Design and Implementation of High Power Pulse Constant Current Source

Weitong Miao, Jun Huang*, Haitao Chen, Yuchen Wang
Shanghai Institute of space power, Shanghai, China

*Corresponding author: junhuang@sast.cn

Abstract. According to the requirement of the semiconductor laser for driving power supply, aiming at the problem of how to produce the current pulse with high amplitude, short pulse width and high stability on the low impedance load, a method of realizing the constant current output of the pulse by using the combination of the buck transform circuit and the linear regulation module is proposed. The Buck circuit is hysteresis controlled to control the storage capacitance voltage, and then the MOSFET working in the linear region is adjusted by the PI module to ensure constant current output on the load. The key factors affecting the output pulse amplitude, pulse width, front and back edge parameters are also analyzed and verified by experiments. The results of 170V DC power supply show that the circuit designed in this paper can output 30A, 250us pulse width and rise time less than 10us pulse constant current output on 5Ω low impedance load.

1. Preface
Semiconductor laser has many advantages, such as wide wavelength range, small volume, light weight, simple structure, long life, easy modulation and so on. It plays an important role in production, life and military application, such as laser drilling and cutting, optical fiber communication, laser micro processing, semiconductor laser ranging, semiconductor laser radar, semiconductor laser guidance, etc. [1] Although the structure of semiconductor laser is various, its working principle can be regarded as an equivalent composed of a resonant cavity and a PN junction diode. Therefore, when the semiconductor laser is not excited, its volt ampere characteristics are similar to those of the traditional diode [2]. For the pulse laser diode, the performance of the driving power will have a great impact on the performance of the whole machine.

The two development directions of high-power pulse constant current source are also its two technical difficulties, that is, how to obtain a larger pulse current and a smaller pulse width. [3] Therefore, this paper mainly studies the design method of the pulse constant current source used to drive the semiconductor laser, designs a reasonable pulse generation circuit, and verifies it by experiments. Combined with the experimental results, the circuit is improved so that the output pulse current amplitude, pulse width, rise and fall time, overshoot oscillation amplitude and other technical indicators meet the requirements of technical indicators, and finally achieve high power Target of current amplitude and small pulse width.

In this paper, the circuit design scheme of realizing stable pulse constant current output is proposed, which is powered by buck circuit and energy storage capacitor, and regulated by linear regulator.
Compared with the traditional single energy storage capacitor power supply scheme, the combined power supply can effectively reduce the capacitance value, avoid the use of large volume and weight capacitance, and significantly improve the power density of the overall power supply. Meanwhile, uses the linear regulator to adjust, which can greatly improve the output accuracy, and the efficiency of the power supply system will not be significantly reduced.

2. Design of Pulse Constant Current Source System

The general scheme of the high power pulse constant current source system designed in this paper is shown in Fig.1.

![Structure diagram of high power pulse constant current source system](image)

As can be seen from the system structure diagram, the main body of the driver system designed in this paper can be divided into two levels. The charge unit of the former stage consists of the buck circuit provides the energy required by the constant current pulse for the pulse discharge link of the later stage linear regulator, and the latter stage linear regulator outputs the current pulse that meets the index requirements through the linear regulation of the power tube.

Because this scheme supplies the buck circuit and the energy storage capacitor together, the driving signal of the front stage MOSFET is obtained by comparing the voltage on the energy storage capacitor through the hysteresis loop, so the front stage buck circuit will work only when the rear stage MOSFET is on, that is to say, the rear stage MOSFET must be on during the working period of the buck circuit. Therefore, when the circuit works normally, if the pulse discharge gap is not considered, that is to say, during the conduction of the later stage MOSFET, the equivalent circuit is a buck circuit with resistance load, and the equivalent circuit diagram is shown in Figure.2.

The working principle is that during the conduction period of the later stage linear regulator, it is equivalent to a module controlled by current and voltage. The former stage supplies power to the laser load through this module, and the energy storage capacitor provides a stable DS terminal voltage for the regulator so that it can work over stably in the linear area.

