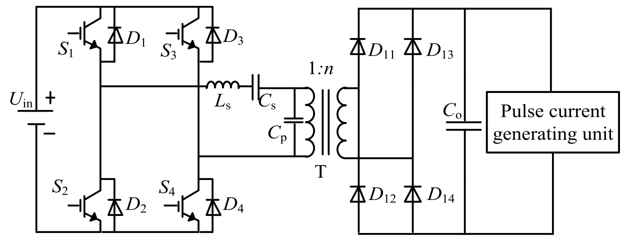

FIGURE 5. Topology of LCC resonant converter.

The pulse power supply is described in Fig. 4, which is mainly composed of LCC charging unit, storage capacitor, pulse current generating unit, DSP control unit and load. The energy of system is supplied by the charging unit. The pulse current is generated by the pulse current generating unit in the control of closed loop regulator. The DSP is used to control the LCC resonant converter to realize the charging of the storage capacitor and to control the pulse current generated by the pulse current generating unit to be smooth and stable without overshoot.

C. LCC CHARGING UNIT

LCC resonant converter topology is adopted by the charging unit, as shown in Fig. 5. The LCC resonant circuit has the characteristics of soft switching and resistance to load short-circuit and open-circuit. The function of constant current charging of the storage capacitor can be realized [19]–[21]. In that way, voltage is ensured to reach the expected voltage to provide energy for the pulse current generating unit.

In Fig. 6, u_a is the storage capacitor voltage at the end of charging. t_{pulse} is the duration of pulse current. u_b is the storage capacitor voltage after a period of discharge, and u_L is the voltage output from the pulse power supply. During the generation of the pulse current, the LCC converter stops charging the storage capacitor, and the storage capacitor voltage drops from u_a to u_b. The drain-source voltage of MOSFET must be ensured to achieve sufficient voltage at the end of the pulse discharge to make MOSFET operate in the linear zone so u_b should be slightly higher than u_L. During the interruption of the pulse discharge, the voltage of the energy storage capacitor is recharged to u_a again.

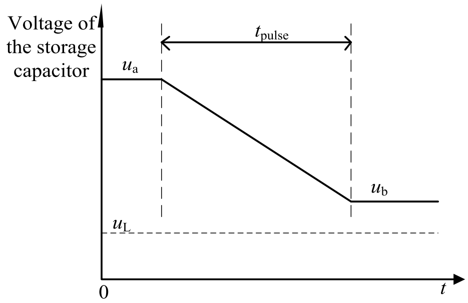

FIGURE 6. Voltage of the storage capacitor during pulse current generation.

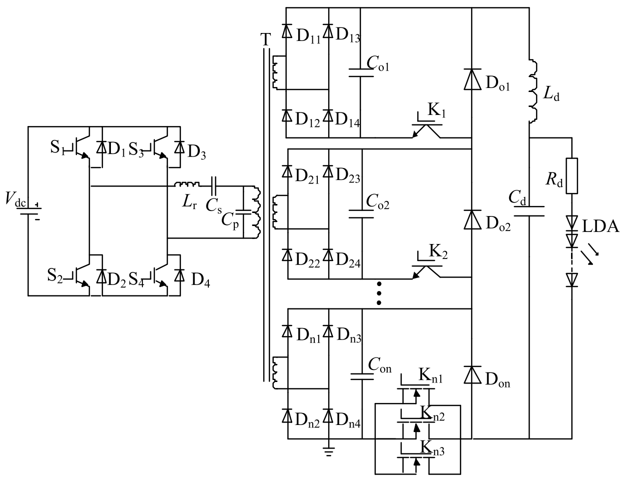

FIGURE 7. Main circuit of pulse power supply.

D. CASCADE TOPOLOGY OF PULSE POWER SUPPLY

At present, the single-module mode is adopted in the pulse power supply basically [22]. In order to improve the output voltage and power of the pulse power supply, the multi-module cascade structure is proposed, and the circuit of pulse power supply is shown in Fig. 7.

Since the power dissipation of the switch is high operating in the linear zone, only choose the switches of the grounding module to operate in the linear zone to control the total current, and the switches of remaining modules work in the switching operation mode to provide a circulating path for the current. Because the a large current flows through the switch working in the switching operation mode, the IGBT is selected as the switch working in the switching operation module, and the MOSFET connected in parallel is selected as the switch working in the linear zone.

