Self-mixing Interferometer: Frequency Modulation Noise Dependence on Laser Source

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Abstract. The acquisition of frequency modulation in self-mixing interferometry opens the way to a new generation of instruments, with significantly superior performance compared to traditional self-mixing interferometers. In this work, we experimentally confirm the noise limit dependence of this kind of interferometer on the laser source linewidth. The obtained results confirm the theoretical prediction, opening the way for a deeper improvement in sensitivity, by employing narrow-line lasers in this interferometric configuration.

1. Introduction

Non-Destructive Testing (NDT) techniques and different industrial measurement applications require instruments for the acquisition of small vibrations at high frequencies [1]. The adopted solution is normally based on optical interferometry [2], offering nanometer resolution up to tens of megahertz. This level of performance is typically reached by very-high cost instruments, not often available for everyday measurements [3]. In recent years, a new interferometry technique has been proposed, which exploits the frequency modulation of a laser subjected to optical back injection [4-8]. The sensitivity demonstrated by this kind of interferometer is about two orders of magnitude higher than the standard amplitude-modulation self-mixing interferometer [9]. The theory predicts a dependence of the noise floor on the laser linewidth. In this work, we experimentally confirm that dependence, considering two different DFB lasers.

2. Self-mixing interferometry

Self-mixing interferometry (SMI) [10-13], also known as optical feedback interferometry, is based on semiconductor lasers which experience changes in their lasing action when the laser cavity is subjected to optical back-injection by a remote target. As a result of these changes, the laser output is subject to both amplitude modulation (AM) and frequency modulation (FM). By recovering the target displacement from the signal carried in the output power (AM), SMI has been used as an approach to measure target status: displacement [14-17], vibration [18-19], speed [20-21], flow [22-25], distance [26-28], and different applications [29-33]. FM is more difficult to read, but it exhibits a sensitivity two orders of magnitude higher than AM [9].

A portion of the light that has been reflected or diffused from the target surface is directed back into the laser. This phenomenon leads to a coherent detection of the radiation, resulting in the modulation of the optical power emitted by the laser in both amplitude (AM) and frequency (FM). Consequently, it generates an interferometric signal with fringes. Once this signal is converted into an electrical form, it allows for the determination of the target's displacement [11-13].

With respect to classical interferometers following Michelson's structure, this type of interferometer is significantly simplified. This is because the interferometric signal is inherently present within the laser beam itself and doesn't require the generation of interference from two beams traveling along different paths. Therefore, there is no need for optical components to separate the reference and measurement paths. Consequently, it can be concluded that a self-mixing interferometry instrument boasts a compact design, eliminates the need for complex alignment procedures (essential in traditional configurations), and can be constructed at a very low cost.

Self-mixing laser interferometry, particularly in amplitude modulation (AM), has found applications in a number of measurements [14-32]. However, its performance typically lags behind that of conventional interferometers. This limit is primarily due to the signal-to-noise ratio (SNR) of the AM self-mixing signal. Laser shot noise is associated to the whole emitted power, while the amplitude of the signal is usually quite small, often around 1% or less of the emitted power [12]. This limitation confines AM self-mixing interferometry to specialized applications where its simplicity is advantageous, for example in optical mouse devices [33]. Recently, it was demonstrated a possible improvement in AM self-mixing, through a sort of balanced detection [34]: by subtraction of the signal from an internal monitor photodiode and an external photodiode it is possible to double the signal and reduce the noise [35]. But with this technique the improvement is less than 10 dB, significantly lower than the possibilities offered by FM self-mixing.

3. Frequency modulation Self-mixing interferometry

In the last years, there has been an exploration of frequency modulation induced by the self-mixing effect for various measurement applications [4-6]. Although the theory of Lang and Kobayashi had predicted the existence of the FM signal [7], the focus had predominantly remained on amplitude modulation (AM) signals for approximately three decades, primarily because it is easier to acquire. Nevertheless, apart from the challenges in measuring FM signal, it exhibits a substantial improvement in terms of signal-to-noise ratio (SNR) when compared to AM signal. This improvement is attributed to the fact that FM signals are not constrained by laser shot noise but rather by the laser's linewidth. A comprehensive explanation of the theory behind FM self-mixing can be found in [8].

To transform frequency modulation into amplitude modulation, an effective choice is to employ a Mach-Zehnder filter [9]. This filter is characterized by a sinusoidal and repetitive transfer function in the frequency domain, offering great flexibility in this conversion process. Fig. 1 shows the realized setup for the measurements.

