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Abstract

Semiconductor lasers are very different from other lasers because refraction variation can't be avoided when the gain is changed. Refraction variation can be introduced the theory of semiconductor laser by a dimensional parameter. This parameter is called linewidth enhancement factor (LEF). The value of LEF is very important for many aspects of laser behavior. The LEF characterizes the linewidth broadening and chirp due to fluctuation in the carrier density. A simple method to measure the linewidth enhancement factor of laser diodes is presented in this paper. The method uses the self-mixing effect at a weak feedback level. An optical beam is reflected and injected into the laser diode cavity by an external target, and is then mixed with the light inside the cavity, causing variations of the optical output power. The waveform of the optical power is determined by the feedback factor C and the LEF. A theoretical formula to compute LEF is proposed for the case when the feedback level C is smaller than 1. The experimental results show this method is feasible and simple when a laser diode operates at single longitudinal mode.

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Measuring the Linewidth Enhancement Factor of Semiconductor Lasers Based on Weak Optical Feedback Effect

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ABSTRACT

Semiconductor lasers are very different from other lasers because refraction variation can't be avoided when the gain is changed. Refraction variation can be introduced the theory of semiconductor laser by a dimensional parameter α . This parameter is called linewidth enhancement factor (LEF). The value of LEF is very important for many aspects of laser behavior. The LEF characterizes the linewidth broadening and chirp due to fluctuation in the carrier density. A simple method to measure the linewidth enhancement factor of laser diodes is presented in this paper. The method uses the self-mixing effect at a weak feedback level. An optical beam is reflected and injected into the laser diode cavity by an external target, and is then mixed with the light inside the cavity, causing variations of the optical output power. The waveform of the optical power is determined by the feedback factor C and the LEF. A theoretical formula to compute LEF is proposed for the case when the feedback level C is smaller than 1. The experimental results show this method is feasible when a laser diode operates at single longitudinal mode.

Keywords: Linewidth enhancement factor, optical feedback self-mixing interferometry, semiconductor laser

1. INTRODUCTION

Semiconductor lasers (SLs) are very different from other lasers because refraction variation can not be avoided when the gain is changed. Refraction variation can be introduced the theory of semiconductor laser by a dimensional parameter α . This parameter is called linewidth enhancement factor (LEF). The value of α is very important for many aspects of laser behavior. It characterizes the linewidth broadening and chirp due to fluctuation in the carrier density.

Accurate measurement of α and C is an important issue as they characterize the linewidth, the chirp, injection lock range, dynamic performances as well as all kinds of optical feedback effect in SLs. During the past decades people have done extensive research work on measuring α [1] and proposed many different approaches, such as the methods relying on the direct measurement of the relationship between sub-threshold optical spectrum and the injected current [2], the methods based on RF measurements [3] and the techniques based on the analysis of the locking regimes induced by optical injection from a master laser [4,5]. However, most existing approaches require sophisticated system setups or involve many complicated procedures, which thus make implementation difficult. With regard to the measurement of C , the task is more challenging and there is not much work reported yet.

The technique based on optical feedback self-mixing effect is an emerging technique in which a small fraction of the laser beam backscattered by a target is re-entering the laser active cavity. Initially, this back-reflection was seen as a major source of disturbance, strongly changing both frequency and amplitude of the lasing field. Presently, sensors based on this physical phenomenon in low-cost commercial laser diodes (LD) have been designed in a variety of applications such as dimensional control, vibration measurements, blood flow measurement, sound reproduction, angle measurements or even mass-market mobile telephones [6,7]. Applying this new technique on measuring α and C will be significant issue.

In 2004, an new approach [8] was proposed for the measuring α just based on the self-mixing optical feedback effect. However the approach can only be used for the case of a moderate feedback regime with $1 < C < 3$. This paper, is also

based on same principle, to measure α but for the weak feedback that is in the case of $0 < C < 1$. Using this method, no strict requirement for the applied external cavity but in the approach [8] a symmetric return movement of the external cavity must be provided.

The paper is organized as follows: Section 2 briefly reviews the theory of self-mixing optical feedback interferometric effect, where a set of well-known mathematical models is presented and the formula used for calculating α and C are deduced. Then in Section 3 the experimental set-up and the measuring method are described and the testing results on α values for the different types laser diodes (LDs) are listed. Finally Section 4 concludes the paper.

2. MEASUREMENT THEORY

There are two alternative and equivalent methods for the analysis of self-mixing optical feedback inteferometric effects: the Long and Kobayashi equations based approach [9] and the three-mirror cavity based approach [10]. Both approaches yield the same description about the behavior of a single-mode SL with optical feedback, given by the following equations:

$$\phi_F(\tau) = \phi_0(\tau) - C \cdot \sin[\phi_F(\tau) + k] \quad (1)$$

$$P(\phi_F(\tau)) = P_0 [1 + m G(\phi_F(\tau))] \quad (2)$$

$$G(\phi_F(\tau)) = \cos(\phi_F(\tau)) \quad (3)$$

Equation (1) is called the phase equation, equation (2) describes laser emitting power or self-mixing signal, and equation (3) is interference function. Where $k = \arctan(\alpha)$ and α is linewidth enhancement factor; $\phi_0(\tau) = \omega_0 \tau$ and $\phi_F(\tau) = \omega_F(\tau) \tau$, where ω_0 and $\omega_F(\tau)$ are the angular frequencies of the SL without and with feedback respectively; $\tau = 2L/c$, where L is the length of the external cavity and c the speed of light; C is the feedback level factor.

