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Estimating the parameters of semiconductor lasers based on weak optical feedback self-mixing interferometry

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Keywords

Linewidth enhancement factor (LEF), optical feedback, optimization algorithm, self-mixing interferometry, semiconductor lasers

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

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***Abstract*—The paper presents a practical approach for measuring the linewidth enhancement factor α of semiconductor lasers and the optical feedback level factor C in a semiconductor laser with an external cavity. The proposed approach is based on the analysis of the signals observed in an optical feedback self-mixing interferometric system. The parameters α and C are estimated using a gradient-based optimization algorithm that achieves best data-to-theoretical model match. The effectiveness and accuracy of the method has been confirmed and tested by computer simulations and experiments, which show that the proposed approach is able to estimate α and C with an accuracy of 6.7% and 4.63%, respectively.**

***Index Terms*—Linewidth enhancement factor (LEF), optical feedback, optimization algorithm, self-mixing interferometry, semiconductor lasers.**

I. Introduction

The optical feedback interferometric self-mixing (OFISM) effect occurs when a small fraction of the light emitted by a semiconductor laser (SL) is backscattered or reflected by an external target (that formed the external cavity for the SL) and re-enters the laser active cavity, resulting in variance of both the amplitude and the frequency of the laser oscillating field. The OFISM effect has been studied extensively based on Lang–Kobayashi equations [1] and well-known mathematical expressions for the steady-state gain and the phase condition have been developed [2]–[4]. These expressions are used as the basic measurement model for an OFISM system [5]–[10]. With the model, the influence of the OFISM system parameters to the emitted laser intensity is described. In other words, the emitted laser intensity carries information about the OFISM system parameters, including metrological quantities of the external target as well as the parameters of the SL. Therefore, the observed laser intensity from an OFISM, also called the self-mixing signal (SMS), can be used to measure the metrological quantities [7], [8] of the external target as well as the parameters of the SL itself [9], [10].

Linewidth enhancement factor (LEF) (denoted as α) is a fundamental parameter of SLs as it characterizes the linewidth, the chirp, the injection lock range, and the response to optical feedback [11]. Establishing an accurate measurement of α has been a challenging and active research topic that has attracted extensive research work during the past two decades [11]. Existing approaches include the direct measurement of the subthreshold optical spectrum as the injected current is varied [12], approaches based on radio-frequency measurements [13] and techniques based on the analysis of the locking regimes induced by optical injection from a master laser [14], [15]. Another important characteristic parameter associated with the OFISM effect is the optical feedback level factor (OFLF) C, which measures the relative strength of the optical feedback. A variance in C will cause significant change in the intrinsic behavior of OFISM systems [2].

The influence of the parameters α and C on the emitted laser intensity has been extensively analyzed in [2] and [5]. It was indicated in [2] that α and C can be estimated using an OFISM system by comparing the experimental waveform with the theoretical one. However, the specifics of how the latter may be achieved are not discussed in [2].

Recently, an approach [10] has been proposed for measuring α based on the OFISM effect for moderate feedback where $1 < C < 3$. With the approach in [10], α is obtained by geometrically measuring the waveforms of the SMSs on the screen of oscilloscope. The approach is simple but potentially suffers from noise effects contained within the waveforms as only four samples of the experimental data are used for each the computation of α.

This paper presents a generic approach for estimating both α and C, based on the analysis of SMS waveform observed at OFISM systems. The idea is to estimate the parameters so that the theoretical model incorporating the estimated parameter values gives the best matches to the observed SMS data. In contrast to the approach in [10], the proposed method makes use of the whole SMS waveform and hence higher accuracy is expected when the observed SMS data contains additive noise. In addition, as the OFISM system operates at the case of $0 < C < 1$, the theoretical model based on the Lang–Kobayashi equations is more accurate for describing the OFISM system as the equations were built at weak feedback regime. Hence the proposed approach is considered superior to existing methods in terms of overall accuracy performance for measuring α.

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II. Basic Theory

The basic theoretical model for an OFISM system is as follows [1]–[10]:

$$\phi_F(\tau) = \phi_0(\tau) - C \cdot \sin[\phi_F(\tau) + k] \tag{1}$$
$$P(\tau) = P_0[1 + mG(\tau)] \tag{2}$$
$$G(\tau) = \cos(\phi_F(\tau)). \tag{3}$$

Equation (1) is called the phase condition, in which the parameters are defined as follows. $\phi_0(\tau) = \omega_0\tau$ 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, $k = \arctan(\alpha)$.