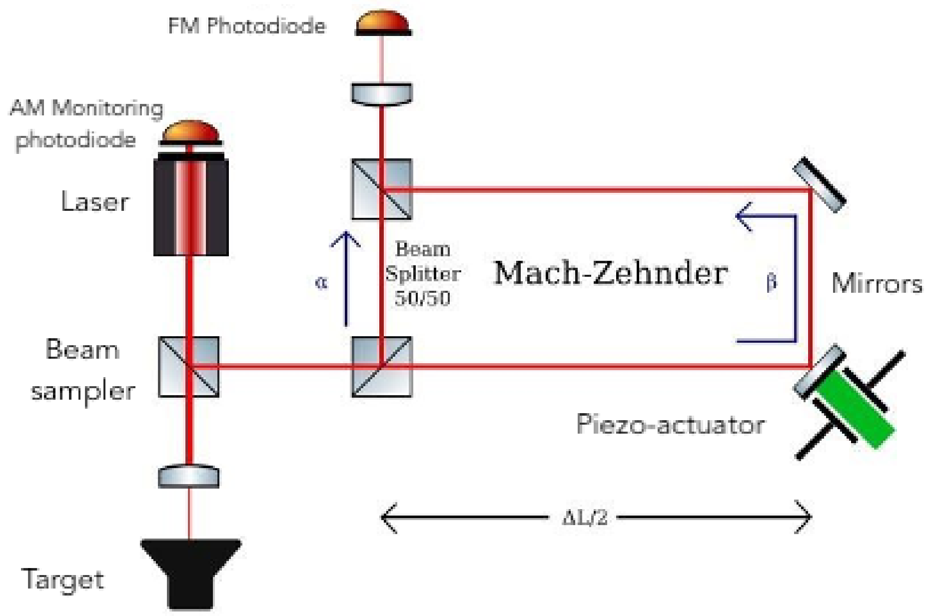

Figure 1. FM Self-mixing configuration.

As in common self-mixing instruments, the laser light is focused on the remote target, and the AM modulation is acquired by the laser package's monitor photodiode. A beam sampler is added to the measurement path, to take out a small fraction of the emitted light (about 4% depending on the beam's polarization) and redirect it to the Mach-Zehnder interferometer. The need to transmit just a small fraction of power to the FM reading is due to its extreme sensitivity. The photodiode reading FM signal is acquired by a 35 MHz trans-impedance amplifier, while the monitor photodiode is acquired by a 28 kHz electronics, because it is used only to confirm the effectiveness of the self-mixing interference.

4. Noise floor measurements

The aim of this work is to experimentally confirm the theoretical dependence of the noise σ_{FM} on laser linewidth $\Delta\nu$ [8]:

$$\sigma_{FM} = [\Delta\nu \, B / \pi]^{1/2} \tag{1}$$

where B is the measurement bandwidth.

In [36] it was already demonstrated the noise reduction with back-injection strength, measured by the C parameter, due to the laser linewidth dependence on C. It was measured an FM noise level reduction equal to $(1+C)$. For the comparison of noise measurement with different laser sources, great care should be taken to equalize the values considering the amplitude of the self-mixing signal, depending on the power acquired on the photodiode and on the alignment of the Mach-Zehnder interferometer.

The first measurement campaign of the noise floor, as a function of the back-injection strength, was realized with the DFB laser WSLD 1550-020m, from WaveSpectrum. This laser has a wavelength of 1550 nm with an emission power of about 15mW. Figure 2 shows some noise measurements as a function of the C parameter. The self-mixing fringes amplitude for C=1 was about 1 V.

