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Balanced detection for self-mixing interferometry

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We propose a new detection scheme for self-mixing inter-ferometry using two photodiodes for implementing a differential acquisition. The method is based on the phase opposition of the self-mixing signal measured between the two laser diode facet outputs. The subtraction of the two outputs implements a sort of balanced detection that improves the signal quality, and allows canceling of unwanted signals due to laser modulation and disturbances on laser supply and transimpedance amplifier. Experimental results demonstrate the benefits of differential acquisition in a system for both absolute distance and displacement vibration measurement. This Letter provides guidance for the design of self-mixing interferometers using balanced detection.

OCIS codes: (280.3420) Laser sensors; (140.5960) Semiconductor lasers; (230.0040) Detectors; (120.3180) Interferometry.

Self-mixing interference (SMI) effect, also named optical feed-back interference, applied in laser metrology was first reported by King and Steward [1], and the core model of semiconductor laser diode (LD) feedback effect was presented by Lang and Kobayashi [2] in 1980. Since the 1990s, SMI technology [3,4] has been variously applied in displacement [5,6], vibrations [7–9], flow speed [10–12], absolute distance [13–15], and other laser cavity related measurements [16,17].

In SMI optical configuration, a modulation of the laser fre-quency and amplitude is induced by coupling a fraction of the emitting light into the laser cavity [18]. A two cavity Fabry–Perot resonator model well describes the phenomenon. The ef-fect of the coupling factor C induces the change of gain, carrier density, and current threshold [3,4,19]. SMI signals are typi-cally acquired by measuring the modulation of the power by a photodiode (PD) with a reasonable signal-to-noise ratio (SNR) even when the feedback is very weak (down to −90 dB) [20], or by amplifying voltage variation of the LD junction [21]. As presented by de Groot et al. [22], the front and rear outputs of a LD are experimentally seen in phase opposition. By contrast, the two facet outputs are in phase concordance for the He–Ne laser interferometer presented by Donati [23]. Li et al. [24] uses a wave plate in the external cavity to generate two polarization eigenstates inducing a phase difference for a Nd:YVO4 laser. Randone and Donati explained the phase opposition of the two LD facet outputs as the result of multiple interferences in addition to the self-mixing effect [25]. The phase opposition takes place when the laser pump current is well above the threshold.

When possible, balanced detection is often used in various electronic or optoelectronic applications for improving the signal quality. For example, it is used in photonic links [26], trace-gas detection [27], optical coherence tomography [28], and range finders [29].

The basic method consists of canceling out the common mode to get the differential signal. It is ob-tained either as a direct subtraction on the PD current [26], or by voltage subtraction of signals created by two identical trans-impedance amplifiers (TIAs) [27]. Some techniques implement a feedback loop for minimizing the difference between the detected signals. It can improve the SNR, and in some situations allows it to reach the shot noise limit [30].

In this Letter, we propose to use two PDs to monitor the self-mixing modulation of the power emitted from both LD facets. Then, the self-mixing signal is in phase opposition for the two LD outputs. Therefore, their subtraction in some way doubles the signal, while canceling common disturbances on laser supply and LD modulations.

The realized experimental setup is shown in Fig. 1. We applied the balanced detection with and without laser current modulation in order to include both displacement–vibration and absolute distance measurement systems. The laser source is a distributed feedback (DFB) LD (model WSLD-1310-020m-1-PD) with built-in monitor PD (PD2), emitting up to 20 mW at $\lambda = 1310$ nm on a single longitudinal mode. When we measure vibration it is driven by a 30 mA dc current, and the speaker, covered by white paper, is driven by a triangular signal. The optical section consists of a collimation lens (A110TME-C by Thorlabs) and a beam splitter with reflection R3 $\approx$ 10%, enough to have a good signal on the external PD without introducing a significant loss on the SMI measurement channel. This value is suitable, because the front output power of the DFB LD is about 10 times that of the rear output. The front PD (PD1 in Fig. 1) is an InGaAs model (KPDE030-46 by Kyosemi), while the rear one (PD2 in Fig. 1) is the LD mon-itor PD. A second lens (C240TME-C by Thorlabs) focuses the light on PD1. For measuring absolute distance, the LD is

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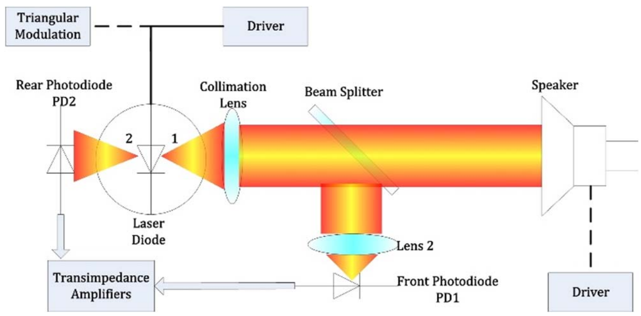

Fig. 1. Schematic of the experimental setup.

