Study on Fast Response of Semiconductor Laser Driven by Impulse Current

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Abstract. A simulation model based on single-mode rate equations of semiconductor laser and its typical parameters shows that, the photon stimulated emission rate at the early turn-on time of the semiconductor laser is increased with the increase of the injection current, and the corresponding rise time is reduced with the increase of injection current. However, for an output power of fixed semiconductor laser, increasing the injection current to reduce the rise time of the transmitted pulse leads to increase in temperature of semiconductor laser. We show that adding an impulse current in the front of the normal luminous pulse current can reduce the rise time of the transmitted pulse and ensure the stable output of the semiconductor laser. This method is verified by simulation and an experiment using PLTB450B semiconductor laser. The simulation and test results show that for an output power of fixed semiconductor laser, the rise time of the transmitted pulse can be reduced significantly by adding impulse current.

1. Introduction

As a precise optoelectronic device, semiconductor laser has a poor toleration with the change of current. A big change in current will affect the performance of semiconductor laser and even damage semiconductor laser. Excessive current leads to increase in temperature of semiconductor laser[1], therefore, a stable and appropriate driving current is needed for semiconductor laser. When laser pulse is used in distance measurement, according to the running time method, if the rising edge of laser pulse is wider, the scale of useful pulse in distance measurement is lower. Thus, time error in the running time method larger, and finally, the error in results of distance measurement is larger. One of the way to reduce the error in distance measurement is to narrow rising edge of laser pulse. The objective of this study is to find appropriate driven current for semiconductor laser, reduce the rise time of output laser pulse, and realize fast response of semiconductor laser. In Ref. 2[2], a simple rate equation is derived for a four-level laser assuming enhanced spontaneous emission into the cavity, the authors analyzed the rate equation, and get the numerical results, which show that increasing the coupling of spontaneous emission into the cavity mode causes the improving of dynamic response speed. But they didn’t mention how to increase the coupling of spontaneous emission. In Ref. 3[3], the authors derived the relational formula between electro optical delay time of DB laser and pulse current amplitude, and get the conclusion that electro optical delay time of DB laser decreased with the increase of pulse current amplitude. However, they did not analyze the relationship between the rise time of laser pulse and the input current, nor did they mention of how to control driven current of semiconductor laser to reduce rise time. A simulation model based on rate equation was built in Ref. 4[4], the authors analyzed the output response of carrier and photon for DFB laser. This study built a simulation model based on single-mode rate equations of semiconductor laser, and proposed that
adding an impulse current have appropriate width and height in the front of the normal luminous pulse current can reduce the rise time of the transmitted pulse. The simulation model proved this method is feasible, then applied this method in a test using PLTB450B semiconductor laser. the result is same as simulation result.

2. Simulation of single-mode rate equation for semiconductor laser

2.1. Single-mode rate equation for semiconductor laser

The single-mode rate equation for the carrier density and photon density in active region of semiconductor laser are given in Eq.(1) and Eq.(2). Among them, The meaning of each character in the formula and the detailed derivation of the process need to be found in the references given later.

\[
\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_n} - g_0 \frac{N - N_p}{1 + \varepsilon S} S \tag{1}
\]

\[
\frac{dS}{dt} = \Gamma g_0 \frac{(N - N_p)S}{1 + \varepsilon S} - \frac{S}{\tau_p} + \frac{\Gamma \beta N}{\tau_n} \tag{2}
\]

In Eq. (1), the first term on the right side is growth rate of carrier caused by injection current, the second term represents reduced rate of carrier caused by spontaneous emission, and the last term represents reduced rate of carrier caused by stimulated emission. In Eq. (2), the first term on the right side is growth rate of photon caused by stimulated emission, the second term represents reduced rate of photon caused by photon loss, and the last term represents growth rate of photon caused by spontaneous emission.

2.2. Simulation of single-mode rate equation for semiconductor laser

Based on single-mode rate equation Eq. (1) and Eq. (2), we built a simulation model using SIMULINK in MATLAB, this model is given in Figure 1. Place a scope at the output end, in order to get the response to different input injection current.

![Figure 1. Simulation model based on single-mode equation of semiconductor laser](image)

Typical value of semiconductor laser used in this simulation model can be found in Table 1. When the input injection current range from 20mA to 100mA, the response to different injection current is shown in Figure 2.
Table 1. Parameters values for single-mode equation of semiconductor laser

| Parameter | Description                  | Value     | Unit      |
|-----------|------------------------------|-----------|-----------|
| $V$       | Volume of active region      | $9.0e-11$ | $cm^3$    |
| $\tau_n$ | Carrier lifetime             | $3.0e-9$  | $s$       |
| $\tau_p$ | Photon lifetime              | $1.0e-12$ | $s$       |
| $g_0$     | Differential gain            | $3.0e-6$  | $cm^3/s$  |
| $N_{tr}$  | Transparency carrier density | $1.2e18$  | $cm^{-3}$ |
| $\varepsilon$ | Gain compression factor    | $100e-17$ | $cm^3$    |
| $q$       | Charge of electron           | $1.6e-19$ | $C$       |
| $\Gamma$ | Confinement factor           | $0.44$    |           |
| $\beta$  | Spontaneous emission coupling factor | $4.0e-4$ |           |

Figure 2. The photon density under different input injection current

The photon density in balance situation and corresponding rise time under different injection current get from waveform in Figure 2 can be found in Table 2. As we can see in Table 2, the photon density increased linearly with the increase of injection current, and the rise time also increased with the increased of injection current, but the photon density remains unchanged when the injection current increased to a certain value. The average rate of photon stimulated emission is calculated according to the photon density in balance situation and corresponding rise time in Figure 2. The relation between average rate of photon stimulated emission and injection current is shown in Figure 3, from which we can see that the average rate of photon stimulated emission show a linearly increased trend with the increase of injection current which above threshold current.

