Study on enlarging chaos frequency in two coupled lasers using both optoelectronic cross-feedback and self-feedback

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Abstract. This paper presents an optoelectronic delayed time cross-feedback and self-feedback method to enlarge chaotic frequencies of two semiconductor lasers as two chaotic signal oscillators and to enhance the oscillation behaviours of the lasers. The technical solution of enlarging-frequency of two lasers is that the light from one laser is converted into a photocurrent by the photoelectric converter, and then the delayed time photocurrent is divided into two currents. One is cross fed to another laser while the other photocurrent is fed to self-laser, which can result in enhancing chaos oscillation to realize enlargement of chaotic frequency of two semiconductor lasers. We adjust the feedback levels or the delayed time to realize enlargement of chaotic frequency of two semiconductor lasers. When the feedback level increased, enlargement of the chaotic frequency of two semiconductor lasers is obviously enhanced. When a feedback is performed, enlargement of chaotic frequency of one laser is obviously enhanced. When the two feedbacks are performed, enlargements of chaotic frequencies of two lasers are obviously enhanced. These results illustrate that enlargement of chaotic frequency of two laser can be effectively obtained via the optoelectronic delayed time cross-feedback and self-feedback method. The research result of this paper is a reference value for enlargement of chaotic frequency, chaos communization, and laser technology etc.

1. Introduction

In the past several decades, the optics chaos dynamics have been found to show some irregular behaviour and random oscillation [1-4]. The chaotic movement is very sensitive to its initial state, which will result in a random behaviour and a white noise spectrum. So there is a large difficulty for people to predict the chaotic behaviour or dynamic regular. And the chaotic semiconductor laser signal has the characteristics of high frequency oscillation and about a few GHz spectrum [1-4]. At present, a lot of laser chaos systems have been reported, such as an optical feedback semiconductor laser and an external optical injection semiconductor laser, as the first used transmitter in the application of laser chaotic secure communication [1-4]. So a chaotic semiconductor laser and its application to secure communication is becoming a nonlinear science and communication hotspot [1-4]. We find that a high rate communication bases on carries frequency or oscillation behaviour of signal oscillator of transmitter, so a high frequency signal from a chaotic laser source can perform on a high rate communication. But a chaotic semiconductor laser has a difficulty for it to produce a high frequency signal because its inherent oscillation behaviour limits a generation of a high frequency signal. To enlarge communication rate, we expect to present some methods to enlarge the chaotic frequency or to enhance oscillation behaviour of signal oscillator of laser chaos transmitter. People always pay their attention to the optical feedback and the external optical injection methods to enlarge chaotic frequency [1-4]. And the mainly aim to the enlargement of chaos frequency can lead to a single
chaotic laser system to enhance oscillation frequency. It will be very significant to study on the enlarging chaotic frequencies of two semiconductor lasers and to enhance laser oscillation behaviour [5]. And it is helpful to present other methods about enlargement of chaos frequency. This paper will focus on chaos in two coupled lasers, especially on how to realize to enlarge chaotic frequency of two semiconductor lasers, and to enhance their oscillation behaviours by an optoelectronic cross-feedback and self-feedback method.

2. Model
Due to the two field nonlinear coupled interaction, two coupled semiconductor lasers as two chaotic signal oscillators show some complex nonlinear dynamic behaviours, such as the phenomena of bifurcation and chaos. We present an optoelectronic delayed time cross-feedback and self-feedback method to perform on enlarging chaotic frequencies of two coupled lasers or enhancing chaos oscillation. When both optoelectronic delayed time cross-feedback and self-feedback are performed on two lasers, the dynamic behaviours of lasers as two chaotic signal oscillators are described by the following rate equations [3-6]:

