

# FM Self-mixing Interferometer Measurement Performance

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**Abstract.** Self-mixing interferometry achieves remarkable performance thanks to the frequency modulation reading. In this case the noise floor is no longer due to shot noise, as for amplitude modulation, but to the laser's frequency noise. This work experimentally compares the noise floor of this particular kind of interferometer for different laser types, DFB and VCSEL, which exhibit different line broadenings. Experimental measurement of the FM noise spectrum confirms the theoretical treatment that it is determined by the laser's linewidth. In the particular case of a VCSEL laser, the  $1/f$  noise in frequency modulation clearly indicate a gaussian broadening of the laser linewidth.

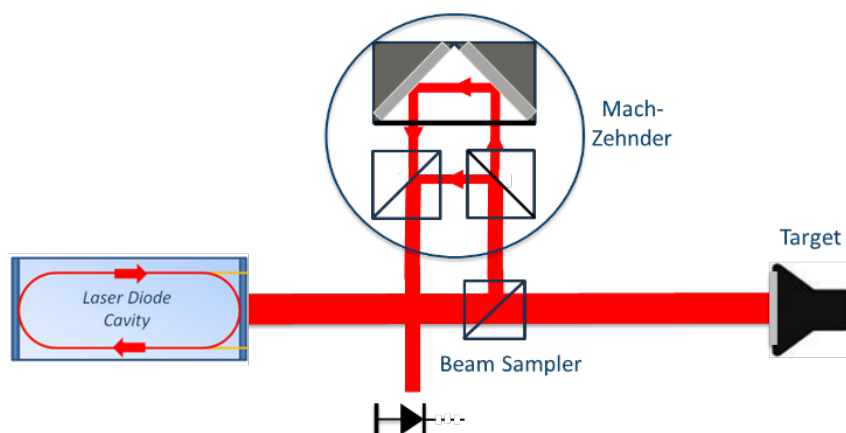
## 1. Introduction

Self-mixing interferometry (SMI) [1] is a well-known technique based on optical back-injection: the laser emission is influenced both in amplitude and frequency by a small fraction of power reflected by a remote target. Standard SMI takes advantage of the amplitude modulation (AM), measured by a monitor photodiode, to get measurement of the target status, for example speed or distance [2-4]. This type of interferometry typically can reach lower performance than classical techniques, since the modulation signal is a small fraction of the emitted power, usually less than 1%, while the shot noise is given by the entire laser power. However, it has the notable advantage of simplicity, as it is mainly composed only of the laser itself, with its monitor photodiode, and a focusing lens.

A further advantage of the SMI is the possibility to easily modulate the laser wavelength through a current modulation, in order to realize different types of instruments, such as absolute distance meters, exploiting various signal processing techniques [5-8]. There is also the possibility of slightly improving the signal-to-noise ratio through a sort of balanced detection between the two laser outputs [9]: the correlation of the shot noise emitted by the two faces of the laser is exploited, which is counteracted by the self-mixing signal which is instead inverted on the two outputs.

Recently, the measurement of frequency modulation (FM) in self-mixing interferometer has been proposed [10-14]: FM cannot be directly acquired, because there is the need of a frequency discriminator, acting as a frequency-to-amplitude converter. It can be realized by an edge filter [10] or by another interferometer in quadrature [14]. However, the performance achievable with FM-SMI is approximately two orders of magnitude higher than that of AM-SMI, both in sensitivity and achievable bandwidth [13].





**Figure 1.** Scheme of FM-SMI: the laser diode is focused on the target, while a small fraction of the emitted power is fed to a Mach-Zehnder interferometer, to measure the FM signal on an external photodiode.

## 2. Measurement Setup for Frequency Modulation in Self-Mixing Interferometry

Figure 1 shows a scheme of FM-SMI, based on a Mach-Zehnder interferometer (MZI) used as a frequency discriminator. With respect to a standard self-mixing interferometer, composed by the laser diode focused on a target, there is the addition of a beam sampler, that shifts about 4% of the emitted power to a MZI. It is composed by two 50% beam splitters and a prism used as retroreflector. Finally, an external photodiode measures the output of the MZI, read by a 35 MHz bandwidth transimpedance amplifier. The MZI is kept in quadrature through an electronic feedback that acts on a piezoceramic that holds the prism. The structure of this kind of FM-SMI is better described in [13].