When the voltage $V_C$ of the energy storage capacitor is lower than the lower hysteresis voltage $U_L$, the PWM module starts to work. When the driving signal is high, the switch Q is on, and the current flowing through the inductance L rises. At this time, the circuit supplies power to the load and charges the capacitor at the same time.
3. Linear adjustment Module

3.1. Working principle

Figure 3 shows the basic principle of the linear regulation module. It can be seen that the current flowing on the load resistance $R_{\text{load}}$ is:

$$I_{\text{out}} = \frac{V_{\text{in}}}{R_{\text{in}} + R_L}$$  \hspace{1cm} (1)

Where $I_{\text{out}}$ is the output current, $V_{\text{in}}$ is the input voltage, $R_{\text{in}}$ is the variable resistance, and $R_{\text{load}}$ is the load resistance. To fix the output current, the sum of $R_{\text{in}}$ and $R_L$ should be fixed, that is to say, the varistor $R_{\text{in}}$ needs to change with the load resistance $R_L$.

In this paper, the MOS transistor working in the linear region is used instead of the variable resistor $R_{\text{in}}$. The MOSFET has the characteristics of good linearity, fast switching speed and low driving power. Its equivalent resistance value is shown in formula 2. The resistance value is affected by the bias voltage $V_{\text{GS}}$ and the threshold voltage $V_{\text{TH}}$ [4]. The working area of the regulator is as shown in Figure 4. The drain current $I_D$ is determined by the gate source voltage $V_{\text{GS}}$. Therefore, the purpose of controlling the drain current $I_D$ can be achieved by controlling the $V_{\text{GS}}$, realizing fast response and dynamic tracking of load change, and constant current output can be achieved by negative feedback regulation.

$$R_{\text{in}} = \frac{1}{\mu C_{\text{ox}} (W/L)(V_{\text{GS}} - V_{\text{TH}})}$$  \hspace{1cm} (2)
In the control part of the circuit, PI regulator is used to change the size of $V_{GS}$ by generating a dynamic bias grid voltage through monitoring the sampling signal, and the grid voltage also considers the effect of body effect on the threshold voltage, so as to ensure the accuracy of the equivalent resistance [5]. As shown in Figure 5, the whole module is composed of four parts: regulator, feedback network, error amplifier and PI regulator. The output is compared with the reference voltage through the feedback network. The error amplifier adjusts the drain current of the power tube by amplifying the difference, so as to realize the stability of the output current of the system.

3.2. Stability analysis
The post-stage discharge circuit is equivalent to a linear voltage regulator, which consists of three parts: error amplification circuit, sampling circuit and linear regulation circuit [6].

The output current is converted to a voltage signal by sampling resistance. Compared with a given reference voltage signal, the difference is amplified by error amplification module and the power tube control signal is generated, which drives the MOSFET to adjust the output current linearly for the purpose of constant current output.

To analyze its stability, a small signal model of the system is first established, as shown in the Figure7. And the small signal model of power tube $g_{m2}$ is shown in Figure 8 [7].
In the small signal model, $g_{m1}$ is the error amplifier transconductance, $R_{o1}$ is the output impedance of the error amplifier, $g_{m2}$ is the power tube transconductance, $R_{o2}$ is the output impedance of the power tube, $C_{par}$ is the parasitic capacitance of the power tube, and $K_1$ is the proportional amplification factor of the sampling module.

The transfer function block diagram of the system can be obtained as follows:

![Transfer function block diagram](image)

Figure 9. Transfer function block diagram

So the open-loop transfer function of the system can be expressed as:

$$G_{ref-fb}(s) = \frac{g_{m2} \cdot R_{o2} \cdot K_1 \cdot g_{m1} \cdot R_{o1}}{1 + s \cdot R_{o1} \cdot C_{par}}$$  \(3\)

It can be seen from equation (3) that the transfer function of this system only contains one pole, which is the reciprocal of the equivalent time constant of power tube opening, which can be expressed as:

$$s = \frac{1}{R_{o1} \cdot C_{par}}$$  \(4\)

PI correction link is added. The transfer function of the correction link is:

$$G(s) = K_p \left(1 + \frac{1}{T_i \cdot s}\right)$$  \(5\)

