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Laser Diode Linewidth Measurement by means of Self-Mixing Interferometry

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Introduction

As it is well known, several methods are available for the measurement of laser diode (LD) linewidth [1-2], all basically derived by either an unbalanced or a fringe visibility measurement. We propose a new technique, based on the self-mixing interferometric configuration [3], for 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 set-up of relatively short overall length and it does not require RF measurements.

Theory

A 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 interferometric amplitude modulation of the emitted power, called self-mixing signal, which is a periodic function of the backreflected field phase :

$$\phi = \frac{4\pi}{c}\nu D \tag{1}$$

where c is light speed, ν is laser frequency and D is the target distance. At low level of optical feedback, the self-mixing signal is sinusoidal as in a conventional interferometer. At moderate feedback (i.e. 10^{-4} in power), the self-mixing signal waveform gets distorted, becomes sawtooth-like and exhibits hysteresis. This effect has been exploited to develop a non-ambiguous displacement sensor with $\lambda/2$ resolution [3]. A typical sawtooth-like self-mixing signal obtained when driving the target with a sinusoidal displacement is reported in Fig. 2.

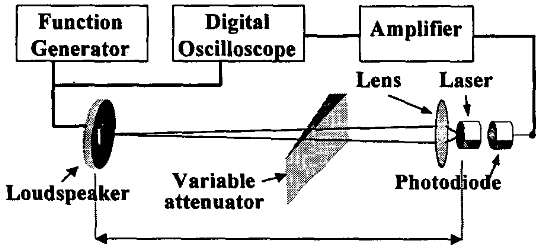

Fig. 1. Experimental set-up for self-mixing interferometry

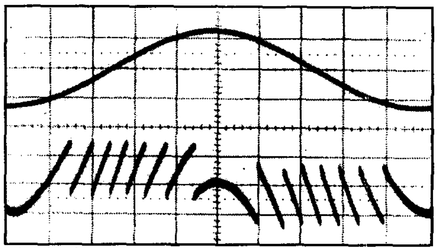

Fig. 2. Self-mixing signal waveform taken from an analog oscilloscope (lower trace). Upper trace : target displacement, 1.25μm/div. Time scale : 2 ms/div.

When light from a laser source enters an interferometer, the fluctuations of the laser frequency generate phase noise. Thus, a measurement of the interferometric phase noise gives information on the laser linewidth [4]. From (1), phase noise in a self-mixing interferometer is generated by a frequency fluctuation $\Delta\nu$ of the LD and by target distance fluctuation ΔD. If we assume $\nu = \nu_0 + \Delta\nu$ and $D = D_0 + d(t) + \Delta D$, where $d(t)$ is the sinusoidal displacement imposed to the target, the RMS phase noise is obtained as :

$$\sqrt{<\Delta\phi^2>} = \frac{4\pi}{c}\sqrt{\nu_0^2 <\Delta D^2> + D_0^2 <\Delta\nu^2>} \tag{2}$$

When phase noise is measured as a function of target distance D_0 and the condition $\left(D_0^2 <\Delta\nu^2>\right) >> \left(\nu_0^2 <\Delta D^2>\right)$ is satisfied, a linear dependence $\sqrt{<\Delta\phi^2>} = {}^{4\pi D_0}\!/_{c} \cdot \sqrt{<\Delta\nu^2>}$ is obtained. The slope is proportional to the LD linewidth, which can be therefore easily recovered.

An advantage of the self-mixing configuration compared to conventional interferometry lies in the fact that the sawtooth-like signal with hysteresis allows an easy and accurate measurement of phase noise. To explain this, we let the target displacement be periodic in time and analyze on a 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 displacement have a randomness. Thus, there is a statistical distribution of switching instants around the most probable value (the one that would be observed in absence of phase noise). Fig. 3 reports an example of the self-

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mixing signal waveform sampled by a digitizing oscilloscope. The scope is triggered by the sinusoidal signal that drives the target and it acquires one point at each trigger pulse. The spread in switching times caused by phase noise is clearly seen.

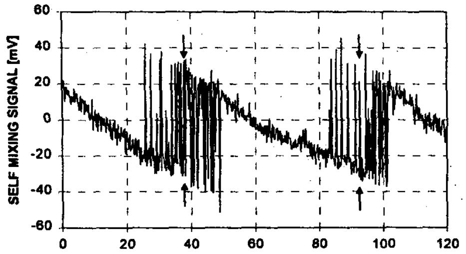

Fig. 3. Self-mixing signal waveform with phase noise sampled by a digitizing oscilloscope that acquires one point at each trigger pulse. The trigger signal is the sinusoidal waveform imposed to the target. The arrows indicate the switching time in absence of phase noise.

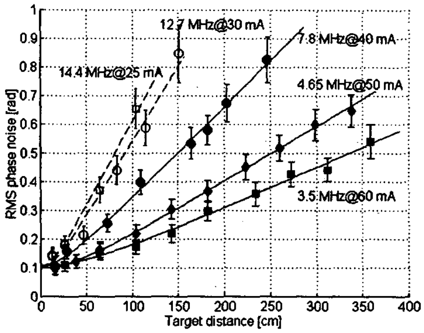

Fig. 4. RMS interferometric phase noise as a function of target distance D_0. Dashed lines : ML2701. Solid lines :SDL5401.

The variance of the phase noise, supposed to have gaussian statistic, can be numerically evaluated using a maximum likelihood method. To this end, each sampled point as in Fig. 3 is classified either as being a "low level" (switching not already occurred) or a "high level" (switching already occurred). Then, the probability of each event as a function of the phase variance is calculated, and multiplied by the probability of the realization of each point, obtaining the PDF of the phase noise variance. The result is a narrow curve whose maximum gives the most likely phase variance. The procedure is repeated for different samples of the signal, to improve the estimation confidence. Since the LD linewidth is affected by optical feedback [5], the measured linewidth value may differ from that of the solitary (unperturbed) LD. A comparison with the self-heterodyne method results shows that the linewidth measured with the self-mixing method is twice as large the linewidth of the unperturbed LD. This scale factor is in agreement with theoretical predictions derived from [5].

Experimental results

The experimental set-up is shown in Fig. 1. Light is focused on a target stuck to a loudspeaker. The target can be a mirror, a corner-cube or a reflective adhesive tape; in the latter cases the interferometer is self-aligned. The variable attenuator is used to obtain the proper feedback level. The self-mixing signal is collected by the monitor photodiode, amplified and acquired by a sampling oscilloscope. Two single-mode Fabry-Perot LDs have been measured at different injected currents : a 850 nm Mitsubishi ML2701 with 17 mA threshold current emitting 8 mW at 40 mA ; and a 800 nm SDL5401 with 35 mA threshold current emitting 50 mW at 85 mA. Fig. 4 reports the measured RMS phase noise versus target distance D_0. The lines are the least-squares fit of (2). For small distances, mechanical fluctuations of the set-up start to be significant. For larger distances, the theoretical linear dependence is obtained. The linewidth estimated from the fit is reported on the curves (Fig. 4). These figures refer to LDs with optical feedback and, as expected, are a factor 2 larger than those found with the self-heterodyne measurement.

Conclusions

We have demonstrated a new technique for the measure of 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 isolator, it does not require any RF equipment nor long fiber of adjustable length and it is in agreement with the self-heterodyne technique.

References

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