| Table 1. Laser parameters |
|---------------------------|
| **Parameter** | **Symbol** | **Value** |
| the cavity length | \( L \) | 350\( \mu \)m |
| the volume of laser cavity | \( V \) | 105\( \mu \)m\(^3\) |
| the mode coefficient | \( \Gamma \) | 0.29 |
| the photon loss | \( \alpha_{ns} \) | 49\( \text{cm}^{-1} \) |
| the carrier density | \( n_{th} \) | 1.2\( \times 10^{18} \text{cm}^{-3} \) |
| the nonradiative recombination rate | \( A_{nr} \) | 1.0\( \times 10^8 \text{s}^{-1} \) |
| the radiative recombination coefficient | \( B \) | 1.2\( \times 10^{-10} \text{cm}^3/\text{s} \) |
| the Auger recombination coefficient | \( C \) | 3.5\( \times 10^{-29} \text{cm}^6/\text{s} \) |
| the optical field amplitude at saturation | \( E_s \) | 1.6619\( \times 10^{11} \text{m}^{3/2} \) |
| the optical linewidth enhancement factor | \( \beta_c \) | 6 |
| the gain constant | \( a \) | 2.3\( \times 10^{-16} \text{cm}^2 \) |
| the frequency detuning | \( \Delta \omega \) | 2 GHz |
| the photon round-trip time | \( \tau_t \) | 8.8667\( \times 10^{-12} \text{s} \) |
| the mode volume | \( V_p / V / \Gamma \) |
| the referenced amplitude | \( E_0 \) | 0.1\( E_s \) |
| the optical coupling factor | \( K \) | 0.05 |
| the current | \( I_1, I_2 \) | 24 mA, 26 mA |
| the unit charge | \( q \) | 1.60219\( \times 10^{-19} \text{C} \) |

\[
\frac{dE_i}{dt} = \frac{1}{2} ( G_i - \gamma_p ) E_i + \frac{K}{\tau_{Li}} E_2 \cos(\varphi_2 - \varphi_i) \\
\frac{d\varphi_i}{dt} = \frac{1}{2} \beta_c ( G_i - \gamma_p ) + \frac{K}{\tau_{Li}} \frac{E_2}{E_i} \sin(\varphi_2 - \varphi_i) - \Delta \omega \\
\frac{dN_1}{dt} = \frac{I_1 \times \left[ 1 + \eta_1 E_1^2 (t - \tau_i) / E_0^2 \right]}{q} - \gamma_{e1} N_1 - G_i V_p E_1^2
\]
\[
\frac{dE_2}{dt} = \frac{1}{2} (G_2 - \gamma_p) E_2 + \frac{K}{\tau_L} E_1 \cos(\phi_1 - \phi_2) \\
\frac{d\phi_2}{dt} = \frac{1}{2} \beta_2 (G_2 - \gamma_p) + \frac{K}{\tau_L} E_1 \sin(\phi_1 - \phi_2) + \Delta \omega \\
\frac{dN_2}{dt} = \frac{1}{q} \left[ 1 + \eta_2 E_1^2 (t - \tau_2) / E_2^2 \right] - \gamma_c N_2 - G_2 V_p E_2^2
\]

Where the subscripts “1” and “2” represent the two lasers 1 and 2. The variables \(E, \varphi\) and \(N\) describe the amplitude and phase of the optical field and the carrier number. \(\eta\) and \(\tau\) are the optoelectronic feedback and the relayed time factors, where these factors are adjusted to realize chaotic frequency enhancement of lasers. The carrier nonlinear loss rate is \(\gamma_c = A_0 + B(N/V) + C(N/V)^2\), and the mode nonlinear gain is \(G = (\gamma_0 a/V_p)(N-N_0)/(1+E^2/E_0^2)^{1/2}\). The other parameter instructions are listed in table 1.

### 3. Results

#### 3.1. Enlarging Frequency Using the self-feedback on one laser t1

First, we perform only the optoelectronic delayed time self-feedback on the laser t1 to enlarge frequencies of chaos in two lasers. We can use Eqs. (1) and (2) to operate the enlarging frequencies of the lasers while the parameters are taken in table 1, then the enlarging frequency parameters \(\eta\) and \(\tau\) are adjusted to enhance oscillation behaviours and frequencies of two lasers.

