A new approach for measuring the line-width enhancement factor

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Abstract

The paper presents a new approach for measuring the line-width enhancement factor (LEF) of semiconductor lasers (SLs). LEF can be measured using a technique called optical feedback self-mixing interferometry (OFSMI). However, the existing OFSMI based approaches require that optical feedback factor (denoted as C) associated with the SL systems within a narrow range. The proposed new method is also based on OFSMI principle. The method does not rely on the C factor, and is suitable for the whole moderate optical feedback regime. The associated simulations and the experiments are carried out for verifying the proposed method.

A New Approach For Measuring the Line-width Enhancement Factor

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***Abstract*— The paper presents a new approach for measuring the line-width enhancement factor (LEF) of semiconductor lasers (SLs). LEF can be measured using a technique called optical feedback self-mixing interferometry (OFSMI). However, the existing OFSMI based approaches require that optical feedback factor (denoted as *C*) associated with the SL systems within a narrow range. The proposed new method is also based on OFSMI principle. The method does not rely on the *C* factor, and is suitable for the whole moderate optical feedback regime. The associated simulations and the experiments are carried out for verifying the proposed method.**

Keywords-semiconductor laser; linewidth enhancement factor; optical feedback sensing

I. INTRODUCTION

Optical feedback slef-mixing interferometry (OFSMI) based on semiconductor lasers (SLs) has been considered as a highly promising and emerging technique for non-contact measurement and sensing with wide applications in industry, such as measurement of vibration, distance, displacement, piezo-ceramic transducer (PZT) parameters, and three dimensional imaging [1], amongst others. This technology is based on the influence of the external optical feedback on the output power and spectrum. OFSMI was firstly demonstrated by gas lasers [2]. With the development of SLs, OFSMI using SLs has become increasingly attractive[3], as compared to other conventional interferomic techniques, such as Michelson and Mach-Zehnder [1], OFSMI is low in component count and hence simple in structure, easy to align, and most importantly very compact in physical size.

In addition the applications for measuring metrological quantities listed above, another important application has been recognized recently for OFSMI which is the measurement of the linewidth enhancement factor (LEF) of SLs [4-6]. The LEF is a parameter quantifying the amplitude-phase coupling in a laser, which is a fundamental parameter of SLs that characterizes the characteristics of the SLs, such as the linewidth, the chirp, the injection lock range and the dynamic performances. However, the existing OFSMI based approaches for LEF measurement suffer from a problem that the measurement can only be carried out under a certain optical feedback level. That is, there is a limitation in the existing OFSMI approaches for LEF measurement. This paper will develop a new approach where the feedback range is broadened to cover the whole moderate optical feedback regime.

II. THE NEW APPROACH

A. Principle for Measuring C and α

OFSMI effect occurs when a small fraction of light emitted by a laser is reflected or backscattered by an external target and re-enters the laser internal cavity. The reflected component mixes with the emitting laser, resulting in a variation of the overall power and frequency of the emitted laser. OFSMI makes use of such effect for sensing. The OFSMI based sensing model is developed from Lang and Kobayashi (L-K) Equations [7], described as follows [1, 4-6]:

$$\phi_F = \phi_0 - C \cdot \sin[\phi_F + \arctan(\alpha)] \tag{1}$$

$$g(\phi_0) = \cos(\phi_F) \tag{2}$$

$$P(\phi_0) = P_0[1 + m \times g(\phi_0)] \tag{3}$$

Equation (1) describes the phase variation due to the optical feedback, with the variables defined as follows. $\phi_0 = 2\pi\upsilon_0\tau$, $\phi_F = 2\pi\nu_F\tau$, where ϕ_0 and ϕ_F are the external light phases of a SL without and with optical feedback respectively. υ_0 and υ_F are the optical frequencies of the SL in the two situations, and τ is the external roundtrip delay determined by the external cavity length *L* and the speed of light as $\tau = \frac{2L}{c}$.

Equation (2) is called interferometric function. $g(\phi_0)$ is called OFSMI signals. (3) gives the output power of the laser, denoted by $P(\phi_0)$, where P_0 is the power emitted by the free running SL, *m* is modulation index.

There are two important parameters in the model, that is, the optical feedback level factor *C*, and the LEF of a SL, denoted as α. *C* measures the influence of optical feedback

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on the behavior of a SL system [8, 9]. The situation for $0 < C < 1$ is referred to as weak optical feedback regime, while the case for $C > 1$ is called moderate regime. At the moderate regime, an OFSMI signal exhibit hysteresis phenomenon as shown in Fig. 1. When ϕ_0 increases, $g(\phi_0)$ follow the path A'-B-B', which is different from the path B'-A-A' for decreasing ϕ_0.