Equation (2) gives the intensity of laser emitted by the SL, where $P(\tau)$ and P_0 denote the laser intensities of the SL with and without the external cavity, respectively. It is seen that $P(\tau)$ deviates from P_0 by a factor of $mG(\tau)$ when the external cavity exists, m is called modulation index (typically $m \approx 10^{-3}$). $G(\tau)$ is defined by (3) which gives the influence of the external cavity length to the laser intensity.

The above parameters can be described in more detail. The LEF α is defined as $\alpha = ((\partial n_R/\partial N)/(\partial n_I/\partial N))$, where N, n_R, n_I are the carrier density in laser medium, the real and imaginary part of the refractive index, respectively. $C = \varepsilon((L \cdot \sqrt{1+\alpha^2})/(l \cdot n))\sqrt{R_{\text{ext}}}((1-R_2)/\sqrt{R_2})$, 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 a coefficient that accounts for spatial mode overlap mismatch between the back-reflected light and the lasing mode (typically $\varepsilon = 0.1 - 0.8$).

With an OFISM experimental setup, the laser intensity $P(\tau)$ can be observed with respect to different values of τ. By intentionally varying the length of external cavity, a trace of $P(\tau)$ with respect to τ (or time t) can be obtained which is referred to as SMS. Clearly from (1)–(3), it is evident that the observed SMS can be used to determine the parameters within the equations and some very important applications can be found based on this principle. Two examples are given as follows.

1) Measurement of the α and the feedback level factor C: when $P(\tau_i)$ $(i = 1, 2 \ldots N)$ is observed, C and α can be estimated based on (1)–(3).
2) Displacement measurement: When C and α are known, the observed $P(\tau_i)$ can be used to yield the information about τ_i $(i = 1, 2, \ldots, N)$ and hence the displacement of the target using $\tau = 2L/c$.

In this paper, we consider the situation in 1) above. As $G(\tau)$ can be obtained by (2), i.e., $G(\tau) = ((P(\tau) - P_0)/(mP_0))$, we can simply use $G(\tau)$ to find the parameters C and k (and thus α since $k = \arctan(\alpha)$). In other words, we assume that N data samples $G(\tau_i)$ (for $i = 1, 2, \ldots, N$) are observed by an experimental system, and our purpose is to estimate the values of C and k based on those data samples.

Obviously the theoretical relationship between $G(\tau)$ and the parameters τ, k, and C plays a key role for achieving the measurement. In other words, it is useful to introduce the following expression for the interference function based on (1) and (3):

$$G(\tau, k, C) = \cos[\omega_0\tau - C\sin(\omega_F(\tau)\tau + k)]. \tag{4}$$

III. Algorithm

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

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

where $\hat{G}(\tau_i, \hat{k}, \hat{C})$ are the values based on computation using (1) and (3) incorporating the estimated values of $\hat{C}$ and $\hat{k}$. Clearly the above-defined cost function is the summation of square errors between the observed data samples and the calculated ones using the model. $\hat{C}$ and $\hat{k}$ are considered as optimal if the above cost 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 cost functions decreases (the negative gradients)

$$\hat{C}_j = \hat{C}_{j-1} - \mu_1 \frac{\partial F}{\partial \hat{C}}\Big|_{\hat{C}=\hat{C}_{j-1}} \tag{6}$$
$$\hat{k}_j = \hat{k}_{j-1} - \mu_2 \frac{\partial F}{\partial \hat{k}}\Big|_{\hat{k}=\hat{k}_{j-1}} \tag{7}$$

where $\mu_1, \mu_2 > 0$ are 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:

$$\begin{aligned}\frac{\partial F}{\partial C} &= 2\sum_{i=1}^{N}\{G(\tau_i) - \hat{G}(\tau_i, \hat{k}, \hat{C})\}\frac{\partial \hat{G}(\tau_i, \hat{k}, \hat{C})}{\partial \hat{C}}\\ &= -2\sum_{i=1}^{N}\{G(\tau_i) - \hat{G}(\tau_i, \hat{k}, \hat{C})\}\\ &\quad \times \sin[\phi_0(\tau_i) - \hat{C}\sin(\phi_F(\tau_i) + \hat{k})]\\ &\quad \times \sin(\phi_F(\tau_i) + \hat{k})\end{aligned} \tag{8}$$

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

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

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

TABLE I
SUMMARY OF THE ALGORITHM

Start: Set initial values for C and k;
Step 1: Starting from the initial value $f_0(\tau_i) = \omega_0 \tau_i$, update $\phi_F(\tau_i)$ iteration using Equation (10) until a steady state is reached which will be used as $\phi_F(\tau_i)$;
Step 2: Calculate the gradients using Equations (8) and (9);
Step 3: Update C and k using Equations (6) and (7);
Step 4: Go to Step 1 or stop.