We find that the enlarging frequency can be realized by the optoelectronic delayed time self-feedback method while oscillation behaviours of two chaos lasers can be enhanced. Figure 1 shows two chaotic dynamics behaviours of two chaos lasers without the optoelectronic feedback, where a chaotic laser 1 oscillates at 2.7GHz and another chaotic laser 2 oscillates at 3.5GHz.

When the optoelectronic delayed time self-feedback is performed, enlarging frequencies of two lasers can be obtained while two enhanced oscillations are led to show in two lasers. Figure 2 shows realizations of enlarging frequencies of two lasers while laser 1 oscillation is enlarged to 4GHz and laser 1 oscillation is enlarged to 10GHz when the parameters are taken as \(\tau=1\ ns, \eta=0.22\). Figure 2 (a) shows an oscillation in the laser 1 with 4 GHz, figure 2 (b) shows another oscillation in the laser 2 with 10 GHz, where two oscillations are enhanced, and laser 1 frequency is enlarged 1.42 times and laser 2 frequency is enlarged 2.85 times. Which implies realization of enlarging oscillations of chaos movements of two lasers. Figure 2 (c) shows a chaotic orbit in the laser 1 and figure 2 (d) shows another chaotic orbit in the laser 2. And figures 2 (e) and (f) show spectrum of two lasers, where spectrum widths are obviously enlarged by the optoelectronic delayed time self-feedback, and which implies realizations of enlarging frequencies of two lasers.

![Image](a). A chaotic oscillation of the laser 1 .

![Image](b). A chaotic oscillation of laser 2.
(c). A chaotic attractor of the laser 1.
(d). A chaotic attractor of the laser 2.
(e). Spectrum of the laser 1.
(f). Spectrum of the laser 2.

Figure 1. Chaos movement of two lasers, where figure (a) shows chaos movement in the laser 1, figure (b) shows chaos movement in the laser 2, figure (c) shows chaos trajectory in the laser 1, figure (d) shows chaos trajectory in the laser 2, figures (e) and (f) show spectrum of the two lasers.

We find realizations of enlarging frequencies and enhancing oscillations of two lasers 1 and 2 show at 4GHz and 9 GHz, respectively, when $\tau_1=1\text{ ns}$, $\eta=0.13$.

When $\tau_1=1\text{ ns}$, $\eta=0.2$. Realizations of enlarging frequencies and oscillations of two lasers 1 and 2 show at 4GHz and 10 GHz, respectively.
Figure 2. Chaos movement of two lasers, where figure (a) shows chaos movement in the laser 1, figure (b) shows chaos movement in the laser 2, figure (c) shows chaos trajectory in the laser 1, figure (d) shows chaos trajectory in the laser 2, figures (e) and (f) show spectrum of two lasers.

When another optoelectronic delayed time self-feedback is performed on two lasers when the parameters are taken as $\tau_1=0.8$ ns, $\eta_1=0.15$, enlarging frequencies of two lasers can be obtained, where laser 1 oscillation is enlarged to 3.1GHz, and laser 2 oscillation is enlarged to 12GHz. When the parameters are taken as $\tau_1=0.8$ ns, $\eta_1=0.25$, enlarging frequencies of two lasers can be obtained, where laser 1 oscillation is enlarged to 3.2GHz, and laser 2 oscillation is enlarged to 13GHz, namely laser 2 frequency is enlarged to 3.4 times.

3.2. Enlarging Frequency Using the cross-feedback
Second, we perform only the optoelectronic delayed time cross-feedback on two lasers to enlarge frequencies of chaos in two lasers.
A chaotic attractor of the laser 1.

A chaotic attractor of the laser 2.

Spectrum of the laser 1.

Spectrum of the laser 2.

Figure 3. Chaos movement of two lasers, where figure (a) shows chaos movement in the laser 1, figure (b) shows chaos movement in the laser 2, figure (c) shows chaos trajectory in the laser 1, figure (d) shows chaos trajectory in the laser 2, figures (e) and (f) show spectrum of two lasers.