The noise floor for this kind of interferometry depends mainly on the laser coherence [15]: if the frequency discriminator is well designed, the shot noise is negligible and FM noise  $\sigma_{FM}$  is predominant. From the basic theory of laser frequency noise, it is well known that Lorentzian broadening of laser line corresponds to a white spectrum of frequency noise, while Gaussian broadening corresponds to  $1/f$  noise [16]. The real shape of the laser linewidth is a convolution of these two broadening effects, known as Voigt profile [17]. Considering dominant the white noise contribution in the FM signal, the theoretical dependence of the FM noise on laser linewidth  $\Delta\nu$  is

$$\sigma_{FM} = [\Delta\nu B / \pi]^{1/2} \quad (1)$$

or, easier, from the Power Spectral Density (PSD)  $S(f)$  of the frequency noise you directly get the laser linewidth  $\Delta\nu$ :

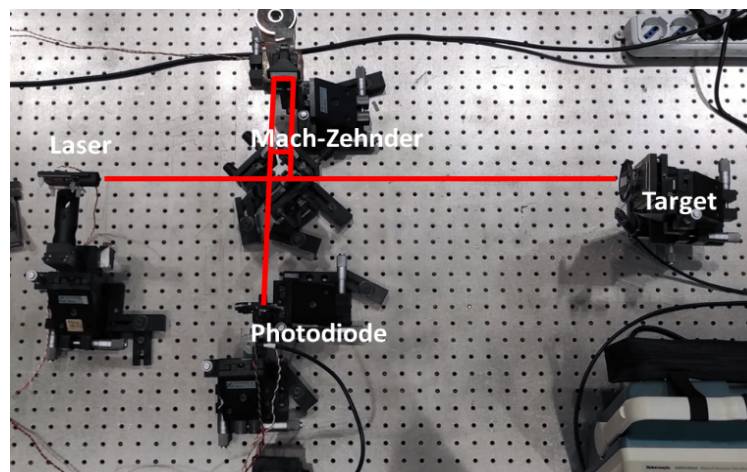
$$\Delta\nu = \pi S(f), \quad (2)$$

To characterize the real performances obtainable with this type of interferometer, we created a test setup with which we measured three different types of lasers: two DFB lasers and one VCSEL. The laser diodes parameters are reported in table I.

**Table 1.** Parameters of the laser diode under test.

Laser diode Model	structure	$\lambda$ [nm]	$P_o$ [mW]	$I_{th}$ [mA]	$I_{bias}$ [mA]
WSLD1550-020m	DFB1	1550	20	10	90
ML720J11S	DFB2	1310	5	6	20
PS85F1P1U	VCSEL	850	0.5	2	5

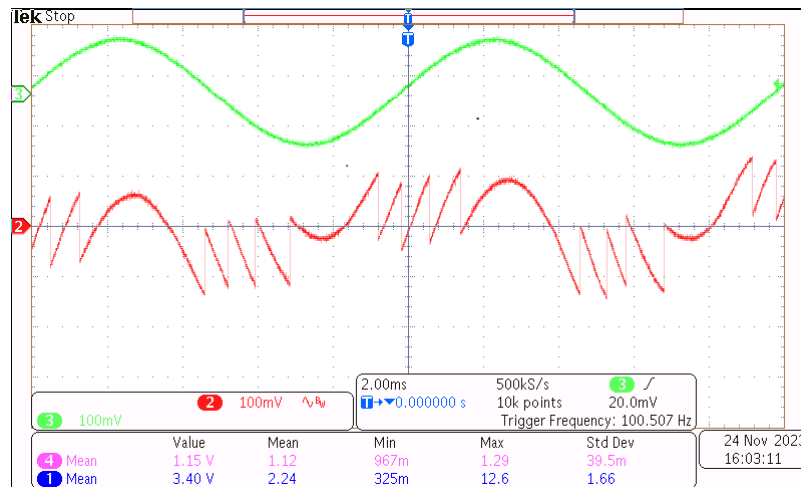
Figure 2 shows a photo of the realized setup: the laser beam is focused on a loudspeaker used as vibrating target.

