Laser Diode Linewidth Measurement by Means of Self-Mixing Interferometry

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***Abstract*—We demonstrate an easy-to-implement method to determine the linewidth of a laser diode based on the measurement of phase noise in a self-mixing interferometer. The method features a self-aligned experimental setup with an overall length much shorter than the laser coherence length; the method does not require rf measurements and gives results in agreement with the self-heterodyne technique.**

***Index Terms*—Laser measurements, optical feedback, optical interferometry, semiconductor lasers.**

I. INTRODUCTION

As IS well known, several methods are available for the measurement of laser diode (LD) linewidth [1], all of which are basically derived by either an unbalanced interferometer or a fringe visibility measurement.

In this letter, we propose a new technique, based on the self-mixing interferometer [2], in which a fraction of the light reflected by a remote target is allowed to re-enter the LD cavity. The linewidth is evaluated from the phase noise of this interferometer. The sawtooth-like shape of the self-mixing interferometric signal is the key point for an accurate measurement of the phase noise. The proposed method features a simple and self-aligned experimental setup of relatively short overall length, does not require rf measurements, and gives results in good agreement with the self-heterodyne technique [3].

II. THEORY

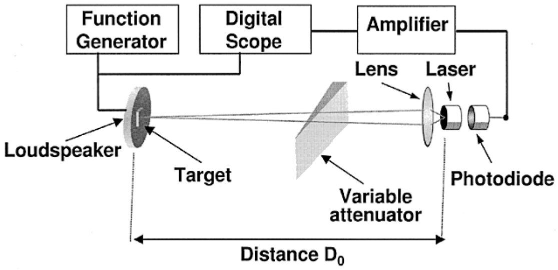

Fig. 1. Experimental setup for self-mixing interferometry.

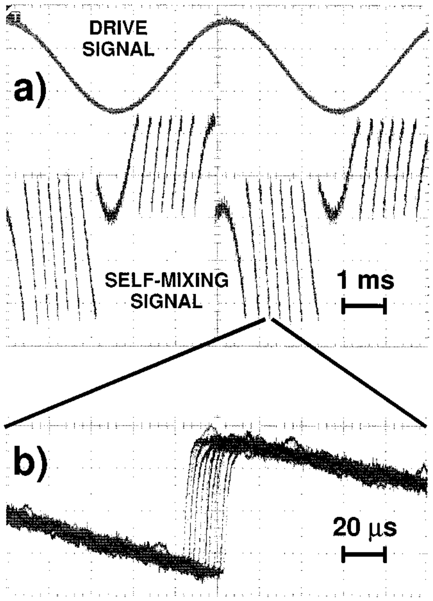

Fig. 2. (a) Lower trace: sawtooth-like self-mixing signal waveform, (10 mV/div). Upper trace: loudspeaker drive signal (1 V/div, corresponding to 1.43 μm/div target displacement). Time scale: 1 ms/div. (b) Zoomed frame reporting the superposition of subsequent single-sweep acquisitions of the self-mixing signal corresponding to a specific fringe (10 mV/div). Horizontal scale: 20 μs/div, corresponding to 0.50 rad/div when converted into interferometric phase. The switching time randomness caused by phase noise can be observed.

The self-mixing interferometer is shown in Fig. 1. A small fraction of the light reflected by the moving target is fed back into the LD cavity. Its interaction with the active medium and the lasing field generates an amplitude modulation of the emitted power, called the self-mixing signal, which is a periodic function of the backreflected field phase

$$\phi = \frac{4\pi}{c}\nu D \qquad (1)$$

where c is light speed, ν is the laser frequency, and D is the remote-target distance. At a low level of optical feedback, the self-mixing signal is sinusoidal as in a conventional interferometer. At moderate feedback (e.g., around 10^{-6} in power), the self-mixing signal waveform gets distorted, becomes sawtooth-like, and exhibits hysteresis. This effect has been exploited to develop a nonambiguous displacement sensor with $\lambda/2$ resolution using a single interferometric channel [2]. A typical sawtooth-like self-mixing signal obtained when driving the target with a sinusoidal displacement $D(t) = D_0 + d(t) = D_0 + d_0 \cdot \sin(\omega t)$ is reported in Fig. 2(a). The fast upward and downward switchings occur at every $\lambda/2$ target displacement.