Table 2. Simulation results under different injection current

| Injection current I/A | Photon density in balance situation $S/cm^{-3}$ | Rise time $t_r/s$ | Average rate of photon stimulated emission $v/cm^{-3}/s$ |
|-----------------------|--------------------------------------------------|-------------------|----------------------------------------------------------|
| 0.03                  | $0.5636e+15$                                     | $0.6181e-9$       | $0.9118e+24$                                             |
| 0.04                  | $0.8376e+15$                                     | $0.6295e-9$       | $1.3305e+24$                                             |
| 0.05                  | $1.1133e+15$                                     | $0.6344e-9$       | $1.7517e+24$                                             |
| 0.06                  | $1.3849e+15$                                     | $0.6413e-9$       | $2.1595e+24$                                             |
| 0.07                  | $1.6584e+15$                                     | $0.6471e-9$       | $2.5628e+24$                                             |
| 0.08                  | $1.9319e+15$                                     | $0.6488e-9$       | $2.9776e+24$                                             |
| 0.09                  | $2.2055e+15$                                     | $0.6469e-9$       | $3.4093e+24$                                             |
| 0.10                  | $2.4787e+15$                                     | $0.6469e-9$       | $3.8157e+24$                                             |
Figure 3. The relation between average rate of photon stimulation emission and injection current

3. Fast response of semiconductor laser driven by impulse current

According to the simulation results in Table 2 and Figure 2, the rate of photon stimulated emission increased linearly with the increase of injection current which above threshold current, but for an output power is fixed semiconductor laser, its threshold current and operating current is fixed, so we can’t increase the injection current to reduce the rise time of the transmitted pulse. To realize fast response of semiconductor laser, we put forward adding an impulse current have appropriate width and height in the front of the normal luminous pulse current.

Compared the response of a semiconductor laser driven by injection current adding an impulse current which width is 3\text{ns}, height is 0.1\text{A}, in the front of normal luminous pulse current which width is 9\text{ns}, height is 0.06\text{A}, with the response of a semiconductor laser driven by normal luminous pulse current which width is 12\text{ns}, height is 0.06\text{A}. The comparison result is shown in Figure 4.

Figure 4. The output of simulation model under two different injection current

The photon density in balance situation, rise time and the average rate of stimulated emission get from waveform in Figure 4 is given in Table 3.
Table 3. Simulation result under two different injection current

| Injection current           | Photon density in balance situation S/cm⁻³ | Rise time tr/s | Average rate of photon stimulated emission v/cm⁻³/s |
|-----------------------------|--------------------------------------------|----------------|-----------------------------------------------|
| width is 3ns, height is 0.1A+ | 1.3852e+15                                | 8.2552e-11     | 1.6779e+25                                   |
| width is 12ns, height is 0.06A | 1.3852e+15                                | 6.3996e-10     | 2.1645e+24                                   |

In Table 3, for a semiconductor laser driven by injection current adding an impulse current with appropriate width and height in the front of the normal luminous pulse current, and the photon density in balance situation is same as no impulse current, but the rise time reduced significantly. So adding an impulse current have appropriate width and height in the front of the normal luminous pulse current speeds up the response of semiconductor laser.

4. Experiment
The semiconductor laser model used in this experiment is PLTB450B, which threshold current is 0.2A, operating current is 1.2A.

The circuit structure[6][7] used in this experiment to produce pulse current and impulse current is a current negative feedback circuit structure based on operational amplifier, including operational amplifier, triode and resistance. The controller controlled the DAC produced a pulse current excitation signal, then operational amplifier and triode produced a pulse current to drive semiconductor laser. To produce injection current with impulse current, the controller controlled the DAC produced a higher pulse current excitation signal, which is remained in a certain time, and then reduced to normal voltage. The circuit structure is shown in Figure 5.

![Figure 5. The circuit structure used in this experiment](image)

In Figure 6, channel 1 is the waveform of injection current, channel 3 is the waveform of laser pulse, and channel 4 is the waveform of synchronous signal. We can see that the rise time closing to 6μs.

In Figure 7, channel 1 is the waveform of pulse current with impulse current, the higher part is impulse current, which width is 800ns, height is 2.2 times the normal pulse current, and the lower part is pulse current. Channel 3 is the waveform of laser pulse and channel 4 is the waveform of synchronous signal. We can see that the rise time is less than 1.2μs.
5. Conclusion
We have built a simulation model based on single-mode equations of semiconductor laser and its typical parameters, and it shows that increasing injection current can reduce the rise time, but the rise time remain unchanged when the injection current increased to a certain value, and increasing injection current leads to increase in temperature of semiconductor laser. Moreover, for a semiconductor laser, the threshold current and operating current is fixed. So increasing injection current to reduce rise time is impractical. We proposed adding an impulse current which have appropriate width and height in the front of the normal luminous pulse current to reduce the rise time. The simulation and experiment results proved that this method speeds up the response of semiconductor laser indeed. This will advantage the designer to reduce the error in distance measurement.

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