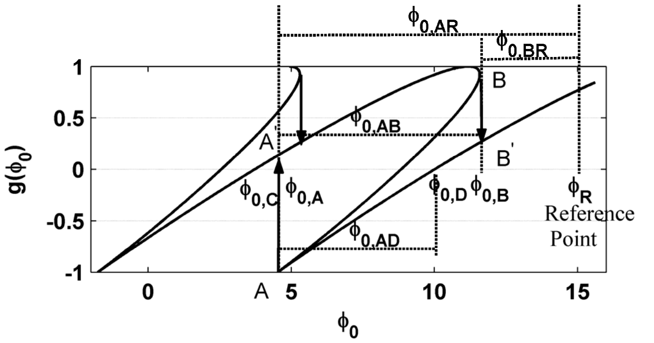

Figure 1. the OFSMI waveform at the moderate regime

The area A'-B-B'-A is called hysteresis area. Points A and B are jumping locations where $\frac{d\phi_F}{d\phi_0} \to \infty$. As shown by Figure 1, there are some characteristic points, including zero-crossing points $\phi_{0,C}$ and $\phi_{0,D}$, as well as jumping points $\phi_{0,A}$ and $\phi_{0,B}$. Based on (1)-(3) we can derive the following equations:

$$\phi_{0,AB} = 2\left\{\sqrt{C^2-1} + \arccos(\frac{-1}{C}) - \pi\right\} \qquad (4)$$

$$\phi_{0,AD} = \sqrt{C^2-1} - \frac{C}{\sqrt{1+\alpha^2}} + \arccos(-\frac{1}{C}) + \arctan(\alpha) - \frac{\pi}{2} \qquad (5)$$

where $\phi_{0,AB}$ and $\phi_{0,AD}$ are phase differences between jumping points A, B and zero-crossing point D respectively as shown in Figure 1. The above expressions can also be found in [4, 8]. Obviously, for measuring C and α, the key issue is to measure $\phi_{0,AB}$ and $\phi_{0,AD}$ using the observed OFSMI signal waveform. The approach in [4] has addressed this issue. However, when $C > 3$, the required characteristic points in the approach, some of them do not exist. Therefore we must choose other characteristic points which always exist and do not rely on C value.

For the simplicity of our description, we use 'up fringes' to denote the variance of $g(\phi_0)$ corresponding to increasing ϕ_0, and 'down fringes' to stand for the segments corresponding to decreasing ϕ_0. Let us suppose that the optical feedback is formed by an external target subject to an reciprocate movement. We will notice that in this situation we should be able to locate a reference point $\phi_{0,R}$ on the OFSMI waveform, which is the point when ϕ_0 reaches it maximum, shown in Fig. 1. We can also see that and there is always a zeros-crossing point $\phi_{0,D}$ on the down fringe segment following $\phi_{0,R}$ (that is, after ϕ_0 passes over it maximum $\phi_0 = \phi_{0,D}$). If we are able to measure $\phi_{0,AR}$ on the up fringe, and to measure $\phi_{0,BR}$ and $\phi_{0,DR}$ on the down fringe part, we can get $\phi_{0,AB}$ and $\phi_{0,AD}$ using $\phi_{0,AB} = \phi_{0,AR} - \phi_{0,BR}$ and $\phi_{0,AD} = \phi_{0,AR} - \phi_{0,DR}$.

B. Implementation of the Approach

In practice, OFSMI signal is obtained when ϕ_0 varies. As $\phi_0 = 4\pi v_0 L/c$, ϕ_0 can be modulated by changing the length of external cavity. In this case, OFSMI waveforms we observed are with respect to time rather than ϕ_0. In other words, the characteristic points $\phi_{0,A}$, $\phi_{0,B}$, $\phi_{0,D}$ and $\phi_{0,R}$ can not be directly located. However, we can locate the time instances corresponding to these characteristic points and what we should do is to convert the time intervals into the phase intervals.

Let us consider the case where the external target vibrates simple harmonically with the cavity length given by $L(t) = L_0 + \Delta L \sin(2\pi f t)$. Here f is the vibration frequency, ΔL is the vibration magnitude and L_0 is the initial external cavity length. The external light phase can be described as follows:

$$\phi_0(t) = A_0 + A_1 \sin(2\pi f t) \qquad (6)$$

where, $A_0 = \frac{4\pi L_0}{\lambda_0}$ and $A_1 = \frac{4\pi \Delta L}{\lambda_0}$.