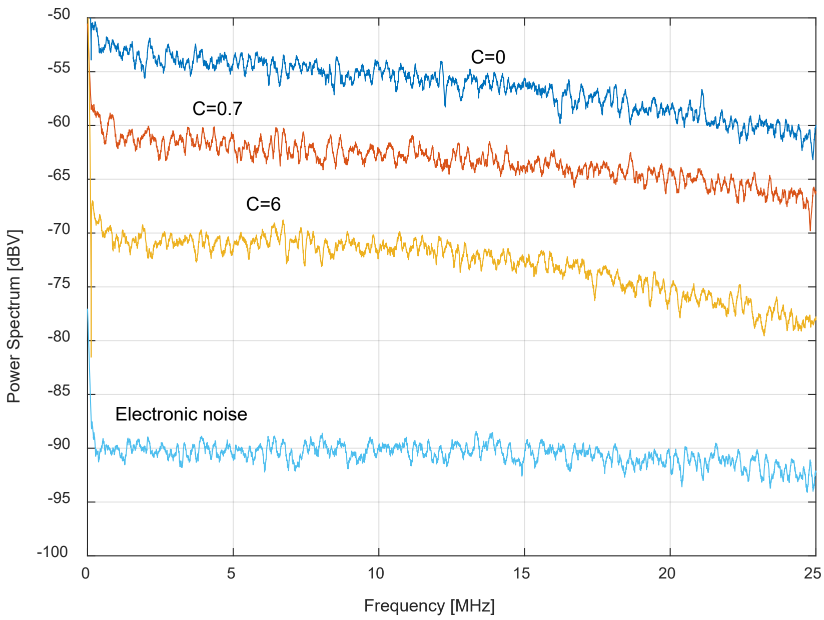

Figure 2. FM noise measurements carried out with WSLD 1550-020m laser.

The second laser considered was Mitsubishi Laser ML720J11S-03, a DFB laser emitting 5 mW at 1300 nm. This laser experimentally show a better coherence length with respect to the first one: it can measure a good self-mixing signal up to 20 m, while the first one is limited to about 4 m. This evidence indicates a narrower laser linewidth. Figure 3 shows a new series of noise measurements as a function of C, for the second laser. We have to consider that the obtained fringe amplitude, for C=1, is now equal to about 500 mV. This reduction with respect to the first laser is mainly due to the lower laser power.

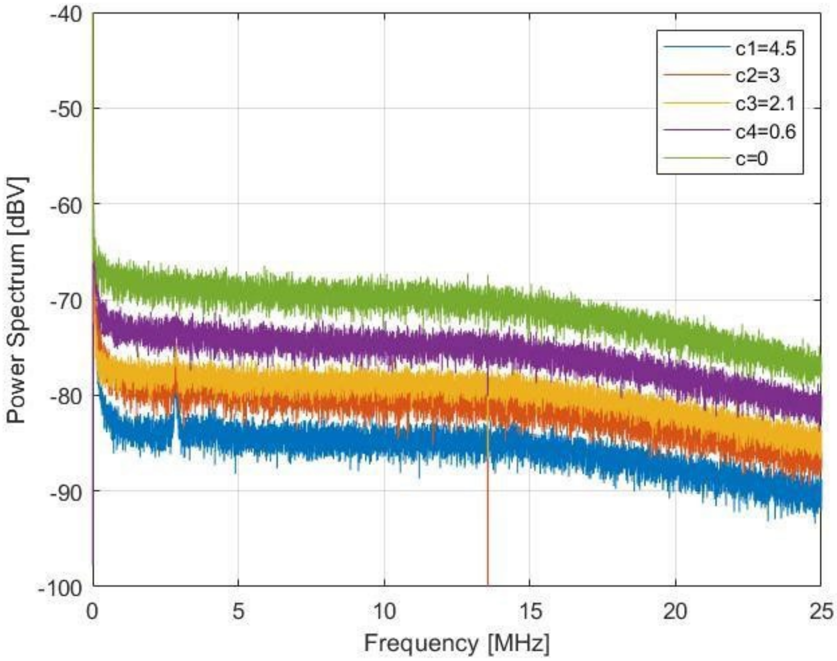

Figure 3. FM noise measurements carried out with ML720J11S-03 laser.

We have to note that it is not a problem, because the shot noise level is still well below the FM noise level. In conclusion, we have to consider a factor 2, corresponding to 6 dB, of reduction in the sensitivity of the interferometer with the second laser.
The dependence on C parameter is confirmed for both lasers, but the correspondent noise levels are different: it can be noticed that there is a reduction of about 7 dB in the noise without feedback (C=0) for the second laser. This reduction is also confirmed for the other feedback levels. The improvement is justified by the different coherence lengths of the two lasers. It indicates that the Mitsubishi laser has a linewidth 5 times smaller than the Wavespectrum, as expected by the measurement of self-mixing interference at different target distances.

5. Conclusions
In this work, we presented a series of noise measurements for FM self-mixing laser interferometer, with the aim of confirming the theoretical dependence on laser linewidth. This result confirms the theoretical prediction [8], opening the way for the design of an instrument with a deeper improvement in sensitivity, by employing narrow-line lasers in this interferometric configuration. Considering that the actual noise floor is lower than 1 pm/$\sqrt{\text{Hz}}$, there is room for a number of demanding industrial applications, such as laser ultrasonic techniques [1].

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