We must choose an initial estimate for $f_0(\tau_i)$ in order to start the iterative process. As $\phi_F(\tau_i)$ varies around $\phi_0(\tau_i)$, a straightforward selection is that $f_0(\tau_i) = \phi_0(\tau_i) = \omega_0\tau_i$. Starting from the initial value, (10) is used iteratively to update $f_j(\tau_i)$ until a steady state is reached which can be tested by $|f_j(\tau_i) - f_{j-1}(\tau_i)| < \delta$ (where $\delta > 0$ is a small positive number). Then the phase $\phi_F(\tau_i)$ can be obtained as follows:

$$\phi_F(\tau_i) = f_\infty(\tau_i) \tag{11}$$

where $f_\infty(\tau_i)$ denotes the steady-state value. It can be shown that the iterative operation in (10) will always yield a steady-state value which must be the solution of (1).

The gradient-based algorithm derived above is summarized in Table I.

According to optimization theory, the performance of a gradient-based approach depends on the characteristics of the cost function with respect to the optimizing variables. For the proposed approach, the surface shape of the cost function in (5) with respect to the estimated parameter values $\hat{C}$ and $\hat{\alpha}$ plays a key role for the convergence of the algorithm. For this reason computer simulations have been performed to evaluate the surface shape. In our simulations, $G(\tau_i)$ (for $i = 1, 2, \ldots, N$) is firstly created using (1) and (3) for specific values of C and α. The cost function is then evaluated to yield the surface shape by varying the estimated values of C and α. The simulations show that the cost function is always unimodal, which implies good convergence of the proposed algorithm with proper selection the step size. As an example, Fig. 1 illustrates the surface shape of the cost function for the case with the true parameters $C = 0.5$ and $\alpha = 4$.

IV. PERFORMANCE SIMULATION

Computer simulations were performed to test the effectiveness of the proposed algorithm. The firstly step is to create SMS samples $G(\tau_i)$ (for $i = 1, 2, \ldots, N$) which are used as the observed data in our simulation. We assume that the external target is subject to a simple harmonic vibration, that is, $L(t) = L_0 + \Delta L \cos(2\pi f t)$, where L_0 is the initial distance between laser emitting surface and the target, f is the vibration frequency, t is time variable. Letting $\phi_0(\tau_i) = \phi_0(\tau(t_i))$ denote the laser phase at N time instances t_i (for $i = 1, 2, \ldots, N$), we have

$$\phi_0(\tau_i) = \phi_0(\tau(t_i)) = \frac{4\pi L(t_i)}{\lambda_0} = \varphi_0 + \frac{4\pi\Delta L}{\lambda_0}\cos(2\pi f t_i) \tag{12}$$

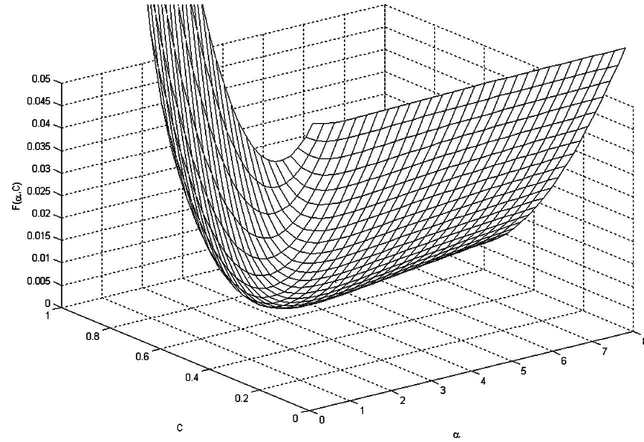

Fig. 1. Surface shape of the cost function versus α and C.

where $\varphi_0 = ((4\pi L_0)/\lambda_0)$, and λ_0 is laser wavelength without feedback.