In order to show the details of implementing the proposed approach, we plot the vibration phase $\phi_0(t)$ and its OFSMI waveform $g(t)$ as shown in Fig. 2 based on (1)-(3) and (6). The parameters for generating the OFSMI waveform in Fig. 2 are as follows: $A_0 = 3.9\times10^6$ (rad) $A_1 = 20.2$ (rad), $C = 4.5$ and $\alpha = 5$ respectively. t_R (corresponding to $\phi_{0,R}$) is the time instance when the target changes its movement direction, that is, when the external target has longest (or shortest) distance to the SL. We fold the right half of the waveform (i.e., down fringes) to the left (i.e., up fringes) along the axis $t = t_R$. The time instances corresponding to $\phi_{0,A}$, $\phi_{0,B}$, and $\phi_{0,D}$ are marked as t_A, t_B, and t_D shown in Fig. 2 (c). t_A is the first jumping moment in the down fringe area after t_R. t_D is the

first zero-crossing point in the down fringe area after t_R . t_B is the last jumping point in the up fringe area before t_R .

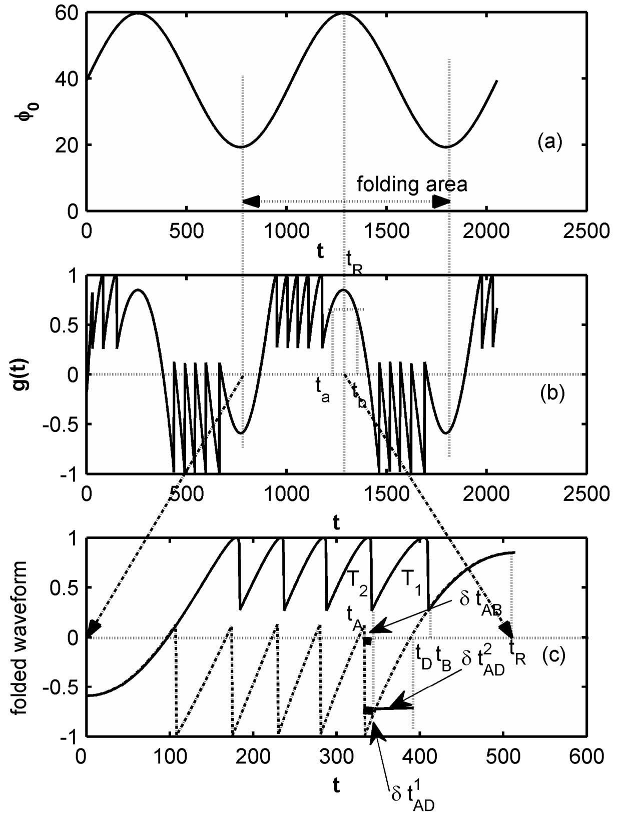

Figure 2. The measurement principle for $\phi_{0,AB}$ and $\phi_{0,AD}$ on a OFSMI waveform. (a) A sinusoid vibrating phase $\phi_0(t)$, (b) the simulated OFSMI signal with C=4.5, $\alpha = 5$, t_R is the reverse point of the vibration also the center of t_a and t_b, (c) the wrapped waveform for parameter measurement

With the above analysis the approach can be implemented by the following steps.

1) Determination of the reverse point t_R

The vibration reversing point can be located based on the local symmetric property at t_R moment. A simple way is to set a level line crossing the OFSMI signal around t_R , marked as t_a and t_b in Figure 2 (b), and the central position of the time t_a and t_b should be the time instance t_R .

2) Measurement of C

As indicated by Equation (4), we must obtain $\phi_{0,AB}$ in order to determine C . $\phi_{0,AB}$ can be obtained by measuring t_{AB} , which can span a few up fringes and can be expressed as $t_{AB} = T_1 + T_2 + \cdots + T_M + \delta t_{AB}$. M is the number of fully spanned fringes, and T_i (i=1, M) are the corresponding time interval covered by these fringes. δt_{AB} is the time interval on the fringe partially spanned. As each fringe period corresponds to a 2π in ϕ_0 , $\phi_{0,AB}$ can be estimated as follows:

$$\phi_{0,AB} = 2\pi(M + \frac{\delta t_{AB}}{T_{M+1}}) \qquad (7)$$

where T_{M+1} is the fringe period of the partly spanned fringe.