The multiple transformer secondary side is used to meet the requirements of charging for each storage capacitor. Each module has its own power switch and freewheeling diode, and the goal of wide range voltage output is realized by controlling the on-off condition of the power switch. During the charging stage of storage capacitor, the pulse current generating unit stops working, as shown in Fig. 8.

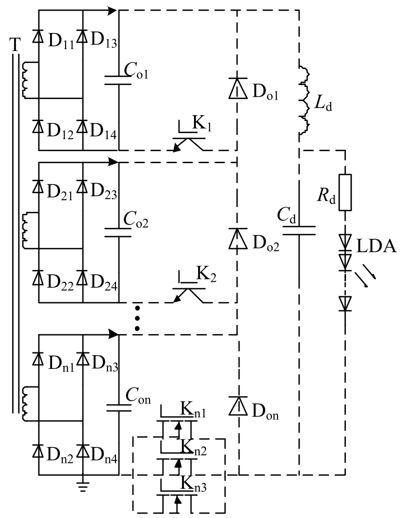

FIGURE 8. Multi-module cascade charging stage.

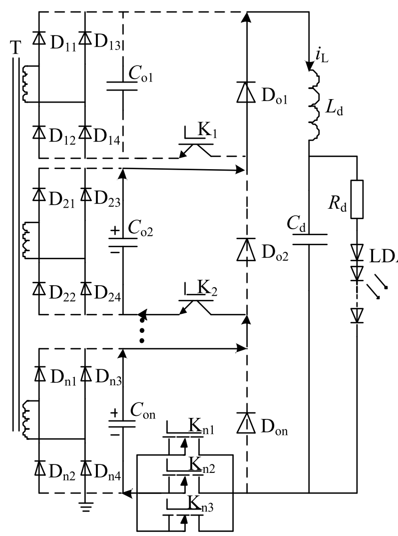

FIGURE 9. Operation mode of pulse power supply without module 1.

When the pulse current generating unit starts to work, the power switch turns on and the voltage on the load is nu_{in}, which is the sum of the capacitor voltage of n modules. The wide range of output voltage is controlled by the on-off condition of the power switch. For example, when the power switch of module 1 turns off, the module 1 does not participate in the work, and the current flows through other modules and the freewheeling diode D_{o1} to the semiconductor laser. At this time, the voltage of semiconductor laser is (n-1)u_{in}, and the voltage is reduced, as shown in Fig. 9.

E. MULTIPLE MOSFET OF THE GROUNDING MODULE WHICH CONNECTED IN PARALLEL

Withstanding current capability of single MOSFET is poor.

In order to increase the output current of pulse power supply, a method of multiple MOSFET connected in parallel which operate in the linear zone is presented in this paper.

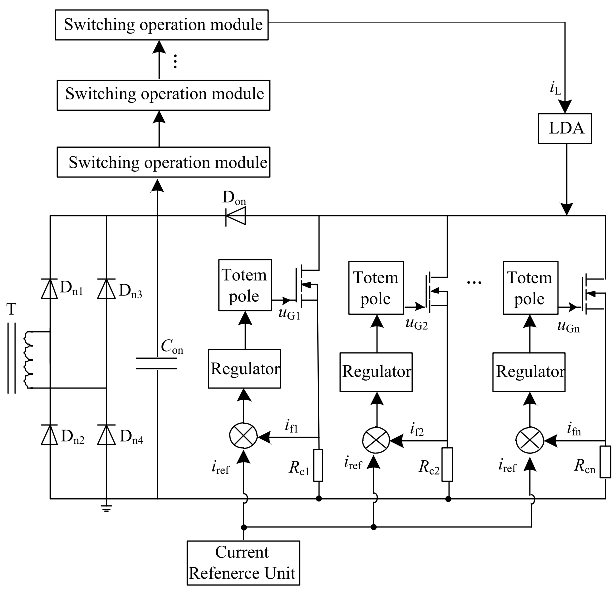

FIGURE 10. Circuit of multiple MOSFET connected in parallel.

In general, multiple MOSFET connected in parallel do not have the problem of current sharing when operating in the switching operation mode. However, the MOSFET is required to operate in the linear zone in this paper, and the drain current (the pulse current flowing through the laser diode array) of the MOSFET is controlled by the gate driving voltage of the MOSFET. Due to the transfer characteristic of each MOSFET device is different, multiple MOSFET connected in parallel directly driven by the same gate driving voltage will result in different current of each MOSFET, which will lead to the thermal damage of excessive current. Therefore, the method in which each MOSFET has a separate closed loop regulator based on the multiple MOSFET connected in parallel operating in the linear zone is proposed to solve the problem of current sharing and ensure reliable operation of the pulse power supply. The switches of the grounding module operate in the linear zone, as shown in Fig. 10. The amplitude of the pulse current reference signal i_{ref} for each MOSFET is 1/n of the pulse current i_L, that is: $i_{ref} = i_L/n$.

