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Pulse Power Supply for High-Power Semiconductor Laser Diode Arrays With Micro-Current Pre-Start Control

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ABSTRACT This paper mainly introduces a pulse power supply for high-power semiconductor laser diode arrays with a novel micro-current pre-start control method. According to the operating characteristics of the semiconductor laser, the output current of the pulse power supply is required to be smooth, stable, and without overshoot. In the method of normal direct pulse start control, semiconductor laser is damaged easily by the overshoot and oscillation of pulse current caused by the switching threshold voltage of MOSFET. And the time delay between the current reference signal and the output pulse current makes the design of closed loop more complicated. Based on the above problems, the method of micro-current pre-start control is proposed. The method is simple to operate and it can solve the nonlinear problem of MOSFET caused by the switching threshold voltage. Therefore, it solve the problems of time delay between the current reference signal and the output pulse current and the overshoot and oscillation of output pulse current in the rising process. A 25.6-kW prototype is intended for verifying the effectiveness of the micro-current pre-start control.

INDEX TERMS Semiconductor laser, micro-current pre-start control, pulse control, threshold voltage.

I. INTRODUCTION

With the development of the laser industry, high-power semiconductor laser arrays have been widely used in the military field, especially in the fields of laser weapons, laser guidance, and laser radar, which have also raised the demand of pulse power supply. High-power semiconductor laser arrays require high-power pulse power supply to generate high energy light pulse [1], [2]. Not only do the output voltage of the pulse power supply is required to be high enough and the pulse current to be large enough, but also a similar rectangular of pulse current waveform is required. Special parameters of pulse current are as follows: the top to be smooth and no overshoot and oscillation occur. The rising edge is steep and a short time is required to be within 20 μs [3]–[5]. In the pulsed power system, when the voltage-controlled device is used, overshoot and oscillation occur normally at the step of pulse current due to the nonlinear of switch caused by the switching threshold voltage. A large overshoot of pulse current will damage the semiconductor laser [6]–[8]. In addition, there is an inevitable time delay between the step reference of current and the real output, so there is a complicated control process during the rising of pulse current. Therefore, a novel method of micro-current pre-start control is proposed to suppress overshoot and oscillation caused by the time delay between the current reference signal and the pulse current during the rising process of pulse current.

In this paper, the principle and working process of the micro-current pre-start control are described, and comparison between the proposed method and conventional direct pulse start control is made in detail. Finally, the validity of the micro-current pre-start control is verified by experiment data.

II. PULSE CURRENT SOURCE TOPOLOGIES

A traditional topology for the generation of high current pulses is a pulse forming network (PFN) which is charged at constant current in the inter-pulse period and discharged to the pump diode via an output switch. In practice, the following solutions for energy storage and pulse shaping for laser diode drive are applied or reported [9]:

1) Magnetic storage in an inductor with shunt switch
2) E-type pulse forming network
3) Synthetic pulse forming network
4) Big capacitor with series switch

5) Capacitor with linear current control
6) Buck Current Source

A. INDUCTIVE STORAGE

A PWM switch mode step-down regulator drives a continuous DC current through inductor L in the Fig. 1. The shunt output switch S_2 is closed when no energy is transferred to the laser diodes, that means the current circulates in the free-wheeling loop L, S_2 and D. When opening S_2, the inductor current commutates into the laser diodes. The diodes figure a damping load in series with the inductor and force the current to decline rapidly.

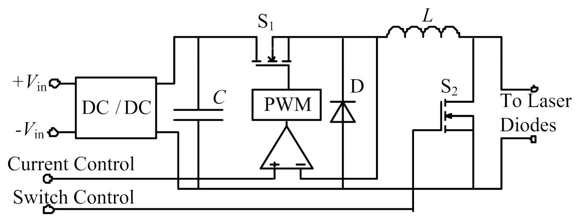

FIGURE 1. Block diagram of inductive store with shunt switch.

The drawback of this approach is the energy density of inductive components is much lower than of capacitors. The inductor is expected to have a mass of several kilograms which is not acceptable.

B. E-TYPE PULSE FORMING NETWORK

The PFN is charged to twice the required load voltage in the Fig. 2. Its impedance is matched to the load impedance. When switched to the load, the PFN is discharged by an almost trapezoidal current pulse. The quality of the pulse shape can be influenced by the number of LC meshes in the PFN.