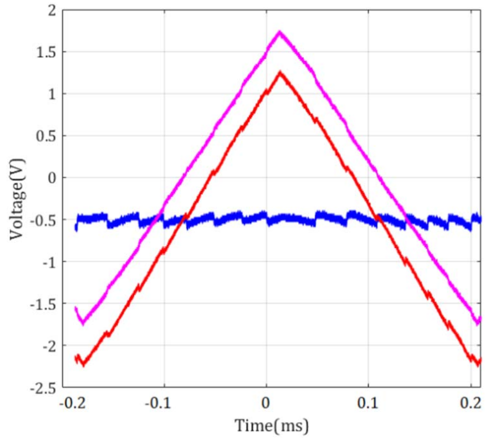

Fig. 3. SMI signals induced by a LD current modulation. Lower triangular trace is monitor PD (PD2) output, upper triangular trace is front PD (PD1) output, and middle trace is the differential acquisition.

driven by triangular modulation [14,15]. These measurements were done with a polarization current of 45 mA and a peak-to-peak modulation $Ipk = 10$ mA, with the speaker turned off and placed at different distances.

The optical system is realized for having almost the same optical power at the two PDs. A double-channel TIA (model OPA2380) reads the photocurrents, and a differential amplifier (with unitary gain) provides the balanced signal. The TIA gain is trimmed in order to have exactly the same signal output amplitude for both PDs. The self-mixing signal of the two detectors may change with the back injection conditions, but the common signal almost remains the same. Therefore, there is no need for a feedback loop; the TIA gain is trimmed only once.

Figure 2 shows the signals acquired for a vibrating target without laser modulation. The upper trace is the signal from PD2, the middle trace is the signal from PD1, and the lower trace is their subtraction. The phase opposition is evident, and the difference signal takes advantage of it.

Figure 3 shows the same acquisitions of Fig. 2 with a modulated laser current and a stable target. The two PD outputs are shown together with their difference for a diffusing target at about 15 cm. As expected, after a proper calibration of the PD gains, the front and the rear signals show the same amplitude modulation, but phase opposition of SMI signals. The effectiveness of the approach is confirmed by the output of the differential amplifier, where there is no trace of the modulating signal, while SMI fringes are evident. This feature is particularly useful for applications of distance measurement. The standard technique for canceling the modulation contribution consist of subtracting the modulating signal at the transimpedance stage [14], but the subtraction cannot be complete due to the dependence of the LD differential efficiency with the pump current.

Figure 4(a) shows the experimental acquisitions of signals from the monitor PD together with the correspondent triangular current modulation and their difference. Figure 4(b) shows the signals acquired by the monitor and the external PDs and their difference.

The comparison between the two difference signals underlines the nonlinearity between the pump current and the laser output. This residual signal could be detrimental for distance measurement, and for each kind of self-mixing modulated system. The proposed balanced detection definitely fixes the problem of residual modulation signals by also enhancing the self-mixing signal, as shown in the next acquisitions.

The next acquisitions consider the improvement in the SMI signal due to the balanced detection. For example, Fig. 5 shows an example of the acquisition of a very low signal, obtained when the speaker is about 150 cm away from the LD. The SNR of each channel would be too low for analyzing the SMI in the time domain (fringe-counting technique) even after

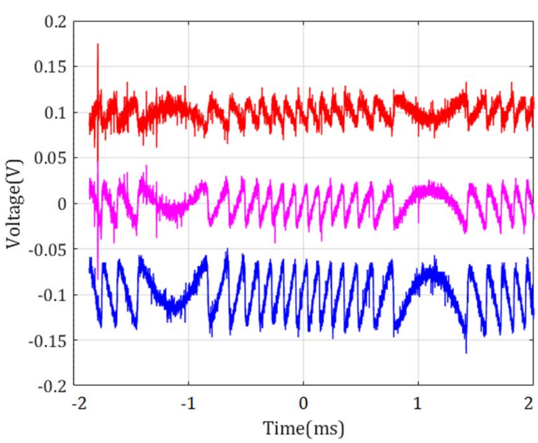

Fig. 2. SMI signals induced by a vibrating target. Upper trace is monitor PD (PD2) output, middle trace is front PD (PD1) output, and lower trace is the differential acquisition.

