High-sensitivity vibrometer based on FM self-mixing interferometry

M Norgia1, F Bandi1, A Pesatori1 and S Donati2

1 Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Via Ponzio 34/5, i-20133 Milano, Italy
2 Dipartimento di Ingegneria Industriale e dell’Informazione, Università di Pavia, Via Ferrata 1, i-27100 Pavia, Italy

michele.norgia@polimi.it

Abstract. We present a new optical instrument for vibrations measurement, based on a method to read the frequency modulation of a laser diode self-mixing interferometer. The laser source, when exposed to back-injection of its emitted power, is perturbed in frequency and amplitude (self-mixing effect). When the optical back-injection level is low, the self-mixing effect introduces a frequency and amplitude modulation (FM and AM) of the emitted optical field. We demonstrated with a prototype instrument that the performances of FM modulation, in terms of resolution, sensitivity and bandwidth, show an improvement of two order of magnitude with respect to well-known AM self-mixing interferometer.

1. Introduction
A number of mechanical applications and Non-Destructive Testing (NDT) techniques require high-frequency and high-resolution measurement of vibrations and displacements [1]. Optical interferometry represents the classical choice for this kind of measurement [2], but for reaching nanometer resolution at tens of megahertz it is normally required a very-high cost instrument [3]. In this work we present a compact prototype of optical instrument, able to measure vibrations with a noise equivalent displacement (NED) of about 0.14 pm/√Hz, with very-high bandwidth. The instrument is based on a recently developed optical technique, able to measure the frequency modulation induced by an optical back-injection, namely self-mixing interferometry.

2. Self-mixing laser interferometry
Self-mixing laser interferometry is an interferometric technique dating back to 1978 [4], known for its structural simplicity: it consists only on a laser diode, a collimation optics and a photodiode, which can even be the "monitor", that is, the one included on the same laser chip [5-8]. Figure 1 shows the principle scheme, in which the light emitted by the laser is focused, through the collimation optics, on the vibrating target.

![Figure 1. Self-mixing configuration.](image-url)
Part of the reflected or diffused light from the target surface goes back into the laser, where it gives rise to a sort of coherent detection of the radiation: here the optical power emitted by the laser results modulated both in amplitude (AM) and in frequency (FM), giving rise to a fringes interferometric signal from which it is possible, once converted into an electrical signal, to derive the displacement of the target [9-12].

Compared to the classical interferometers that follows Michelson's structure, this new type of interferometer is considerably simplified, because the interferometric signal is directly contained in the laser beam and is no longer generated by the beating of two beams coming from different paths: the optic to decouple the reference path from the measurement one is no longer necessary.

Therefore, it can be concluded that the configuration of a self-mixing interferometry instrument is very compact, doesn’t require complex alignment operations (indispensable for the operation of the classic configurations) and can be realized at very low cost.

Self-mixing laser interferometry in amplitude modulation (AM), has been employed for a number of measurement applications [13-26] but its performances are typically lower than the state of the art of classical interferometers. This is mainly due to the signal-to-noise ratio (SNR) of the AM self-mixing signal: the laser shot noise is always present, but the signal amplitude is normally small, typically 1% or less of the emitted power [7]. This limit relegated self-mixing interferometry to niche applications, where it take advantages of its simplicity, for example for optical mouse devices [27]

3. Self-mixing interferometry in frequency modulation

Recently, the frequency modulation (FM) induced by the self-mixing effect was investigated for measurement applications [28-30]. The FM signal was predicted by the theory of Lang and Kobayashi [31], but for about 30 years the applications concentrated on AM signal [6-8] because they are easier to read. However, beyond the readout complexity, the FM signal shows a strong improvement in terms of SNR with respect to the AM one, because it is not limited by the laser shot noise, but only by the laser linewidth. A detailed description of the FM self-mixing theory is reported in [32]. In order to convert the frequency modulation into the amplitude modulation, a very flexible choice is a Mach-Zehnder filter [33], which is characterized by a sinusoidal and periodic transfer function $T(v)$ in frequency.