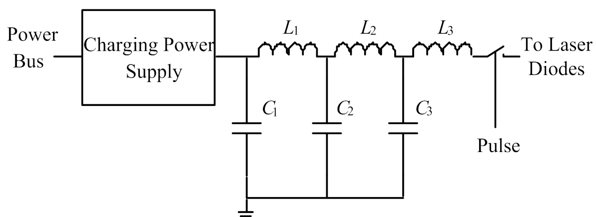

FIGURE 2. Principle of E-type PFN.

The drawback of this solution is the mass of the inductor assembly that is about 600-700 g for the requirements.

C. SYNTHETIC PFN

To save inductor mass, the PFN can be separated into many single *LC* meshes in a parallel configuration which are sequentially switched to the load in the Fig. 3.

The drawback is predominant: high number of switches, current control loops.

D. BIG CAPACITOR WITH SWITCH

The simplest driver concept is a charged capacitor which is switched to the load via a semiconductor switch as shown

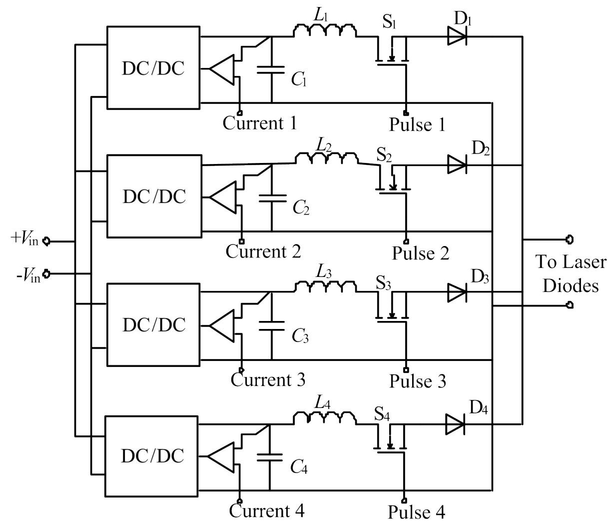

FIGURE 3. Principle of synthetic PFN.

in Fig. 4. The capacitance must be oversized in order to guarantee the ±5 % current tolerance during the pulse. current amplitude can be controlled by the capacitor's charge voltage.

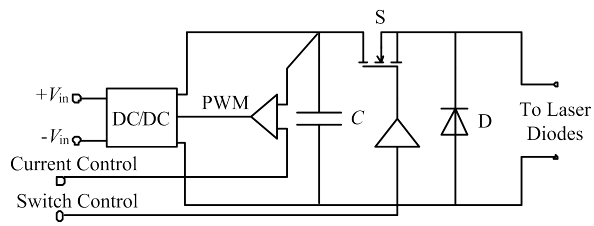

FIGURE 4. Capacitor with switch source.

The principal problem is that the load characteristic is predominantly a constant voltage source. In-pulse current decays rapidly because it is only driven by the voltage difference between capacitor *C* and the load.

E. CAPACITOR WITH LINEAR CURRENT REGULATOR

A means to reduce the size of the capacitor is a linear, dissipative current controller as shown in Fig. 5. It delivers constant current to the diode load. The voltage difference between capacitor *C* and the load is dissipated in the MOSFET *S* which is operated in its saturation.

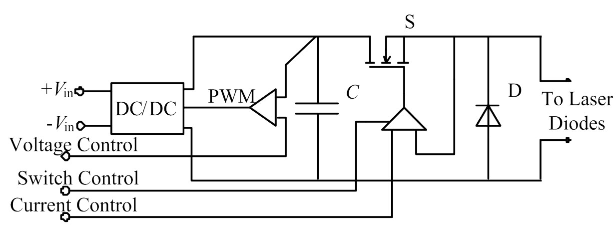

FIGURE 5. Capacitor with linear current regulator.

The benefit of this approach is the lack of a heavy inductor, at the price of obviously high losses.

F. BUCK CURRENT SOURCE

Constant pulse current from a small storage capacitor basically can be generated with good efficiency when using a buck regulator as shown in Fig. 6. This concept allows a higher voltage droop at the storage capacitor C, thus reducing its capacitance.