Where $K_p = R_2 / R_1$ is the proportional coefficient; $T_i = C_1 \times R_2$ is the integral time coefficient. The transfer function block diagram after adding PI correction link can be obtained as follows:
The open-loop transfer function of the system after PI correction is added becomes:

\[ G_{\text{ref}-\beta}(s) = \frac{g_{m2}R_{v2} \cdot K_i \cdot g_{m1}R_{v1} \left(K_p \cdot T_i \cdot s + K_p\right)}{R_{v1}C_{\text{par}} \cdot T_i \cdot s^2 + T_i \cdot s} \] (6)

It can be seen from equation (6) that the transfer function of the system includes two poles and one zero point after the correction link is added. Because the pole is the reciprocal of the turn-on time constant of the power transistor, and the parasitic capacitance of the power transistor is small, so the crossing frequency \( \omega_c \) is very small, and there will be a certain gain at high frequency. However, the switching frequency of the MOS transistor in the later stage of the circuit is 50Hz, so the influence of high frequency gain on the system can be ignored.

Considering the relative stability of the controlled current, the relationship between input and output in the negative feedback network can be simplified as follows:

\[ I_f = \frac{V_{\text{ref}}}{K \cdot R} \] (7)

If \( I_f \) is the output current of the constant current source, \( V_{\text{ref}} \) is the set reference voltage, \( R \) is the sampling resistance, and \( K \) is the negative feedback network feedback coefficient. After differential treatment of equation (7), divide the two sides by \( I_f \) at the same time, and the relative stability of \( I_f \) is obtained as follows:

\[ \frac{dI_f}{I_f} = \frac{dV_{\text{ref}}}{V_{\text{ref}}} - \frac{dK}{K} - \frac{dR}{R} \] (8)

It can be seen that the relative stability of \( I_f \) is related to \( V_{\text{ref}}, K \) and \( R \). Therefore, in order to improve the stability of the output current, we can start from the following three aspects: selecting a high stability regulator chip and a voltage divider to improve the stability of \( V_{\text{ref}} \); selecting an operational amplifier with a high common mode rejection ratio to build a negative feedback network to improve the stability of \( K \); selecting a resistance with a small temperature coefficient and high accuracy As the sampling resistance, the stability of \( R \) is improved \cite{8}.

4. Front charging unit and its control circuit

The schematic diagram of the front stage buck charging unit is shown in Figure 11. The unit has two functions, one is to supplement the energy storage capacitor \( C \) and the other is to supply power for the later stage pulse discharge. In order to achieve the purpose of rapid regulation, the hysteresis comparator with the fastest response speed is used for control, and because it does not need feedback loop compensation, the structure is simple and easy to design.
When the capacitor voltage drops to the low hysteresis level, the hysteresis controller outputs a high level, the buck circuit continues to provide energy for the later stage. When the capacitor voltage is charged to high level, the MOSFET of the buck circuit is turned off.

![Figure 11. Schematic diagram of front stage circuit](image)

According to the input and output characteristics of op amp, when $U_+ = U_-$, the output voltage of op amp will jump. Let the output of the original circuit be $U_o = U_{Z+}$, and the $U_-$ is obtained by sampling the capacitance voltage. When the $U_-$ is gradually increased to $U_+$, the threshold level of $U_o$ jumping from $U_{Z+}$ to $U_{Z-}$:[9]

$$U_{TH+} = R_4 \cdot V_{ref} + R_3 \cdot U_{Z+}$$ \hspace{1cm} (9)

Similarly, when $U_-$ decreases to $U_+$, the threshold level of $U_o$ jumping from $U_{Z-}$ to $U_{Z+}$ is:

$$U_{TH-} = \frac{R_4}{R_3 + R_4} \cdot V_{ref} - \frac{R_3}{R_3 + R_4} \cdot U_{Z-}$$ \hspace{1cm} (10)

$$\Delta U_{TH} = U_{TH+} - U_{TH-} = \frac{R_3}{R_3 + R_4} \cdot (U_{Z+} + U_{Z-})$$ \hspace{1cm} (11)