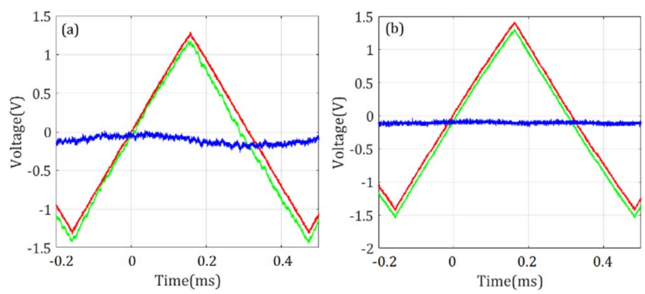

Fig. 4. Comparison of modulation compensations by driving signal subtraction (a) and by balanced detection (b). (a) Upper wave is monitor PD (PD2) output, lower wave is the modulation signal. (b) Upper wave is monitor PD (PD2) output, lower wave is front PD (PD1) output. Difference signal is reported in both figures.

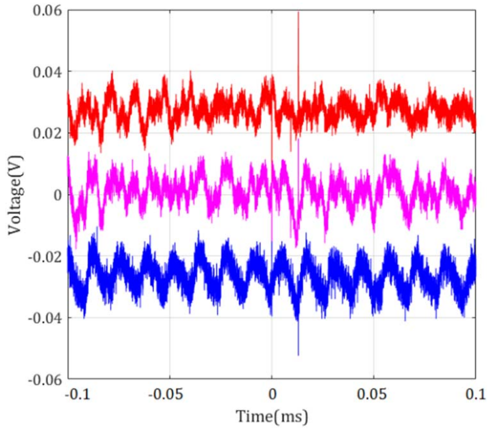

Fig. 5. Balanced detection of a small SMI signal. Upper trace is monitor PD (PD2) output, middle trace is front PD (PD1) output, and lower trace is the differential acquisition.

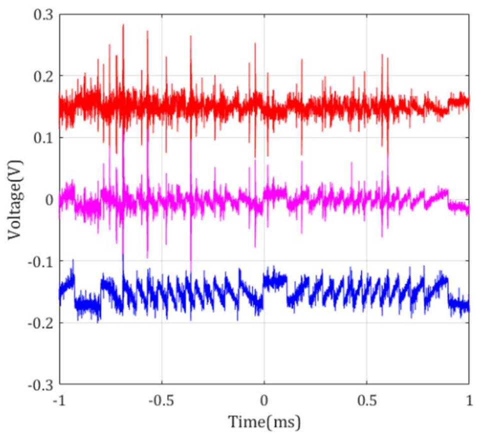

Fig. 6. Balanced detection in the presence of electromagnetic disturbances. Upper trace is monitor PD (PD2) output, middle trace is front PD (PD1) output, and lower trace is the differential acquisition.

bandpass filtering. Instead, the balanced detection shows an evident improvement (lower trace in Fig. 5). The fringes are clearly visible and all the correlated disturbances are canceled. Even in terms of uncorrelated noise, such as shot noise, the balanced detection would improve SNR by almost 3 dB, because the signal is approximately doubled in amplitude (+6 dB), while the noise increases in power (+3 dB).

Figure 6 shows the case of strong electromagnetic disturbances affecting both the laser current supply and the transimpedance stage. In this case, the effectiveness of balanced detection is even more evident. It could be useful for applying SMI in industrial environments, and improving the robustness against electromagnetic interferences.

In conclusion, we proposed a balanced detector for self-mixing interferometry, able to cancel the electromagnetic disturbances coupled with laser pump current and TIA. The balanced detection also removes any signal due to LD modulations, even noise and disturbances on LD power supplies. In addition, it improves the SNR and enhances the useful SMI signal. The small loss induced by the beam splitter is negligible with respect to the obtained benefits. This technique can be applied to several SMI realizations, and it is especially useful in the case of poor signals, or in the presence of LD modulations such as distance measurement systems.

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