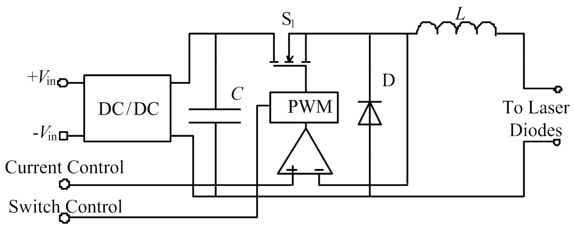

FIGURE 6. Buck current source.

The drawbacks of this solution are switching losses and possibly EMI.

In summary, although the specific experimental waveform is not given, the rising edge of the pulse waveform using the inductor as the output of the energy storage component is longer and relatively flat, and cannot meet the rapidity of the pulse. The topology of capacitor with linear current regulator is used in the paper to fulfill the rapidity, and the micro-current pre-start control is added to reduce oscillation and overshoot.

G. PRINCIPLE OF MICRO-CURRENT PRE-START CONTROL

In the system of pulse power supply, the combination of linear MOSFET and closed loop control is used. During the rising process, the pulse current is required to follow the pulse current reference signal immediately and there is no overshoot and oscillation. Due to the presence of the threshold voltage of MOSFET, the MOSFET will have a non-linear region during the rising process of gate voltage. At this time, the pulse current reference signal will continue to increase and there is no pulse current flowing through the laser bar. After the MOSFET reaches the threshold voltage and operates as a linear amplifier, the amount of error between the pulse current and the pulse current reference signal has accumulated greatly, and the pulse current lags the pulse current reference signal. So it makes the pulse current following features worse and also has overshoot and oscillation during the rising process. The rising process of pulse current depends on the parameters of closed loop control, and the nonlinearity of the MOSFET and the laser bar makes the design of closed loop more complicated. So the micro-current pre-start control method is proposed, the core of which is to eliminate the nonlinearity of the MOSFET. Specific implementation method: an advanced reference of micro-current signal is generated at first to make the MOSFET operate as a linear amplifier before the normal rising edge of current reference signal is produced. Then the pulse current reference signal is produced, and makes the pulse current follow the pulse current reference signal immediately and without overshoot and oscillation. Meanwhile, the MOSFET operates as a linear amplifier and it makes the design of closed loop more easily. The input admittance of MOSFET is shown in Fig. 7.

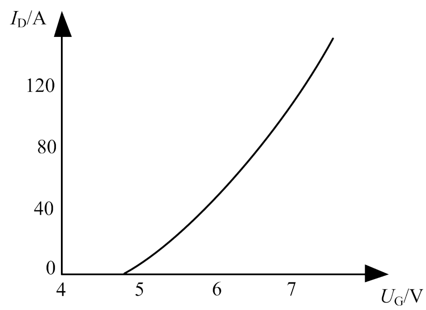

FIGURE 7. Input admittance of MOSFET.

The method of micro-current pre-start control based on the system of pulse power supply [10]–[13], is shown in Fig. 8. The input voltage source U_{in} provides energy for the semiconductor laser. A parallel free-wheel diode D provides a freewheel path for Laser Diode Bar when the MOSFET is turned off. Reference signal i_{ref} of output pulse required by the semiconductor laser is generated by the Current Reference Unit. The closed loop regulator is responsible for the control of the amplitude and shape of pulse current. Current detecting resistor R_c samples the output of pulse current i_L of the semiconductor laser and then put it back as a feedback i_f to the closed loop regulator. The i_f is the same as current i_L, with an amplitude of 0.003 times of $i_{L.}$

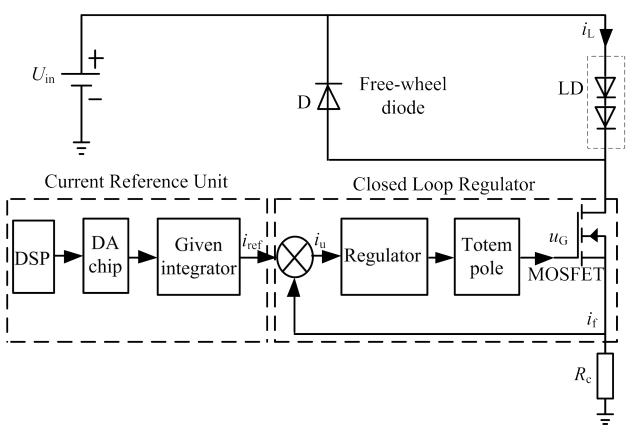

FIGURE 8. The micro-current pre-start control is based the system of pulse power supply.