A. Simulation of SMSs

We use (12), (1)–(3) to generate a set of artificial signal samples, assuming that the true values of C and α are known as C_0 and α_0, respectively. We firstly calculate $\phi_F(\tau_i)$ using Step 1 of Table I, and then obtain the SMS samples $G(\tau_i)$ using (3). For example, if $f = 30$ Hz, $L_0/\lambda_0 = 30\,000$ and $\Delta L/\lambda_0 = 3.3$, we will have $\phi_0(\tau_i) = 376\,800 + 41.45\cos(60\pi t_i)$. In order to emulate the practical situation, a small white noise is also added with a preset signal-to-noise ratio (SNR). The SMS samples with the true parameters of $C_0 = 0.8$ and $\alpha_0 = 4$ are plotted in Fig. 2.

B. Estimation of φ_0

In order to employ the gradient based algorithm proposed in Section III, φ_0 must be available. However φ_0 is unknown in practice and must be estimated. In fact we can also use a gradient based algorithm to estimate φ_0 by the following cost function:

$$F(\hat{\varphi}_0) = \sum_{i=1}^{N}[G(\tau_i) - \hat{G}(\tau_i(\hat{\varphi}_0), k, C)]^2 \tag{13}$$

where we use $\tau_i(\hat{\varphi}_0)$ simply because τ_i is a function of φ_0 as indicated by (12). As $\hat{G}(\tau_i(\hat{\varphi}_{0j}), k, C) = \hat{G}(\tau_i(\hat{\varphi}_{0j} + 2m\pi), k, C)$ for any integer m, it is sufficient to assume that φ_0 is within the range of $(0, 2\pi)$ for optimizing the cost function. However, the cost function contains C and k which are also unknown. Fortunately, we found that the optimal solution for φ_0 is not sensitive to the values of C and k, which makes it possible to use preset values C_0 and k_0 for determining φ_0 by (13).

In order to verify the validity of the above approach, computer simulations have been performed for various preset values C_0 and k_0. For each actual φ_0 with a set of preset values of α_0 and C_0, we repeat simulation 15 times using the generated SMS data, each containing independent additive noise. We use the average of the estimated parameter value as the estimation result, that is $\hat{\varphi}_0 = (1/15)\sum_{i=1}^{15}\hat{\varphi}_0$. The results show that the accurate estimation of φ_0 can be obtained. For illustration purpose, we present some of the simulation results in Table II. Note that δ_{φ_0} denotes the standard deviation of the estimated results from

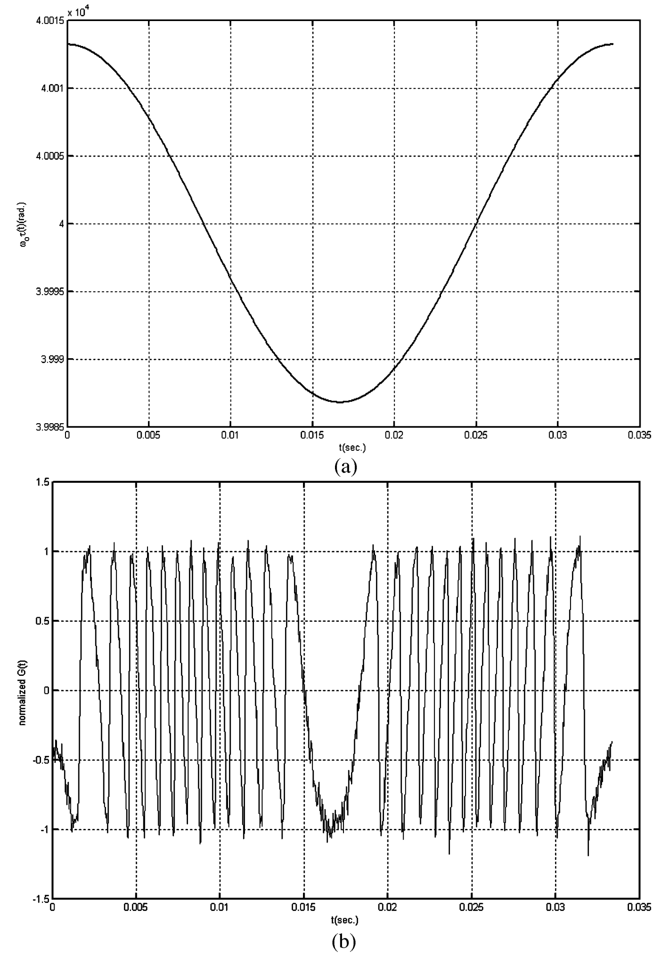

Fig. 2. Simulated data samples created by (1)–(3) and (12) with $C_0 = 0.8$ and $\alpha_0 = 4$. Upper plot: the variation trace of $\omega_0\tau$; Lower plot: the created SMS data superposed a noise signal with $\mathrm{SNR} = 20$ dB.

