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The paper presents a new approach for measuring the linewidth enhancement factor (LEF) of semiconductor lasers (SL) and the optical feedback level factor C in SLs. The proposed approach is based on the analysis of self-mixing signals observed in self-mixing optical feedback interferometry. Unlike existing approaches, the approach tries to estimate the parameters LEF and C by a gradient-based optimization algorithm that achieves best data-to-theoretical model fitting. The effectiveness and accuracy of the method have been confirmed and tested by theoretical analysis and computer simulations.

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Estimating the Parameters of Semiconductor Lasers Based on Weak Optical Feedback Interferometry

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Abstract—**The paper presents a new approach for measuring the linewidth enhancement factor (LEF) of semiconductor lasers (SL) and the optical feedback level factor C in SLs. The proposed approach is based on the analysis of self-mixing signals observed in self-mixing optical feedback interferometry. Unlike existing approaches, the approach tries to estimate the parameters LEF and C by a gradient-based optimization algorithm that achieves best data-to-theoretical model fitting. The effectiveness and accuracy of the method have been confirmed and tested by theoretical analysis and computer simulations.**

Keywords-Linewidth enhancement factor; optical feedback; self-mixing interferometry; semiconductor laser; fitting algorithm

I. INTRODUCTION

The self-mixing optical feedback interferometric effect occurs when a small fraction of the light emitted by a semiconductor laser (SL) is backscattered or reflected by an external target and re-enters the laser active cavity, resulting in the modulation of both the amplitude and the frequency of the lasing field. As the modulation carries information about the external target as well as the SL, the observed emitted power, also called the self-mixing signal, can be used to measure the metrological quantities [1,2] as well as the parameters of the SL's itself [3,4].

The self-mixing interferometric effect has been studied extensively with the results of a set of well-known mathematical models [5,6]. In the model, there are two parameters that are particularly important: linewidth enhancement factor (LEF) α and the optical feedback factor C. These two parameters are significant in that their values characterize the linewidth, the chirp, the injection lock range, and the response to optical feedback [7].

The measurement of linewidth enhancement factor á has been an active research topic and extensive work has been conducted [7]. Conventional approaches include those based on the direct measurement of the sub-threshold optical spectrum as the injected current is varied [8], approaches based on RF measurements [9] and techniques based on the analysis of the locking regimes induced by optical injection from a master laser [10,11].

Recently, an approach [4] has been proposed for the measuring α based on the self-mixing optical feedback interferometric effect in the cases of moderate feedback with 1<C<3. By the approach in [4] α is obtained by geometrically measuring the waveform of the self-mixing signals on the screen of oscilloscope. The approach is simple, but may suffer from low accuracy due to the resolution of the screen of oscilloscope as well as noises or interferences contained within the waveform.

This paper presents a new approach for measuringá, also based on the analysis of self-mixing signal. In contrast to the approach in [4], the proposed one is characterized by two advantageous aspects. Firstly, the proposed approach is based on the self-mixing effect in the conditions of weak feedback, that is, 0<C<1. In the weak feedback state, the nonlinear gain effect can be neglected, and the behavior is closer to those described by Lang-Kobayashi equation, and thus giving more accurate value of α. Secondly, instead of directly measuring the waveform, the proposed approach yields the parameters by a data-to-model fitting technique based on optimization of an objective function. In other words, parameters are determined so that the theoretical model incorporating the parameters gives the best matches to the observed data. The proposed approach is expected to have high accuracy in the cases of noisy environment.

II. BASIC 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 [5] and the three-mirror cavity based approach [6]. Both approaches yield the same description about the behavior of a single-mode SL with optical feedback, given by the following equations:

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

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

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

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 factor.

The above parameters are described in more details as follows: á 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 ε= 0.1-0.8).

The power emitted by the SL is given by Equation (2) where $P(\phi_F(\tau))$ 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 $mG(\phi_F(\tau))$ where m is called modulation index (typical $m \approx 10^{-3}$), and $G(\phi_F(\tau))$ is called the interferometric function which gives the effect of the external cavity length to the emitted power.