The working process is as follows: an advanced reference of micro-current signal is generated at first before the normal rising edge of current reference signal is produced. In the function of the closed loop regulator, the gate driving voltage of MOSFET is increased to the switching threshold voltage, and makes the MOSFET operate in the saturation in which the MOSFET works as a linear amplifier. Meanwhile, a micro-current is generated flowing through the semiconductor laser which ensured that the micro-current is below the threshold current of the semiconductor laser. So there is no laser emitting in the process. Since there is a given integrator in the current reference unit, the pulse current reference signal would be adjusted to be a linear signal with a certain slope from a step signal. After the micro-current is stable, the current reference unit generates the rated pulse current reference signal, and controls the current of semiconductor laser to rise to the rated current value. The pulse current of the semiconductor laser will follow the pulse current reference signal immediately in accordance with the required slope of the rated pulse current reference signal, thereby overcoming the nonlinear caused by the threshold voltage of the voltage-controlled device. In the circumstance of micro-current pre-start control, the semiconductor laser does not emit laser, so there is no influence on the normal operation of the semiconductor laser.

In conclusion, the proposed method of micro-current pre-start control can solve the problems of overshoot and oscillation that occur during the rising process of pulse current, depending on the elimination of the delay between the pulse current reference and practical output one, and it makes it simple to design the parameters of closed loop regulator.

III. COMPARED THE METHOD OF DIRECT PULSE START CONTROL WITH MICRO-CURRENT PRE-START CONTROL

The P-I characteristic curve of the semiconductor laser describes the relationship between the output optical power and the input excitation current, which is of great significance to the application of pulse power supply. In this paper, a single BAR is chosen to describe the P-I characteristics of the laser. The model number is ARR179P200 produced by Northrop Grumman corporation, and the single BAR is shown in Fig. 9.

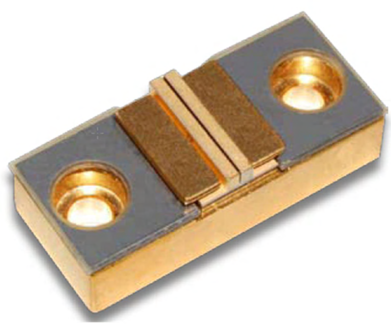

FIGURE 9. ARR179P200 feature.

Operating characteristics of ARR179P200 is shown in Table I.

This experiment parameters: a 160-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 320V; the amplitude of pulse current is 80A.

TABLE 1. Units for ARR179P200.

Parameter	Typical	Units
QCW power output	200	W
operating current	175	A
threshold current	15	A
center wavelength	808	nm
series resistance	0.002	Ω
operating voltage	2.0	V

The P-I characteristic curve of single BAR is shown in Fig. 10 that there is a certain linear relationship between the injected current and the output optical power after the injected current exceeds the threshold current I_{th}. As the injection current increases, the output optical power increases accordingly. Therefore, the intensity of the output optical power can be controlled by adjusting the injected current, and the threshold current of different semiconductor laser is different.

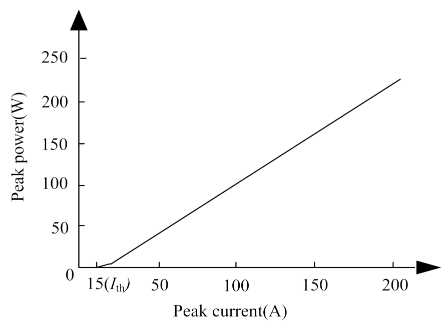

FIGURE 10. P-I characteristic curve of a single BAR, the I_{th} is used for the method of micro-current pre-start control.