III. CONTROL METHOD OF PULSE POWER SUPPLY

A. VOLTAGE CONTROL OF STORAGE CAPACITOR

In order to provide sufficient energy for the pulse generating unit, it is necessary to control the voltage of storage capacitor. Since the storage capacitor has a large capacitance value and the voltage variation at the single pulse output is small, the hysteresis control method is used to control the output voltage. When the capacitance voltage at the time t_a reaches the rated value u_a, the charging is stopped. The pulse current starts to be generated at the time t_b. When the voltage drops to the specific value u_b, the charging is started (In this experiment, $u_{a-}u_b = 3V$). The control process is shown in the figure below.

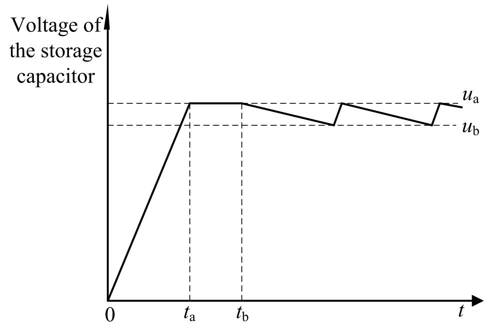

FIGURE 11. Voltage control of storage capacitor.

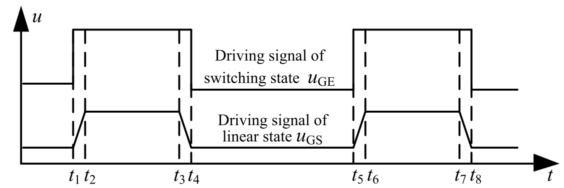

FIGURE 12. Driving signal of switch in different state.

B. PULSE CURRENT GENERATING UNIT

Pulse driving circuit is driven by a pulse signal with definite amplitude and width, which can be adjusted by the parameters of the pulse current generating unit. The waveform of pulse current is required in this paper: the top to be smooth and no overshoot and no oscillation. The rising edge is steep and required to be within $20\mu s$. Therefore, the MOSFET operating in the linear zone is selected as the power switch to control the waveform of the pulse current.

The topology of multi-module cascade is applied in the pulse power supply, and each module has its own power switch and freewheeling diode. The driving signals of the switches are shown in Fig. 12.

At t_1, the switches working in the switching operation mode turn on instantaneously. The semiconductor laser does not emit laser, because the total capacitor voltage of *(n-1)* modules is less than the threshold voltage of the semiconductor laser. During the period of t_1 to t_2, the switch operating in the linear zone turns on in the control of the closed loop regulator. There is a certain linear relationship between the gate driving voltage u_{GS} and the drain current i_D after the gate driving voltage u_{GS} exceeds the threshold voltage of the MOSFET. The drain current i_D (the pulse current i_L flowing through the laser diode array) of the MOSFET is controlled by the gate driving voltage u_{GS} of the MOSFET which operates in the linear zone, and u_{GS} of the MOSFET is controlled by the pulse current generating unit, as shown in Fig. 13. In this period, the sum voltage of the multi-module capacitor exceeds the threshold voltage of the semiconductor laser, and the semiconductor laser turns on.

The working process is as follows: the pulse current reference signal i_{ref} is generated by the current reference unit at first. In the control of the closed loop regulator, the gate driving voltage u_{GS} of MOSFET is increased gradually.

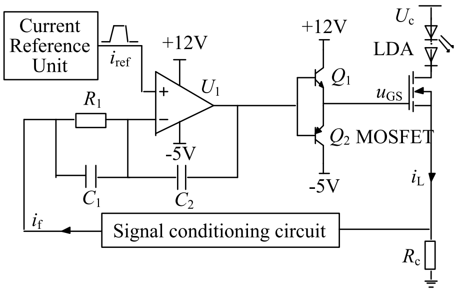

FIGURE 13. Circuit of pulse current generating unit.

TABLE 1. Equipment used in experiments.