**Figure 2.** Photo of the realized setup.

### 3. FM Noise Measurement

For each laser under test we measured the noise floor at the external photodiode, that is always an order of magnitude higher than shot noise and electronic noise. In order to compare the measurement performances, the voltage signal measured by the external PD was reported as frequency modulation, considering the sensitivity of the MZI, and the peak-to-peak amplitude of the modulation signal, with the same procedure described in [18]. In addition, in this work the DFB lasers performances are compared with the ones of a low-cost VCSEL, with different behavior in noise contribution: for the VCSEL the gaussian contribution is no more negligible, and it should be evident in the Power Spectral Density (PSD) of the FM-noise.

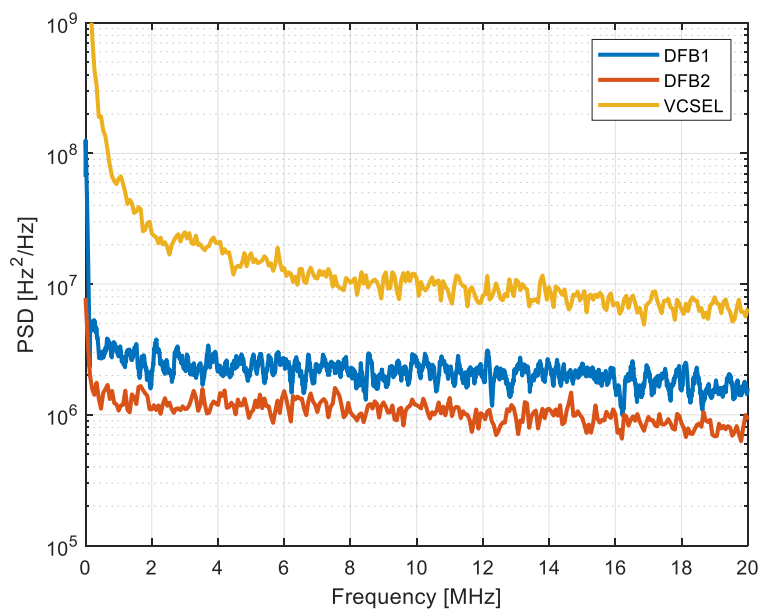
Figure 3 shows an example of FM signal acquired with the VCSEL, with 35 MHz bandwidth. It is evident the very-good signal-to-noise ratio, even considering the high bandwidth. In literature, indeed, the AM-SMI signal is normally filtered down to a few tens of kilohertz, in order to show a good signal-to-noise ratio.



**Figure 3.** FM self-mixing signal given by the VCSEL.

Figure 4 shows the comparison of the PSD of the three lasers, without optical back-injection. The Lorentzian contribution of laser linewidth, given by (2) are  $\sim 7$  MHz for DFB1,  $\sim 3$  MHz for DFB2, and  $\sim 30$  MHz for VCSEL.

The gaussian contribution is negligible for the DFBs, while should be considered for the VCSEL. Following [16], it is possible to calculate the gaussian contribution by measuring the  $1/f$  component of the FM-noise [18]. The calculated gaussian broadening is about 1 MHz for the two DFBs, while it is about 20 MHz for the VCSEL.



**Figure 4.** FM noise measurements carried out with 3 different lasers without optical back-injection.

## 4. Conclusion

The experimental measurements carried out on three different lasers confirm the theoretical dependence of the FM noise [13] with the laser linewidth. Noise measurements on a VCSEL also allowed to highlight the different broadening contributions of the laser line, in full coherence with the well-known laser linewidth theory [17].

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