A. METHOD OF DIRECT PULSE START CONTROL

As shown in the Fig. 11, i_{ref} is the pulse current reference signal. u_G is the gate driving voltage of MOSFET and U_{th} is the switching threshold voltage. i_L is the pulse current of semiconductor laser and i_f is the feedback signal of pulse current. The rated amplitude of the pulse current reference signal is I_{ref1}, and the corresponding gate driving voltage of MOSFET is U_{G1}, then the pulse current is I_{L1}. Based on the pulsed power system, the relationship between the i_{ref}, i_L, and u_G is shown correspondingly in Fig. 11.

$[t_0, t_1]$: The pulsed power system is initial.

$[t_1, t_2]$: At t_1, the current reference unit generates i_{ref}, and i_{ref} rises linearly from zero. In the function of the closed loop regulator, the u_G of the MOSFET is increased. During this period, u_G is below the U_{th} of the MOSFET, so the MOSFET is closed all alone and there is no current flowing through the load.

$[t_2, t_3]$: At t_2, u_G is increased to U_{th}, then the MOSFET turns on and operates in the saturation in which the MOSFET works as a linear amplifier. Meanwhile, i_L begins to increase,

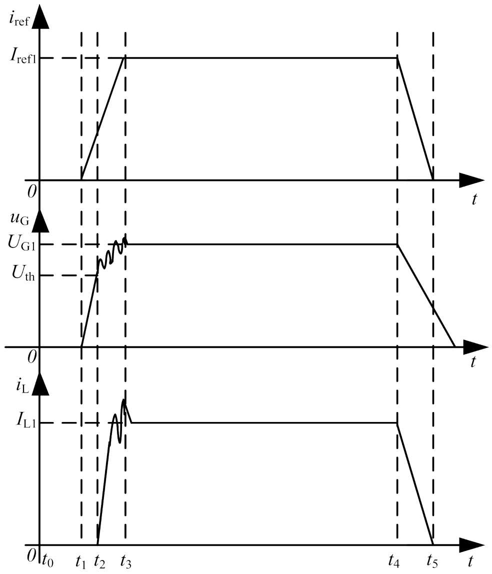

FIGURE 11. **Oscillogram of direct pulse start control.**

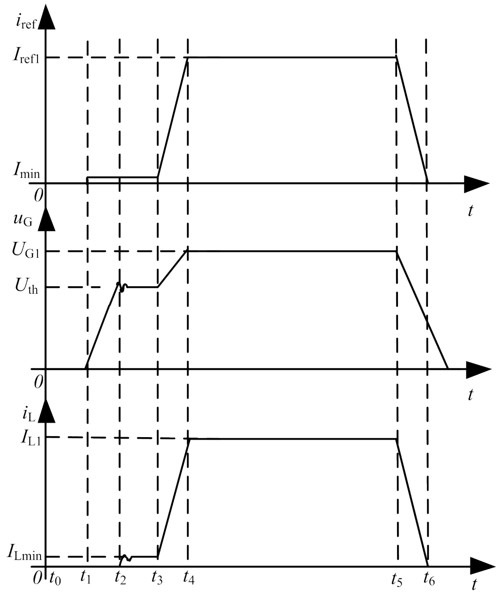

FIGURE 12. **Oscillogram of micro-current pre-start control.**

and i_{ref} is much larger than the i_f. So u_G will increase rapidly in the function of the closed loop regulator, causing i_L to increase rapidly. After this process, the rising slope of i_L is already much higher than the i_{ref}, therefore an overshoot of i_L will be inevitable when the i_L follows the i_{ref} rapidly. Due to the closed loop regulator, the u_G also fluctuates during the rising process, so that the i_L oscillates. At t_3, i_{ref} increases to the I_{ref1} and the i_L increases to the I_{L1}.

[t_3, t_4]: During this process, the i_{ref} is stabilized at I_{ref1}, and the i_L is stabilized at I_{L1} in the function of the closed loop regulator, then the semiconductor laser emits laser.

[t_4, t_5]: At t_4, the i_{ref} begins to fall, and the u_G is decreased in the function of the closed loop regulator. When the u_G is below the U_{th}, the MOSFET turns off, and the i_L declines to to zero quickly, then one pulse period is terminated.