TABLE II
ESTIMATING RESULTS OF PARAMETER φ_0 WITH ACTUAL VALUES $\alpha_0 = 5$ AND $C_0 = 0.5$

Pre-set values		actual		
$\hat{\alpha}_0$	$\hat{C}_0$	φ_0	$\hat{\varphi}_0$	$\delta_{\varphi_0}/\varphi_0$
2	0.7	1.5708	1.5705	0.15%
5	0.5	3.1416	3.1424	0.13%
8	0.4	4.7124	4.7113	0.06%
0.6	0.7	5.6549	5.6551	0.06%

φ_0 over the 15 rounds of simulations, and the ratios $\delta_{\varphi_0}/\varphi_0$ as a percentage is used to describe the accuracy and consistency of the simulation results.

C. Simulation of the Proposed Gradient-Based Algorithm

Let us now evaluate the proposed gradient-based algorithm for measuring α and k. Various situations were considered using the generated data for each set of actual values of α_0 and C_0.

1) First, we study the performance of the algorithms with fixed initial values. As the surface of the cost function is unimodal then it is appropriate to select an initial estimate in the middle of the possible range that the parameters may appear. As $0 < C < 1$ and generally $0 < \alpha < 9$, we can choose the initial values $\hat{C}_0 = 0.5$ and $\hat{\alpha}_0 = 5$. The SNR is set to be 20 dB. Based on trial and error we choose the step size as $\mu_1 = 0.0001$ for C and $\mu_2 = 0.0007$ for α. The number of iterations taken for updating C and α is 1000. The simulation results for different true values are presented in Table III, in which each row gives the estimated parameter values based on 15 times of data fitting using the same set of SMS data with the actual parameter values. It is seen that $\delta_{\alpha_0}/\alpha_0$ is always less than 5.95% and δ_{C_0}/C_0 less than 1.64%. Note that the errors are different for the cases considered. This might be due to the use of constant step size μ_1 and μ_2 for all the situations. It is expected that better results could be achieved by more careful selection of the step sizes or using variable step-sizes.
2) Second, we investigate the effect of the initial values on the performance. In this case we keep the actual parameter values constant as $C_0 = 0.6$, $\alpha_0 = 4$ and $\varphi_0 = \pi/10$, and run the simulations starting with different initial values of C and k, respectively. The SNR is set at 20dB and the step sizes are chosen as described in part 1). The results are shown in Table IV. It is seen that the approach yields very accurate parameter estimation for all of the initial values chosen. In other words, the proposed algorithm has an excellent convergence property in that the estimated parameters always converge to the actual values from all different directions.
3) Now we study the effect of noise on the accuracy of the algorithm. The actual parameter values are set to be $C_0 = 0.8$, $\alpha_0 = 4$ and $\varphi_0 = \pi/10$, and initial values are $\hat{C}_0 = 0.5$, $\hat{\alpha}_0 = 5$ and $\hat{\varphi}_0 = \pi$. Simulations are performed with different level of SNR. The results are shown in Table V. It is seen that the accuracy is satisfactory when SNR is better than 10 dB.

V. EXPERIMENT RESULTS

The OFISM experimental setup is shown in Fig. 3. The SL is biased with a dc current, a lens is used to focus the light emitted by the SL on the target. A metal plate is used as the target, which is made to vibrate harmonically by placing it close to a loudspeaker driven by a sinusoidal signal. The SMS is detected by the monitor photodiode (PD) and is amplified by a trans-impedance amplifier. The amplified signal is then acquired by personal computer via an A/D card with sampling frequency of 200 KHz. As an example, an experimental SMS is shown in Fig. 4.