When light from a laser source enters an interferometer, the fluctuation of the laser frequency generates phase noise. Thus, a measurement of the interferometric phase noise gives information on the laser linewidth [4]. From (1), phase noise in the

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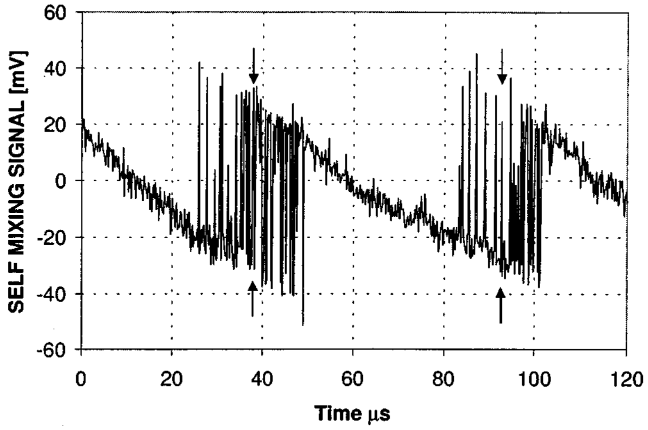

Fig. 3. Self-mixing signal waveform with phase noise, sampled by a digitizing oscilloscope that acquires one point at each trigger pulse. The trigger signal is the sinusoidal waveform imposed on the target. The arrows indicate the switching time in the absence of phase noise.

self-mixing interferometer is generated by the frequency fluctuation $\Delta\nu$ of the LD and by the target distance fluctuation ΔD. If we assume

$$\nu = \nu_0 + \Delta\nu \tag{2}$$

$$D = D_0 + d(t) + \Delta D \tag{3}$$

where $d(t)$ is the sinusoidal displacement imposed to the target, and as the fluctuations are uncorrelated, the rms phase noise is obtained as

$$\sqrt{\langle \Delta\phi^2 \rangle} = \frac{4\pi}{c}\sqrt{\nu_0^2\,\langle \Delta D^2 \rangle + D_0^2\,\langle \Delta\nu^2 \rangle}. \tag{4}$$

When phase noise is measured as a function of target distance D_0 large enough to have $D_0^2\langle\Delta\nu^2\rangle \gg \nu_0^2\langle\Delta D^2\rangle$, a linear dependence $\sqrt{\langle\Delta\phi^2\rangle} \approx (4\pi D_0/c)\sqrt{\langle\Delta\nu^2\rangle}$ is obtained. The slope of the curve $\sqrt{\langle\Delta\phi^2\rangle}$ versus D_0 is proportional to the LD linewidth, which can then be easily recovered from subsequent measures of the rms phase noise at different target distances.

An advantage of the self-mixing configuration compared to conventional interferometry is that the required distance D_0 is, in practice, much smaller than the coherence length $\Delta\nu/c$ usually required by the fringe visibility method. Also, the sawtooth-like signal with hysteresis allows an easy and accurate measurement of phase noise. To explain this, we impose a periodic displacement to the target and analyze using an oscilloscope the fast switching occurring between two specified fringes. The effect of phase noise is such that switching times corresponding to successive observations of the same fringe have a randomness. Thus, there is a statistical distribution of switching instants around the most probable value (the one that would be observed in the absence of phase noise). The zoomed frame of Fig. 2(b) shows the superposition of subsequent single-sweep acquisitions corresponding to a specific fringe, obtained when the scope is triggered by the sinusoidal signal that drives the loudspeaker. It can be noticed that the switching instant changes from one acquisition to another due to the interferometric phase noise. It is worth noticing that the hysteresis in the power-phase characteristic of the self-mixing interferometer prevents the occurrence of multiple switchings with opposite sign for a single target oscillation.