With a self-mixing experimental setup, the emitted power $P(\phi_F(\tau))$ can be observed with respect to different values of τ. By intentionally varying the length of external cavity, a trace of $P(\phi_F(\tau))$ with respect to τ can be obtained which is referred to as self-mixing signal or intereforemetric signal. Clearly from Equations (1), (2) and (3) that the observed self-mixing signal can be used to determine the parameters within the equations and some very important applications can be found based on the principle. Two examples are given as follows:

- Measurement of the linewidth factor and the feedback factor: For given values of $P(\phi_F(\tau_i))$ (i=1,2,..N), C andácan be obtained based on the model of Equations (1)-(3);
- Displacement Measurement: When C and *á* are known, the waveform of can be used to yield the information about $P(\phi_F(\tau_i))$ (i=1,2,..N) and thus the displacement of the target using $\tau = 2L/c$.

Equations (1)-(3) also reveals $G(\phi_F(\tau))$ is a function of k and C. Therefore for clearly expressing the relationships between $G(\phi_F(\tau))$ and those parameters, we introduce the following expression for the interferometric function:

$$G(\tau, k, C) = \cos[\omega_0 \tau - C \sin(\omega_F \tau + k)] \quad (4)$$

III. THE NEW APPROACH

The waveform of the self-mixing signal $P(\phi_F(\tau))$ can be recorded by data acquisition setup. Using Equation (2), we can get $G(\phi_F(\tau))$ by utilizing $G(\phi_F(\tau)) = \frac{P(\phi_F(\tau)) - P_0}{mP_0}$. For simplicity, we will simply consider to use $G(\phi_F(\tau))$ to find the parameters C and k (and thus α by $k = \arctan(\alpha)$). In other words, we assume that N data samples $G(\tau_i)$ (for i=1, 2, ..N) are observed by a experimental system, and our purpose is to estimate the values of C and k based on those data samples.

The proposed technique is based on a data fitting technique. The idea is to find the values of C and k so that the Equations (1) and (3) best fit the observed data samples. In order to achieve the best fitting, we define the following objective function:

$$F(\hat{k}, \hat{C}) = \sum_{i=1}^{N} \left\{ G(\tau_i) - \hat{G}(\tau_i, \hat{k}, \hat{C}) \right\}^2 \quad (5)$$

where $\hat{G}(\tau_i, \hat{k}, \hat{C})$ are the values based on computation using Equations (1) and (3) incorporating the estimated values of $\hat{C}$ and $\hat{k}$. Clearly the above-defined objective function is proportional to the average square of the error between the observed data samples and the calculated ones using the model. $\hat{C}$ and $\hat{k}$ are considered as optimal if the above objective function is minimized.

We will use a gradient-based algorithm for the above optimization problem. The idea is to update the two parameters $\hat{C}$ and $\hat{k}$ toward the direction in which the objective function decreases (the negative gradients):

$$\hat{C}_j = \hat{C}_{j-1} - \mu \frac{\partial F}{\partial \hat{C}} |_{\hat{C} = \hat{C}_{j-1}} \quad (6)$$

$$\hat{k}_j = \hat{k}_{j-1} - \mu \frac{\partial F}{\partial \hat{k}} |_{\hat{k} = \hat{k}_{j-1}} \quad (7)$$

where $\mu > 0$ is the step size and the subscript j refers to the iteration index for updating the parameters.

The gradients of $F(\hat{k}, \hat{C})$ with respect to parameters $\hat{C}$ and $\hat{k}$ can be derived as follows:

$$\frac{\partial F}{\partial C} = 2\sum_{i=1}^{N}\left\{G(\tau_i) - \hat{G}(\tau_i,\hat{k},\hat{C})\right\}\frac{\partial \hat{G}(\tau_i,\hat{k},\hat{C})}{\partial \hat{C}}$$
$$= 2\sum_{i=1}^{N}\left\{G(\tau_i) - \hat{G}(\tau_i,\hat{k},\hat{C})\right\}\sin[\phi_0(\tau_i) - \hat{C}\sin(\phi_F(\tau_i)+\hat{k})]\sin(\phi_F(\tau_i)+\hat{k}) \quad (8)$$

$$\frac{\partial F}{\partial k} = 2\sum_{i=1}^{N}\left\{G(\tau_i) - \hat{G}(\tau_i,\hat{k},\hat{C})\right\}\frac{\partial \hat{G}(\tau_i,\hat{k},\hat{C})}{\partial \hat{k}}$$
$$= 2\hat{C}\sum_{i=1}^{N}\left\{G(\tau_i) - \hat{G}(\tau_i,\hat{k},\hat{C})\right\} \times\sin[\phi_0(\tau_i) - \hat{C}\sin(\phi_F(\tau_i)+\hat{k})]\cos(\phi_F(\tau_i)+\hat{k}) \quad (9)$$