In the experiment, we use a laser diode (HL7851) as the test specimen. The LD is biased with a dc current of 80 mA and operates at single mode. The sinusoidal signal driving the loudspeaker is 195 Hz and has peak-to-peak (p-p) amplitude of 10 V. The temperature of LD is maintained at 25 °C ± 0.1 °C by the temperature controller. The above experiment conditions are kept fixed throughout our experiment. However, in order to get different C levels, we adjusted the target position slightly, obtained four sets of SMSs with different p-p amplitudes, each

TABLE III
RESULTS FOR DIFFERENT TRUE VALUES WITH FIXED INITIAL VALUES $\hat{\alpha_0} = 5$ AND $\hat{C}_0 = 0.5$ $\hat{\varphi}_0 = \pi$

actual α_0	actual C_0	actual φ_0	$\hat{\alpha}_0$	$\delta_{\alpha_0}/\alpha_0$	$\hat{C}_0$	δ_{C_0}/C_0	$\hat{\varphi}_0$	$\delta_{\varphi_0}/\varphi_0$
0.1	0.8	1.2566	0.1000	5.95%	0.8008	0.59%	1.2580	0.32%
0.5	0.6	2.5133	0.4917	3.98%	0.6005	1.00%	5.5143	0.15%
2.0	0.4	3.7699	2.0175	3.08%	0.4065	1.64%	3.7719	0.08%
4.0	0.9	5.0265	4.0613	2.81%	0.9008	0.86%	5.0254	0.09%
8.0	0.7	5.6549	7.9912	4.74%	0.6986	1.59%	5.6542	0.06%

TABLE IV
EFFECT OF THE INITIAL VALUES WITH FIXED TRUE VALUES $\alpha_0 = 4; C_0 = 0.6, \varphi_0 = \pi/10$ AND INITAL $\hat{\varphi}_0 = \pi$

Initial α_0	Initial C_0	Initial φ_0	$\hat{\alpha}_0$	$\delta_{\alpha_0}/\alpha_0$	$\hat{C}_0$	δ_{C_0}/C_0	$\hat{\varphi}_0$	$\delta_{\varphi_0}/\varphi_0$
1.5	0.2	$2\pi/5$	3.9841	2.75%	0.5979	1.00%	0.3146	1.05%
4.1	0.5	$4\pi/5$	3.9567	3.16%	0.5984	1.29%	0.3150	1.09%
5.5	0.3	$3\pi/5$	4.0311	3.51%	0.6024	1.00%	0.3140	1.38%
1.2	0.8	$\pi/5$	4.0098	3.08%	0.6019	1.18%	0.3138	1.03%
7.2	0.6	π	3.9789	2.81%	0.6005	1.19%	0.3156	1.46%

TABLE V
EFFECT OF THE NOISE WITH THE TRUE VALUES $\alpha_0 = 4$ AND $C_0 = 0.8$ $\varphi_0 = \pi/10$

SNR(dB)	$\hat{\alpha}_0$	$\delta_{\alpha_0}/\alpha_0$	$\hat{C}_0$	δ_{C_0}/C_0	$\hat{\varphi}_0$	$\delta_{\varphi_0}/\varphi_0$
40	4.0025	0.25%	0.8004	0.15%	0.3141	0.13%
30	3.9980	0.78%	0.8007	0.26%	0.3140	0.46%
20	4.0017	1.66%	0.8010	0.69%	0.3136	0.85%
10	3.8943	6.33%	0.8033	2.70%	0.3196	3.05%
5	3.9319	11.67%	0.8012	4.84%	0.3198	5.72%

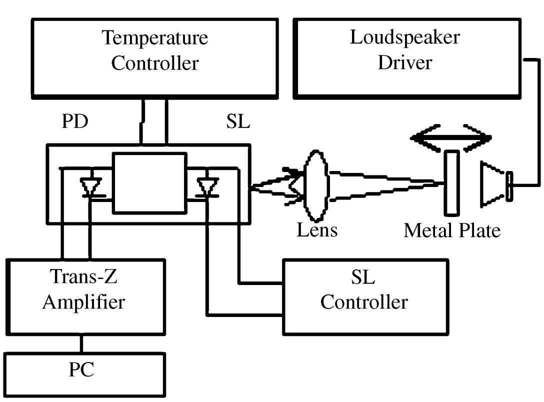

Fig. 3. OFISM experimental setup used for obtaining SMSs.