When the parameters are taken as $\tau_2=1$ ns, $\eta_2=0.75$, figure 3 (a) shows an oscillation in the laser 1 with 8.2 GHz, figure 2 (b) shows another oscillation in the laser 2 with 4.4 GHz, where the two oscillations are enhanced while laser 1 frequency is enlarged 3.03 times and laser 2 frequency is enlarged 1.25 times. The above result implies the realizations of enlarging oscillations or chaos movements of two lasers. Figure 3 (c) shows a chaotic orbit in the laser 1 and figure 3 (d) shows another chaotic orbit in the laser 2. And figures 3 (e) and (f) show spectrum of two lasers, where spectrum widths are enlarged by the optoelectronic delayed time cross-feedback, and which implies realizations of enlarging frequencies of two lasers.

We find realizations of enlarging frequencies and oscillations of two lasers 1 and 2 show at 6.8GHz and 4.5 GHz, respectively, when $\tau_2=1$ ns, $\eta_2=0.45$. And when $\tau_2=1$ ns, $\eta_2=0.9$. Realizations of enlarging frequencies and oscillations of two lasers show at 9GHz and 4.2 GHz, respectively shown in figure 4.

Figure 4. Chaos movement of two lasers, where figure (a) shows chaos movement in the laser 1, figure (b) shows chaos movement in the laser 2.
A chaotic oscillation of the laser 1.

A chaotic oscillation of laser 2.

Figure 5. Other chaos movement of two lasers, where figure (a) shows chaos movement in the laser 1, figure (b) shows chaos movement in the laser 2.

And when \( \tau_2=10.8 \text{ ns}, \eta_2=0.9 \). Realizations of enlarging frequencies and oscillations of two lasers 1 and 2 show at 8.7GHz and 4.2 GHz, respectively shown in figure 5.

3.3. Enlarging Frequency Using both cross-feedback and self-feedback

Last, we perform both optoelectronic delayed time cross-feedback and self-feedback on two lasers to enlarge frequencies of chaos in two lasers.

When the parameters are taken as \( \tau_1=1 \text{ ns}, \eta_1=0.2, \tau_2=1 \text{ ns}, \eta_2=0.01 \), figure 6 (a) shows an oscillation in the laser 1 with 3.9 GHz, figure 2 (b) shows another oscillation in the laser 2 with 12 GHz, where the two oscillations are enhanced while laser 1 frequency is enlarged 1.44 times and laser 2 frequency is enlarged 3.42 times. And which implies realizations of frequency enlargement and oscillation enhancement of chaos movement of two lasers. And figures 6 (c) and (d) show spectrum of two lasers, where spectrum widths are obviously enlarged by both optoelectronic delayed time cross-feedback and self-feedback, and which implies realizations of enlarging frequencies of two lasers.

A chaotic oscillation of the laser 1.

A chaotic oscillation of laser 2.

Spectrum of the laser 1.

Spectrum of the laser 2.

Figure 6. Chaos movement of two lasers, where figure (a) shows chaos movement in the laser 1, figure (b) shows chaos movement in the laser 2, and figures (c) and (d) show spectrum of two lasers.

4. Conclusion

This paper presents an optoelectronic delayed time cross-feedback method and a self-feedback method to enlarge chaotic frequency of two semiconductor lasers as two chaotic signal oscillators and to
enhance two laser oscillation behaviours. We adjust feedback levels or delayed time to realize enlargement of chaotic frequencies of two semiconductor lasers. Two chaotic frequencies of two lasers can be enhanced to 3 times and 3.42 times, respectively. Our results illustrate that enlargement of chaotic frequencies of two lasers can be effectively obtained via the optoelectronic delayed time cross-feedback method and the self-feedback method. Our study is very helpful for enlargement of chaotic frequency, chaos communization, and laser technology etc.

References
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