In order to use the above equations to calculate the gradients, we must get $\hat{G}(\tau_i,\hat{k},\hat{C})$ first. It is seen that for given $\hat{C}$, $\hat{k}$ and τ_i (i=1,2,..N), the phase $\phi_F(\tau_i)$ (i=1,2,..,N) can be obtained by solving Equation (1). However, there is not an analytical solution for $\phi_F(\tau_i)$. A simple way is to use the following iterative operation:

$$f_j(\tau_i) = \phi_0(\tau_i) - \hat{C}\sin(f_{j-1}(\tau_i)+\hat{k}) \quad (10)$$

The gradient-based algorithm is summarized as:

- Start: Set initial values for C and k;
- Step 1: Start from the initial value $f_0(\tau_i) = \omega_0\tau_i$, repeat iterating Equation (10) to yield $\phi_F(\tau_i)$;
- Step 2: Calculate the gradients using Equations (7) and (8);
- Step 3: Update C and k using Equations (5) and (6);
- Step 4: Go to Step 1 or stop.

IV. PERFORMANCE SIMULATION

The firstly step is to create self-mixing signal samples $G(\tau_i)$ (for i=1, 2, .., N) which are used as the observed data in our simulation. We use the model of Equations (1) to (3) to obtain the signal samples, assuming that the true values of C and α are known as C_0 and α_0 respectively. In addition, the external target is assumed to be subject to a simple harmonic vibration that is, $L = L_0 + \Delta L\cos(2\pi ft)$, where L_0 is the initial distance between laser emitting surface and the target, $f = 30\ Hz$ is the vibration frequency, t is time variable. Let L_0/λ_0=30000 and $\Delta L/\lambda_0$=3.3. Hence we have $\omega_0\tau_i = \omega_0\frac{2L_i}{c} = \frac{4\pi L_i}{\lambda_0} = 12\pi[10000 + 1.1\cos(60\pi t_i)]$, for one period of t ([0,1/30]), we make simulation as following. Step 1 is employed to yield $\phi(\tau_i)$ and then data samples are created using Equation (3). In order to emulate the practical situation, a small white noise is also added with a preset the signal-to-noise ration (SNR). The data samples with the true parameters of $C_0 = 0.8$ and $\alpha_0 = 4$ created by Equations (1) to (3) are plot in Figure 1, in which Figure1(a) shows the phase variation of external light when the target vibrates, Figure 1(b) shows the self-mixing signal with SNR=20dB.

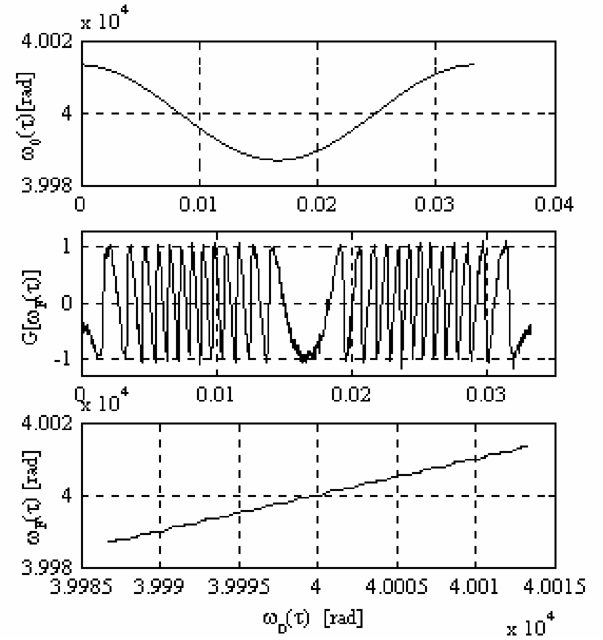

Figure 1. Data samples created by Equations (1) - (3) used for estimating α and C