Door width only depends on $R_3$, $R_4$ and $U_{lo}$ independent of $V_{ref}$. 
5. Experimental Validation and Analysis

![Figure 12. Pulse constant current source output waveform](image)

The experimental waveform is shown in Fig.12. The Purple waveform is the voltage at both ends of the storage capacitor, the Green waveform is the output voltage on the load, the Blue waveform is the output current pulse, and the Yellow waveform is the control signal of the MOS tube. Fig.12.(a) is the signal at both ends of the rear MOS tube GS and Fig.12.(b) is the signal at both ends of the front MOS tube GS.

From the experimental waveform, it can be seen that there is a pulse current output only when the back-stage MOS tube is turned on. At this time, the storage capacitance power-down, and the front-stage MOS tube is turned on by hysteresis control. The front-stage provides energy for the load while maintaining the stability of the storage capacitance voltage, which ensures that the back-stage MOS tube always works in the variable resistance area. The back-stage outputs a constant current pulse waveform with an amplitude of 30A, the pulse width of 250us, and the rise time of 9.6us on the load through linear adjustment of the MOS tube. The current pulse rises rapidly and overshoots are small, and decreases rapidly without reverse current. After the back-stage MOS is switched off, the front-stage continues to work, and the storage capacitance is recharged to the upper limit of hysteresis, then the power is switched off, waiting for the next discharge signal to arrive. The experimental results are consistent with the theoretical analysis.

The rising edge of the output constant current pulse signal is proportional to the equivalent inductance in the circuit and inversely to the dynamic resistance of the laser diode array. Therefore, the rising edge can be steepened by increasing the dynamic impedance or decreasing the loop inductance. However, the number of diodes is usually fixed, and considering the large output current amplitude, the influence of distribution parameters is more obvious, it is necessary to reduce the rise time by reducing the inductance of the loop. The distributed inductance on the wire is proportional to the length of the wire, so the distribution inductance can be as small as possible by reducing the length of the transmission line in the circuit board, controlling the length and thickness of the input and output wires, so as to shorten the rising edge of the pulse.

6. Conclusion

According to the characteristics of Buck circuit and MOS linear working area, a high power pulse driving power supply system is designed in this paper. A hysteresis control Buck circuit and a storage capacitor are used to provide energy. The output current pulse is dynamically adjusted by the MOS tube operating in the linear region to achieve the purpose of constant current output. Through the analysis of the principle and composition of the system, an experimental platform is set up to verify
that the stable output amplitude is 30A, the pulse width is 250us, the rise edge is 18us, and the repetition frequency is 50Hz. The experimental waveform is analyzed, which has some reference significance for the design of related circuits in the future.

References
[1] Wang Qing. Research on the theory and technology of pulse constant current source for semiconductor laser [D]. Jilin University, 2011.
[2] Xue Huiyun. Research and design of high stability two-way constant current source for semiconductor laser [D]. Tianjin University, 2014.
[3] Ma Tianxiang. Research and implementation of 50A high power pulse constant current source technology [D]. Jilin University, 2012.
[4] Liu Chen. Research and implementation of high performance low dropout linear regulator [D]. Xidian University, 2016.
[5] Wang Yi. Research and design of high performance low differential linear regulator [D]. Zhejiang University, 2010.
[6] Dong Renjun. Research on the pulse power supply of high power pumped semiconductor laser [D]. Yanshan University, 2017.
[7] Cheng Chunlai. Stability and frequency compensation technology of CMOS LDO [D]. Xidian University, 2008.
[8] Yu Wangzhu. Development of driving power supply for semiconductor laser [D]. Harbin Institute of Technology, 2010.
[9] Zhao Jinbin, Dai Jianfeng, Qu Keqing. Hysteresis control strategy based on capacitor charge balance [J]. Journal of Electrical Technology, 2015(16): 69-75.
[10] Li Tao, Hu Heping, Yang Hong. Development of high power laser diode driver[J]. Journal of Terahertz Science and electronic information, 2015, 13(3):454-457.