Equipment	Parameter
digital phosphorus oscilloscope	200Mhz
high voltage differential probe	1300V
current probe	150A
high-power DC power supply	500V/30A
auxiliary power supply	±12V,5V

When the u_{GS} is increased to the threshold voltage of MOSFET, the MOSFET turns on and operates in the linear zone. The pulse current i_L will follow the i_{ref} immediately in accordance with the required slope of the i_{ref}. As the u_{GS} of the MOSFET is increased gradually, the i_L is increased to the set point gradually and remains stable in the control of the closed loop regulator, then the semiconductor laser emits laser. When the i_{ref} begins to fall, the u_{GS} of MOSFET is decreased in the control of the closed loop regulator, and the i_L drops to zero quickly, then the semiconductor laser turns off. One pulse period is terminated.

IV. EXPERIMENTS ANALYSIS

The equipment used in the pulse experiment is shown in Table I. The oscilloscope, voltage probe, and current probe are used to measure the experimental waveform; the high-power DC power supply is the power supply for the LCC resonant converter; the auxiliary power supply supplies power to the DSP and the operating amplifier of the pulse discharge circuit. In this paper, IXFK80N50P of IXYS Company is selected as the switch working in linear zone and SKM100GB12V of Semikron International is selected as the switch working in the switching operation mode.EWF109M2GX1RD5SM-Y of SAMXON is selected as the storage capacitor and two capacitors are connected in parallel with a capacitance value of 20000μF.

A. SINGLE-MODULE EXPERIMENT

The experimental platform of single-module pulse power supply is shown in Fig.14. Firstly, the single grounding module with one MOSFET pulse discharge unit is verified by experiment, and the specific experimental parameters are shown in Table II. Due to the limitation of laboratory condition, the semiconductor laser is replaced by a 3Ω resistance.

The output voltage of the pulse power supply is 210V. 10V-additional voltage ensures that the MOSFET works in

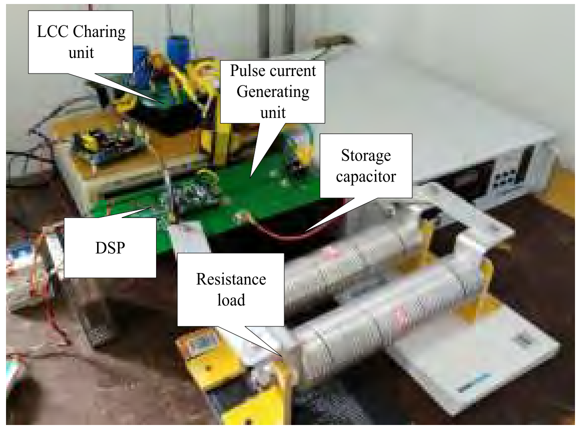

FIGURE 14. Photograph of single-module platform.

TABLE 2. Parameters of single module.

Parameter	Typical	Units
pulse current reference signal	2.73	V
pulse width	200	μs
pulse frequency	100	Hz
pulse current	70	A
pulse voltage	210	V
t_r of pulse current	7.72	μs
pulse power	14.7	kW

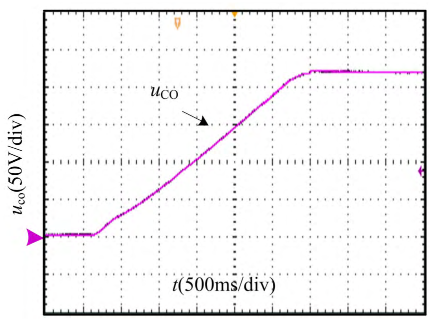

FIGURE 15. Experimental waveform of single module charging.

the linear zone and there is enough voltage to offset the voltage drop when pulse current is generated by the pulse current generating unit. Therefore, the storage capacitor is set to a charging voltage of 220V and its charging waveform is shown in Fig. 15. The capacitor voltage rises linearly, and the LCC resonant converter has good constant current characteristics for the capacitive load charging.

When the charging is stopped, the pulse current reference signal I_{ref} is generated by the current reference unit in the DSP, and the pulse discharge unit starts generating the pulse current. In the following experiments, the pulse current i_L of 1A corresponds to the pulse current reference signal i_{ref} of 0.039V. When the i_L is set to be 70A, the i_{ref} is $70 * 0.039 = 2.73$V. When the storage capacitor voltage drops to a certain value (this experiment is set to 217V), the LCC resonant converter recharges the storage capacitor voltage to the set value of 220V.