As shown in Fig. 11, the i_L has a time delay with respect to the i_{ref} during the rising process of i_L, which will cause the i_L to oscillate during the rising process, and the i_L will overshoot when the i_L increases to the I_{L1}. A large overshoot and oscillation of i_L may damage the semiconductor laser.

B. METHOD OF MICRO-CURRENT PRE-START CONTROL

In order to clear the problems of direct pulse start control, the method of micro-current pre-start control was proposed in this paper. The relationship between the i_{ref}, i_L, and u_G is shown correspondingly in Fig. 12. As shown in the Fig. 12, the pre-start micro-current of i_{ref} is I_{min}, corresponding to the i_L is I_{Lmin}, and the I_{Lmin} is ensured to be below the I_{th} of the semiconductor laser.

[t_0, t_1]: The pulsed power system is initial.

[t_1, t_2]: At t_1, the current reference unit generates i_{ref}, and I_{min} is generated in advance. In the function of the closed loop regulator, the u_G amplitude sharply rises. During this period, u_G is below the U_{th} of the MOSFET all alone, so the MOSFET turns off and there is no current flowing through the Laser Diode.

[t_2, t_3]: At t_2, u_G is increased to U_{th}, then the MOSFET turns on and operates in the saturation in which the MOSFET works as a linear amplifier. Meanwhile, the i_L begins to increase to the I_{Lmin}. There will also be small oscillation during this period, but the value of I_{Lmin} is below the I_{th} of the semiconductor laser, so there is no influence on the output of the semiconductor laser. During this period, the i_{ref} is stabilized at I_{min} and the $u_G$is stabilized at U_{th}. The i_L is stabilized at I_{Lmin}, and the Laser Diode does not emit laser.

[t_3, t_4]: After the micro-current signal is stabilized, the i_{ref} begins to approach the rated pulse current reference signal from I_{min} linearly. Since the MOSFET has operated in the saturation in which the MOSFET has worked as a linear amplifier, the i_L will follow the i_{ref} immediately in the function of the closed loop regulator without overshoot. At t_4, the i_{ref} increases to I_{ref1} and the u_G is increased to U_{G1}, and i_L follows the i_{ref} to increase to I_{L1} then remains stable.

[t_4, t_5]: The i_{ref} is stabilized at I_{ref1} and the i_L is stabilized at I_{L1} in the function of the closed loop regulator, then the semiconductor laser emits laser.

[t_5, t_6]: At t_5, the i_{ref} begins to fall, and the u_G is decreased in the function of the closed loop regulator. When the u_G is below the U_{th}, the MOSFET turns off, and the i_L declines to zero quickly, then one pulse period is terminated.

As shown in Fig. 12, before the rated current reference signal is generated, the MOSFET has worked in the saturation, which solves the nonlinear problem caused by the switching threshold voltage. During the period of t_3 to t_4, the i_L can follow the i_{ref} immediately. Therefore, the method of micro-current pre-start control can solve the overshoot and oscillation that occur during the rising process of pulse current, depending on the elimination of the delay between the pulse current reference signal and practical output one, and it makes it simple to design the parameters of closed loop regulator.

IV. EXPERIMENTS ANALYSIS

Design a circuit of pulse power supply, as shown in Fig. 13.

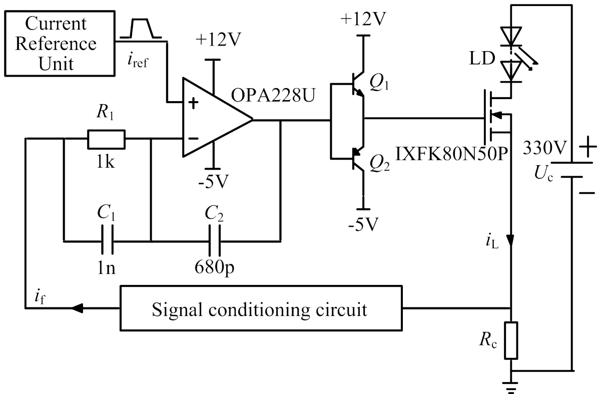

FIGURE 13. Schematic of pulse power supply.

In order to verify the validity of the method of micro-current pre-start control, the experiment platform is set up based on the Fig. 13 and the specific experiment parameters are shown in Table II.