Computer simulations are performed using the created data. The following situations are studied:

- Firstly we study the performance of the algorithms with fixed initial values. A safest way to choose the initial values is to use the middle values of the possible range that the parameters may appear. As $0 < C < 1$ and generally, $0 < \alpha < 9$, we can choose the initial values $\hat{C}_0 = 0.4$ and $\hat{\alpha}_0 = 5$. The SNR is set to be 20dB. The results for different true values are presented in Table I. The error in the table is calculated as relative deviation of the true. It is seen that the approach yield satisfactory estimation of the parameters.
- Then we investigate the effect of the initial values to the performance. In this case we keep the true parameter values constant as $C_0 = 0.8$ and $\alpha_0 = 4$, and run the simulations starting from the different initial values of C and k. Also the SNR is set to be 20dB. The results are shown in Table II. It is seen that the approach still yields very good accuracy, and the initial values don' t affect the results.

- Finally we study the effect of the noise to the accuracy of the algorithm. The true parameter values are set to be $C_0 = 0.8$ and $\alpha_0 = 4$, and initial values are $\hat{C}_0 = 0.5$ and $\hat{\alpha}_0 = 5$. Simulations are performed with the different level of SNR. The results are shown in Table III. It is seen that the accuracy is satisfactory in most cases. Note that for obtaining a better accuracy for a signal with low SNR, we increase the data samples, the iterative times and better selection of step sizes.

TABLE I. THE RESULTS FOR DIFFERENT TRUE VALUES WITH FIXED INITIAL VALUES $\hat{\alpha}_0$ =5 AND $\hat{C}_0$ =0.4

α_0	C_0	$\hat{\alpha}_0$	Error with $\hat{\alpha}_0$	$\hat{C}_0$	Error with $\hat{C}_0$
1	0.2	1.0364	3.64%	0.1950	2.49%
2	0.4	2.0353	1.6%	0.4113	2.8%
3	0.6	3.0289	0.9%	0.6186	3.1%
4	0.8	4.0427	1.0%	0.7904	1.2%
5	0.9	5.0530	1.059%	0.9078	0.86%
6	0.5	6.0966	1.61%	0.5031	0.61%

TABLE II. THE EFFECT OF THE INITIAL VALUES WITH FIXED TRUE VALUES α_0 =4 AND C_0=0.8

Initial $\hat{\alpha}_0$	Initial $\hat{C}_0$	$\hat{\alpha}_0$	Error with $\hat{\alpha}_0$	$\hat{C}_0$	Error with $\hat{C}_0$
1	0.2	4.0667	1.67%	0.7982	0.23%
2	0.4	3.9487	1.28%	0.7908	1.15%
3	0.6	4.0574	1.43%	0.8019	0.23%
5	0.8	4.0551	1.38%	0.8162	2.02%
6	0.9	3.9755	0.61%	0.7980	0.25%

TABLE III. THE EFFECT OF THE NOISE WITH THE TRUE VALUES α_0=4 AND C_0=0.8

SNR(dB)	$\hat{\alpha}_0$	Error with $\hat{\alpha}_0$	$\hat{C}_0$	Error with $\hat{C}_0$
50	4.0004	0.01%	0.8003	0.03%
40	4.0044	0.11%	0.7991	0.12%
30	3.9781	0.55%	0.8007	0.09%
20	4.0538	1.34%	0.8024	0.26%
10	3.8963	2.59%	0.7741	3.23%
5	3.6560	8.6%	0.7733	3.33%

V. CONCLUSION

We have presented a new approach to estimate the linewidth enhancement factor of SLs and optical feedback factor in SLs. This method is based on the analysis of the self-mixing signals of optical feedback interferometry with a single-mode SL operating at weak optical feedback regime. The effectiveness for the proposed gradient-based algorithm has been confirmed from the theoretical analysis and computer simulations. It is shown that that the approach is robust in that the initial values can be arbitrarily chosen within the range of parameters. Also the estimation errors can be less than 3.3% when SNR is higher than 10dB. The proposed approach is expected to have higher accuracy in noisy environment if we increase the number of data samples and the iterations.

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