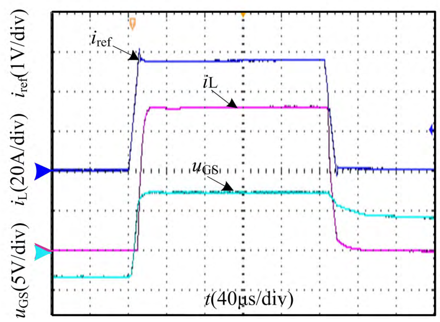

FIGURE 16. Experimental waveform of 70A pulse current.

TABLE 3. Parameters of two-module cascade.

Parameter	Typical	Units
pulse current reference signal	2.73	V
pulse width	200	μs
pulse frequency	100	Hz
pulse current	210(70*3)	A
pulse voltage	630	V
t_r of pulse current	7.72	μs
pulse power	132.3	kW

The experimental waveform is shown in Fig. 16.

It can be seen from Fig. 16 that the rising edge of the pulse current reference signal i_{ref} is steep, and the amplitude is 2.73V in the steady state. In the control of the closed loop regulator, the u_{GS} of the MOSFET is increased rapidly, then the MOSFET operates in the linear zone with the amplitude of 7.2V. The pulse current i_L is increased to 70A gradually in the control of the closed loop regulator. When semiconductor laser emits laser, the i_L is smooth and stable, moreover, there is basically no overshoot. The rising edge of i_L is within 10μs, and the pulse width is 200μs, which meets the requirements of parameter design.

B. TWO-MODULE CASCADE EXPERIMENT

In this paper, the topology of two-module cascade is tested. The experimental parameters are shown in Table III. The two-module pulse power supply experimental platform is shown in Fig. 17. Due to the limitation of laboratory condition, we use a 3Ω resistor to verify the pulse current at 210A, when the voltage level is 630V. It can be equivalent to a 315-BAR in series, which is used as the load of the pulsed power system.

Firstly, the charging experiment is carried out. The multiple transformer secondary side is used to meet the requirements of charging for each storage capacitor. At the same time, the storage capacitors of the two-module are charged and each capacitor is charged to 320V. The total voltage of the two modules is 640V. The output voltage of the two-module cascade experiment is 630V. 10V-additional voltage ensures that the MOSFET works in the linear zone and there is enough voltage to offset the voltage drop when pulse current is generated by the pulse current generating unit. The charge

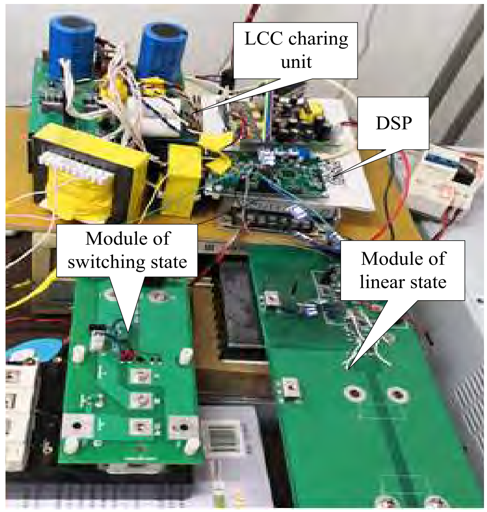

FIGURE 17. Photograph of two-module platform.

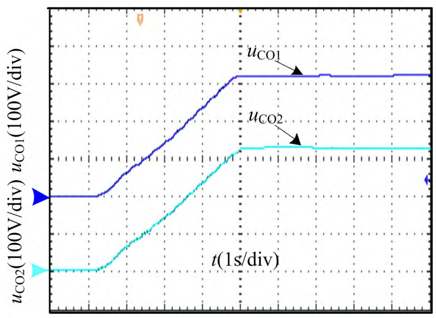

FIGURE 18. Experimental waveform of two-module charging.

voltage waveform is shown in Fig. 18, and the linear rise of two capacitor voltages can be observed.

When the charging is stopped, the pulse current reference signal i_{ref} is generated by the current reference unit in the DSP and the pulse discharge unit starts generating the pulse current. The switch of the ungrounding module works in the switching operation mode and the switch of the grounding module operates in the linear zone. In this paper, IXFK80N50P of IXYS Company is selected as the switch working in linear zone. The MOSFET can withstand a continuous maximum current of 80A at 25 degrees Celsius, but the pulse current is 210A. By parallelling the connection of three MOSFET, the output current capability of the pulse power supply can be improved and the loss of each MOSFET can be reduced. When the i_L is set to be 210A, the i_{ref} is $1/3 * 210 * 0.039 = 2.73$V.