3) Measurement of α

In order to determine the α using Equation (5), we must know $\phi_{0,AD}$. For this purpose we should accurately measure t_{AD} and then convert it into $\phi_{0,AD}$. As shown in Figure 2 (c), t_{AD} also can span a number of up fringes. t_{AD} is divided into several sections by jumping lines of the up fringes, denoted as δt^1_{AD} , δt^2_{AD} , … We can estimate $\phi_{0,AD}$ as follows:

$$\phi_{0,AD} = \delta\phi^1_{0,AD} + \delta\phi^2_{0,AD} + ... = 2\pi(\frac{\delta t^1_{AD}}{T_1} + \frac{\delta t^2_{AD}}{T_2} + ...) \qquad (8)$$

where T_1 and T_2 are the periods of the up fringes associated to t_{AD} . Using (7) and (8), we can convert the measured time intervals to the phase intervals required by (4) and (5). Therefore, C and α can be calculated by the Equations.

The proposed approach can be summarized by the following procedure:

- Take a segment of OFSMI waveform covering at least one vibration cycle of external target, and locate t_R ;
- Fold (Wrap) the down fringe segment of the OFSMI waveform to the left side along the axis $t = t_R$;
- Measure M, T_{M+1} , and δt_{AB} on the folded OFSMI waveform, and then calculate $\phi_{0,AB}$ using (7)
- Measuring T_1 , T_2 …, and δt^1_{AD} , δt^2_{AD} , …, then calculate $\phi_{0,AD}$ using (8).
- Using (4) cooperating with $\phi_{0,AB}$ to get C.
- Using the obtained $\phi_{0,AD}$ and C, calculate α by (5).

III. SIMULATIONS AND EXPERIMENTS

A. Simulations

In order to test the performance, we applied the proposed approach to signals generated using the OFSMI model in Equations (1) –(3) where $\alpha = 3$ but C takes different values in

the moderate feedback regime. Fig. 3 presents the results of the estimated α which are around the true value 3. Note that the results are reasonably accurate as the maximal deviation is less than 0.2. Therefore we can say the proposed approach is able to give a reliable estimation for α at the whole moderate feedback regime.

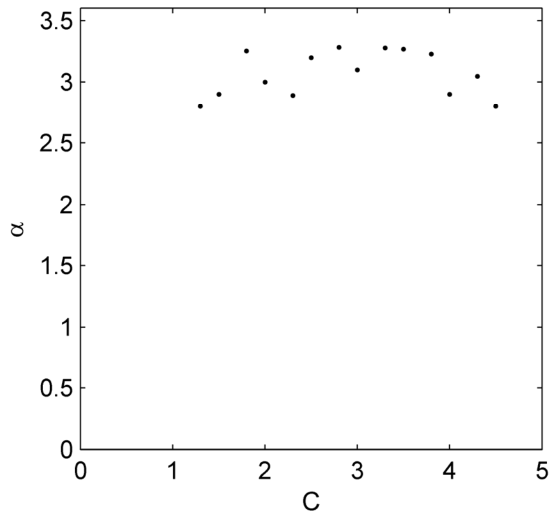

Figure 3. The estimated α using simulation signals at the whole moderate fedback regime

B. Experiments

We also applied the proposed approach to true data

TABLE I. EXPERIMENTAL RESULTS

	Estimated C by the Approach in [4]	*Estimated α by the Approach in [4]*	*Estimated C by the Proposed Approach*	*Estimated α by the Proposed Approach*
C<3	1.3	2.39	1.7	2.3
	1.4	2.7	1.8	2.5
	1.5	2.5	1.9	2.2
	1.8	2.6	2.0	2.4
	2.2	2.4	2.5	2.6
	2.3	2.7	2.8	2.2
	2.6	2.6		
	2.8	2.2		
c>3			3.2	2.9
			3.4	3.4
			4.1	4.5
			3.8	4.4
			4.1	4.3
			4.3	4.2
			4.4	3.8

acquired from an experimental set-up as the one in approach [4]. In the set-up a laser diode (HL7851G) is used. The feedback level can be easily adjusted by using different feedback surface. The measured results are shown in table 1

It can be seen, when C<3, the results of α values by the proposed approach yields are very close to the approach in [4]. While the approach in [4] does not work for C>3， the proposed approach can still give reliable measurement for α. From the results in Table 1, we found that the measured values for α are higher when C>3 in contrast to the case when C<3. This implies that α value is not constant and might be related to the *C* level. This is an interesting phenomenon which requires further investigation.

IV. CONCLUSION

The paper presents a new OFSMI based method for α measurement which works over the whole range of moderate optical feedback. The proposed approach is based on the usage of characteristic points which always exist and can always be located at the moderate optical feedback. Computer simulations and experimental verifications are also carried out in order to test the performance. It is shown that, when C<3, the proposed approach is able to yield α values which are consistent to the approach in [4]. When C>3,while the approach in [4] does not work, the proposed still can give reliable measurement.

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