The above parameters are described in more details as follows: α is defined as $\alpha = \frac{\partial n_R / \partial N}{\partial n_I / \partial N}$, where N , n_R , n_I are the carrier density in laser medium, the real and imaginary part of the refractive index respectively.

$C = \varepsilon \frac{L \cdot \sqrt{1 + \alpha^2}}{l \cdot n} \sqrt{R_{ext} \frac{1 - R_2}{\sqrt{R_2}}}$, where R_2 is the power reflectivity of the SL output facet; R_{ext} is the reflectivity of the external target; l is SL cavity length; n is SL cavity refractive index and ε is an coefficient that accounts for spatial mode overlap mismatch between the back-reflected light and the lasing mode (typically $\varepsilon = 0.1-0.8$).

In Equation (2), $P(\phi_F(\tau))$ and P_0 are the power emitted by the SL with and without the external cavity respectively. It is seen that with the external cavity, the emitted power deviated from P_0 by a factor of $m G(\phi_F(\tau))$ where m is called modulation index (typical $m \approx 10^{-3}$), and interferometric function $G(\phi_F(\tau))$ gives the effect of the external light phase to the emitted power.

With a self-mixing experimental setup, a self-mixing signal $P(\phi_F(\tau))$ can be detected. Clearly $G(\phi_F(\tau))$ can be obtained from $P(\phi_F(\tau))$. We will give a theoretical formula for calculating LEF by analyzing $G(\phi_F(\tau))$.

When $C < 1$, the simulation waveform of $G(\phi_F(\tau))$ is shown as in figure 1.

Figure 1 the waveform of $G(\phi_F(\tau))$ with parameters of $C=0.9$ and $\alpha=4$

From equations (1) and (3), we have

$$\frac{\partial G(\phi_F(\tau))}{\partial \phi_0(\tau)} = \frac{\sin(\phi_F(\tau))}{1 + C \cos(\phi_F(\tau) + \arctan(\alpha))} \quad (4)$$

in the range of $[0, 2\pi]$, let $\frac{\partial G(\phi_F(\tau))}{\partial \phi_0(\tau)} = 0$, the abscissa values of the two peaks marked as x_{M1} x_{M2} on figure 1 can be expressed as

$$x_{M1} = C \sin(\arctan(\alpha)) \quad (5)$$

$$x_{M2} = \pi - C \sin(\arctan(\alpha)) \quad (6)$$

the abscissa values of the zero-crossing points marked as x_{Z1} x_{Z2} on fig. 1 are

$$x_{Z1} = \frac{\pi}{2} + C \cos(\arctan(\alpha)) \quad (7)$$

$$x_{Z2} = \frac{3\pi}{2} - C \cos(\arctan(\alpha)) \quad (8)$$

from equations (5)-(8), we can get

$$k_1 = (x_{M2} - x_{M1}) / 2\pi = 0.5 - C \sin(\arctan(\alpha)) / \pi \quad (9)$$

$$k_2 = (x_{Z2} - x_{Z1}) / 2\pi = 0.5 - C \cos(\arctan(\alpha)) / \pi \quad (10)$$

by equation (9) and (10)

$$\alpha = \left| \frac{0.5 - k_1}{0.5 - k_2} \right| \quad (11)$$

We can determine factors α by measuring k_1 and k_2 . The Equation (11) is the basic formula used to measure α . Then, by using of the measured α , from equation (9) or (10), we may calculate C value.

measurement parameters marked on it. We can get k_1 , k_2 by the following measuring equations:

$$k_1 = \frac{t_1}{T} \quad (11)$$

$$k_2 = \frac{t_2}{T} \quad (12)$$

The values of t_1 and t_2 and T are defined in figure 3.

We tested α values for 3 different types laser diodes by the above method, the experimental results are listed in the table 1. These results are agreed with the values reported in reference [8].

Table 1. Experimental results

Type	from	descriptions	α	error
SDL-7511-G1	SDL	MQW, 635nm, DFB	2.2	$\pm 8.5\%$
DL7140-201	SANYO	AlGaInP, 785nm, MQW	3.0	$\pm 6.9\%$
HL8325G	HITACH	GaAlAs, 820nm, TQW	3.3	$\pm 5.5\%$

Test condition: feedback level C is smaller than 1; temperature controller at $25 \pm 0.1^\circ\text{C}$; Injection current is far above the threshold; LDs operate at single mode. DFB: Distributed Feedback, MQW: Multiple Quantum Well, TQW: Triple Quantum Well; error is calculated as standard deviation of the measured data.

There are 3 main sources of error existed in this experimental setup. One is the low frequency fluctuation from the detecting circuit, which brings out error to measure zero base of the self-mixing signal. One is mode hopping in the laser diode or high optical noise, which can change the waveform of the self-mixing signal. Another one is due to the ambiguity of the peak positions on the waveform. In our experiment, the mode hopping is avoided by controlling the temperature and limiting the maximum feedback level. The low frequency fluctuation effect can be reduced by using high pass filter if applying a higher driving frequency on the target. The accurate identification for the peak positions may be achieved by data processing and fitting. In contrast to approach [8], the propose method in this paper doesn't require strictly symmetry for the return movement of the external target.

4. CONCLUSION

We have presented a new approach to estimate the linewidth enhancement factor of SLs. This method is based on the self-mixing optical feedback effects, in which the SL operates at weak optical feedback regime with $C < 1$. The effectiveness for the proposed method has been confirmed from the experiments.

5. ACKNOWLEDGEMENT

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