The topology of two-module cascade is applied in the pulse power supply. The driving signal of the IGBT and pulse current reference signal i_{ref} are shown in Fig. 19. In the two-module cascade experiment, the IGBT turns on and operates in the switching operation mode firstly. The MOSFET turns on gradually in the control of the closed loop regulator and operates in the linear zone to control the pulse current.

Due to the limitation of laboratory measurement equipment, 210A pulse current can not be measured, so the pulse

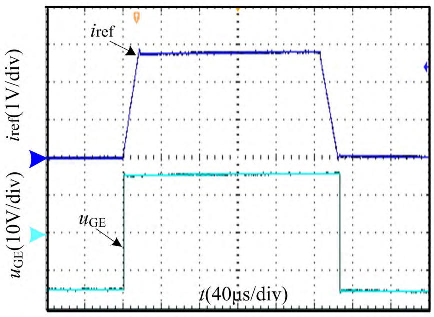

FIGURE 19. Pulse current reference signal of MOSFET and driving signal of IGBT.

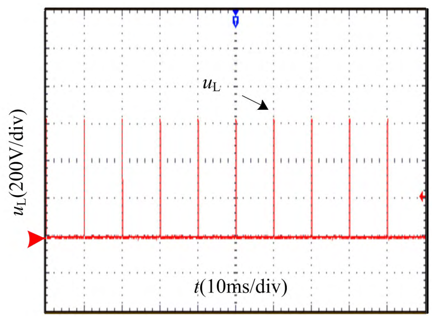

FIGURE 20. Period waveform of pulse current.

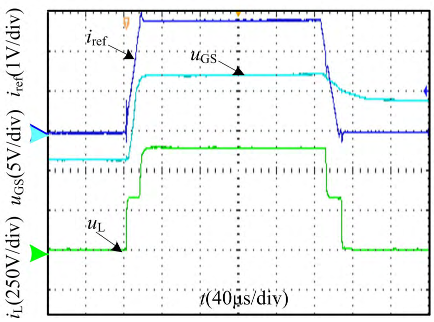

FIGURE 21. Experimental waveform of 210A pulse current.

current is replaced by measuring the pulse voltage. The period waveform of pulse current is shown in Fig. 20. The output pulse current period is 10ms, the pulse width is 200us, and the pulse voltage amplitude is 630V.

As shown in Fig. 21, the rising process of i_{ref} is steep, and the amplitude is 2.73V in the stable state. In the control of the closed loop regulator, the u_{GS} of the MOSFET is increased rapidly, and then the MOSFET operates in the linear zone with the amplitude of 7.2V. During the rising process of i_{ref}, the pulse current i_L is increased to 210A in accordance with the required slope of i_{ref} without overshoot. The rising edge of pulse current is within 20μs, the pulse width is 200μs, and the pulse power can reach 132.3kW, which satisfies the actual demand. Due to a 3Ω resistance is used as the experimental load, the ladder phenomenon will occur during the rising process of pulse current in cascade circuit. However, if the semiconductor laser is used, the cascade voltage is lower than the threshold voltage of the semiconductor laser when the switches turn on which operate in the switching operation mode in the cascade circuit. At this time, the semiconductor laser does not emit laser and the pulse current is zero. When the switches turn on which operate in the linear zone, the pulse current will be increased rapidly, and the ladder phenomenon will be eliminated.

V. CONCLUSION

In this paper, the design of pulse power supply for semiconductor laser is introduced. The output voltage range and power are increased by the multi-module cascade structure, and the output current of the pulse power supply is increased by multiple MOSFET connected in parallel. The pulse current of smooth and stable is achieved by the MOSFET which operates in the linear zone and controlled by the closed loop regulator. Finally, the single-module experiment and the two-module cascade experiment are completed. The experimental requirements of 630V pulse voltage and 210A pulse current are achieved. The feasibility of multi-module cascade topology combined with multiple MOSFET connected in parallel is verified, and the PID parameter setting of closed loop regulator is reasonable.

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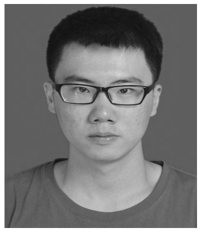

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