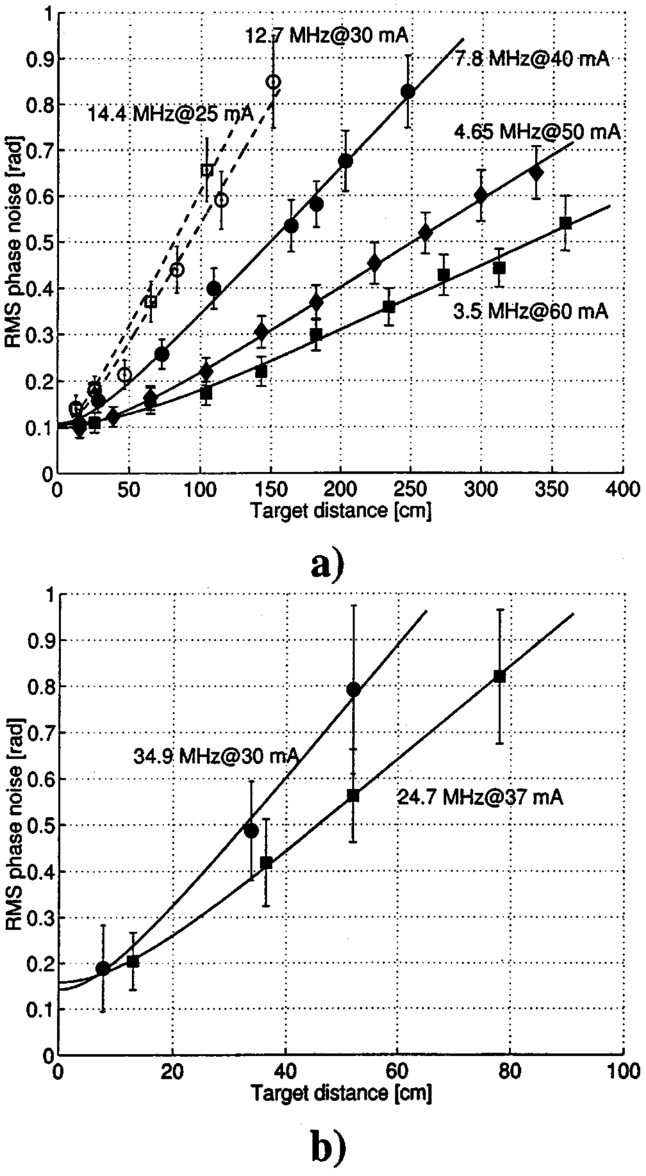

Fig. 4. RMS interferometric phase noise as a function of target distance D_0 for different laser diodes and varying pump currents. The linewidths estimated from the slope of the fitted curves are reported on the graphs. (a) Empty symbols refer to LD1 (ML2701, 850-nm Fabry–Perot); full symbols refer to LD2 (SDL5401, 800-nm Fabry–Perot). (b) LD3 (ML9922, 1550-nm DFB).

The variance of the phase noise, whose statistics are nearly Gaussian in practice, can be evaluated by two methods. In the first one, a sufficient number of waveforms such as in Fig. 2(b) are acquired using a digitizing oscilloscope, and the statistics of the switching instants can be easily calculated. In order to acquire less data, it is possible to use a second method based on a sampling oscilloscope that acquires one point after each trigger pulse. The resulting waveform is shown in Fig. 3, where the arrows indicate the switching time in the absence of phase noise. In this case, slightly more complex data processing is required. Each sampled point as in Fig. 3 is classified either as being “low level” (switching not already occurred) or “high level” (switching already occurred). The probability of the occurrence of the above events (each event corresponds to a sampled point) is calculated by taking the phase variance as a parameter. Thus, the probability of the state of the point being "high" or "low" is obtained as a function of the phase noise variance, and this calculation is repeated for each sampled point. Then, a multiplication of the curves thus obtained yields the joint probability of realization of the experimentally acquired data, as a function of the phase noise variance. The result is a narrow curve: the abscissa of its maximum gives the most likely phase variance of the interferometer. The procedure can be repeated for different samples of the signal, to improve the estimation confidence. Finally, the linewidth of the LD can be estimated from several rms phase noise measurements performed at different target distances.

III. EXPERIMENTAL RESULTS

The experimental setup is shown in Fig. 1. Light is focused onto a target stuck onto a loudspeaker. The target can be a mirror or, to have a self-aligned setup, either a corner-cube or reflective adhesive tape (manufactured by 3M). The variable attenuator is used to obtain the proper feedback level. The self-mixing signal is collected by the monitor photodiode at the rear facet of the LD, is amplified, and then sampled by a digital sampling oscilloscope. The data are processed according to the second method described in Section II.

One DFB and two single-mode Fabry–Perot LDs have been measured at different injected currents. LD1 is an 850-nm Mitsubishi ML2701 (FP) with 17-mA threshold current emitting 8 mW at 40 mA. LD2 is an 800-nm SDL5401 (FP) with 35-mA threshold current emitting 50 mW at 85 mA. LD3 is a 1550-nm Mitsubishi ML9922 (DFB) with 16-mA threshold current emitting 5 mW at 37 mA. Fig. 4(a) shows the measured rms phase noise versus target distance D_0 for LD1 and LD2. The lines are the least-squares fit of (4). For small distances, mechanical fluctuations of the setup are significant. For longer distances (typically 0.5–1 m in our setup), the theoretical linear dependence is obtained. The linewidth estimated from the slope of the fitted curve [see (4)] is reported on the graphs. Fig. 4(b) shows the same measurements performed on LD3.

The linewidth values measured using the proposed technique are in good agreement with the ones we obtained by using the self-heterodyne method [3]. The amount of feedback required to achieve the self-mixing regime is moderate (i.e., around 10^{-6} in power), and there is no evidence of relevant perturbations on the LD linewidth. Thus, the method is valuable for evaluating the linewidth of LD's to be used in self-mixing interferometric configuration, but also for applications to conventional interferometry and optical transmission.

IV. CONCLUSION

We have demonstrated a new technique for measuring the linewidth of laser diodes based on the self-mixing effect. The linewidth is obtained from a measurement of the interferometric phase noise around the switching of the sawtooth-like signal waveform. The method can be applied to all LDs without an isolator, it does not require any rf equipment nor a long fiber of adjustable length, and it yields results that are in agreement with the self-heterodyne technique.

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