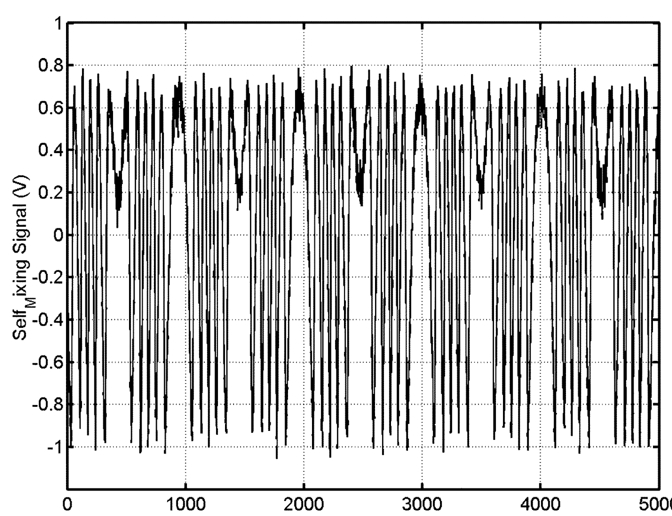

Fig. 4. SMS obtained from the OFISM experimental setup.

containing 50 000 data samples, respectively. For each SMS, we chose ten blocks, each corresponding to a vibration period of the target. We firstly apply the proposed algorithm to each block to yield estimated parameter values for α and C, and then these values are averaged to over the ten blocks to obtain the final estimation. Also we use the $\delta_{\alpha_0}/\hat{\alpha}_0$ and $\delta_{C_0}/\hat{C}_0$ to measure the accuracy of the estimation. The final estimation results and their associated accuracy are given in Table VI. It is seen that the estimated values of α are consistent for the four different SMSs, which is reasonable as the same laser diode should have a constant α. It is also observed that the estimated values for C varies a lot with respect to different SMSs, which is also true as we intentionally changed the optical feedback levels when obtaining these signals. Note that the experimental error is a little larger than the simulation results. This is due to the fact that the vibration is not a pure simple harmonic. In order to confirm the effectiveness of the proposed approach,

TABLE VI
MEASURED RESULTS ON HL7851 LD

No.of SMSs (p-p Amp.)	1(1.7V)	2(1.8V)	3(1.9V)	5(2.2V)
$\hat{\alpha}_0$	3.512	3.2786	3.349	3.229
$\delta_{\alpha_0}/\hat{\alpha}_0$	6.7%	5.80%	6.07%	5.13%
$\hat{C}_0$	0.4642	0.499	0.561	0.656
$\delta_{C_0}/\hat{C}_0$	4.63%	3.76%	1.88%	2.70%

we tested the same LD using the approach proposed in [10] and the resulting α is 3.5% $\pm$ 7.6%, which is close to the estimated value in Table VI. Therefore we can say that proposed approach yields an effective estimation of α. Moreover, we also give the estimated C values as the proposed approach is able to yield both of the two parameters, α and C. We did not verify these C values by other approaches since, to the best of our knowledge, there is no work reported in detail to accurately determine this factor experimentally yet. However, from our results, it is can be seen that C value increases with the p-p amplitudes of SMSs. This is in good accordance with previously reported results in the literature indicating that the amplitude of a SMS is proportional to $C[1, 5, 6, 12]$.

VI. Conclusion

In this paper, a practical approach for determining the LEF α of SLs and optical feedback level factor C has been proposed. The method is based on self-mixing optical feedback interferometry with an external cavity subjected a simple harmonic vibration. The proposed method estimates the parameters α and C using a gradient-based optimization algorithm that achieves best data-to-theoretical model match. Theoretical analysis and computer simulations show that the presented algorithm is robust in that the initial values can be arbitrarily chosen within the range of parameters, and the algorithm yields satisfied estimate accuracy in the case of additive noise environment. Specifically, computer simulation results indicate that the error is less than 5.95% for α and the error is less than 1.64% for C. An experimental OFISM is implemented and the experimental results show that the proposed approach is able to estimate α with the accuracy of less than 6.7% for α and 4.63% for C.

There are a number of clear advantages associated with the proposed approach. First, it is simple in the implementation and the procedures associated with the measurements. Second, the proposed approach can be applied to all single-mode SLs operating at weak optical feedback regime. Third, the proposed is more accurate as it employs all the information contained in the SMS data. The main limitation of the proposed method is the necessity of creating a pure harmonic displacement for the external target. It is expected that higher accuracy can be obtained by making a more pure harmonic vibration for the external target. Besides, as the OFISM works at the weak feedback regime, the proposed approach is only suitable for measuring C for the case of $0 < C < 1$.

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