TABLE 2. Parameters of pulse power supply.

Parameter	Typical	Units
pulse current reference signal	80	A
pulse width	200	μs
pulse frequency	100	Hz
pulse current	80	A
pulse voltage	320	V
t_r of pulse current	16.32	μs
pulse power	25.6	kW

Experiment in the direct pulse start control, and the experiment waveforms are shown in Fig. 14.

As shown in Fig. 14, in the situation of direct pulse start control, the rising process of i_{ref} is steep, and the amplitude is 80A in the steady state. In the function of closed loop regulator, u_G is increased rapidly, then the MOSFET operates in the saturation with the amplitude of 7.2V. During the rising process of i_L, the semiconductor laser would be damaged by the overshoot of 8A. And i_L has a certain delay with respect to the i_{ref}, eventually it is stabilized at 80A.

Experiment in the micro-current pre-start control, and the experiment waveforms are shown in Fig. 15.

As shown in Fig. 15, I_{min} of 6A is generated in advance, and in the function of the closed loop regulator, u_G is increased to the U_{th} of 5.4V gradually. So the MOSFET operates in the saturation and the I_{Lmin} is 6A. After the micro-current is stable, the rated pulse reference signal of 80A is generated,

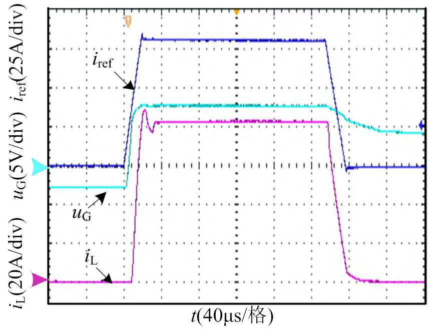

FIGURE 14. Experiment waveforms of direct pulse start control.

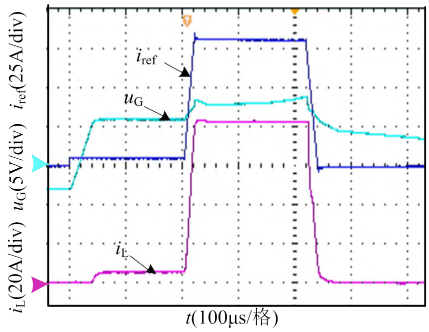

FIGURE 15. Experiment waveforms of micro-current pre-start control.

and the u_G is increased to 7.2V gradually, then the i_L is increased to 80A in accordance with the required slope of i_{ref}. There is no overshoot and oscillation in the rising process of the i_L, and there is no time delay between the i_{ref} and the i_L.

According to the experiment results, a comparison is made between the direct pulse start control and the micro-current pre-start control. Above all, in the situation of micro-current pre-start control, the MOSFET has worked in the saturation before the rated current reference signal is generated, which solves the nonlinear problem caused by the switching threshold voltage. And it rejects the overshoot and oscillation that may occur during the rising process of pulse current, depending on the elimination of the delay between the pulse current reference signal and the pulse current of semiconductor laser.

V. CONCLUSION

Aiming at the problem that the semiconductor laser will be damaged easily by the overshoot and oscillation of the pulse current in the method of normal direct pulse start control, the method of micro-current pre-start control is proposed. In the method of micro-current pre-start control, the MOSFET works in the micro-saturation from the cut-off zone in advance to prepare for the rising process of the pulse current, then the saturation depth of the control loop is reduced and makes it easier to reduce the overshoot under the rated pulse current reference signal and oscillation of the pulse current. In addition, the feasibility of micro-current pre-start control is verified through experiments and it is simple and suitable for the all pulsed power systems. As for the power dissipation in the MOSFET, the MOSFET operates in the saturation and its power dissipation is much larger than that in the switching region. So limit the power dissipation in the reliable region, and the power dissipation of micro-current can be neglected.

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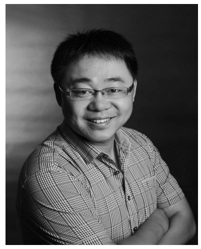

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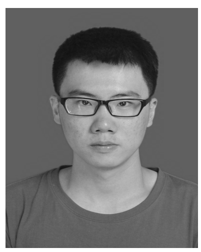

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