It is possible to carry out the conversion, by appropriately calibrating the path difference $\Delta L$ of the optical filter, at any frequency (therefore at any wavelength). Moreover, the length of the path difference $\Delta L$ determines both the “Free Spectral Range (FSR)” of the instrument, coinciding with the bandwidth between two consecutive peaks of the transfer function, and the filter sensitivity $S = dT/dv = 2\pi c/\Delta L$ [33]. In particular, if the length of the Mach-Zehnder's path difference is small, then the sensitivity of the filter will be low, as well as its optical gain, such that the signal amplitude is reduced. In order to design the Mach-Zehnder $\Delta L$, we have to establish a compromise between sensitivity, FSR and dimensions of the instrument, taking into account the main sources of noise in the system.

4. Design of the optical instrument

The configuration adopted for the setup realization of the new instrument is represented in figure 2. It is based on a Mach-Zehnder's filter, as in [PTL FM], realized in free space. There are two FM reading channels and a prism replaces two mirrors, in order to make the configuration as compact as possible.

The signal from the two photodiodes is read by two transimpedance amplifiers with about 40 MHz of bandwidth, and sampled at 100 MHz by an appropriate acquisition card (Digidon 's Analog Discovery 2). Measurements confirmed that the system's dominant noise contribution is that related to laser frequency noise, that depends on the laser linewidth [32]. However, FM noise varies with the length of the filter path difference $\Delta L$, because Mach-Zehnder sensitivity gets changed too. Our goal was to find the minimum $\Delta$, that still keep the FM channel best performing. In this way the instrument size is minimized, the optical alignment becomes easier and the FSR of the Mach-Zehnder is maximized, while keeping always the same SNR.
The measurements were made first at $\Delta L = 44$ cm, then at $\Delta L = 22$ cm and finally at $\Delta L = 16$ cm. It is possible to observe in fig. 3 that, with decreasing of the length of the $\Delta L$, the FM noise floor tends to decrease. As expected, by reducing the path difference by a factor 2, in the same optical conditions, the noise floor decreases by 6 dB.

The final choice was $\Delta L = 16$ cm, because for that dimension the FM noise is still dominant with respect to shot noise and acquisition electronic noise.

The new setup fits in a box of dimensions $30 \text{ cm} \times 18 \text{ cm} \times 6 \text{ cm}$ in aluminium for shielding the internal electronics from external disturbances. In particular, the structure of the vibrometer has been realized on a 4 mm thick aluminium sheet in order to keep all the optical and electronic components...
on a single base as close as possible to the supporting surface (fig. 4), so as to reduce the degrees of freedom of the system and make alignment easier.

![Figure 4. Structure of the realized vibrometer.](image)

The setup is more compact than a typical bench-one, thus allowing the instrument to be portable. Supports for the lenses have been handcrafted in accordance with the dimensions of the instrument. The prism that characterizes the difference path of the filter is directly connected to a piezoelectric actuator which, through a control loop, allows to compensate the variations of the path difference due to temperature effects or vibrations, so as to always keep the Mach-Zehnder filter at the point of maximum sensitivity (interferometer in quadrature).

### 5. System performances

One of the main applications of vibrometer produced is related to Laser Ultrasonics measurements, that is to the measurement of the vibrations caused by a laser power pulse on a structure under test [1]. It should be noted that these vibrations, besides having high frequency components, are characterized by fast transitions due to defects reflections and a short duration. Hence an FM reading system with a high bandwidth is needed in order to be sensitive to these perturbations.

The FM reading channel band can be estimated by measuring the rise or fall time at the fringe jump: in fact, in this part of the signal the maximum spectral content is present. The time measurement is carried out between 10% and 90% of the peak-to-peak value of the wave during its rising front. In the experimental phase, therefore, an acquisition of a rising edge was carried out in the presence of a quite high $C$ value [7], so as to mark the transition and make a significant measurement, as shown in fig. 5. Thus, from the relation (1) we can derive a bandwidth of:

$$BW_{FM} = \frac{0.35}{T_{10→90\%}} = \frac{0.35}{0.233ns} \approx 43 \text{ MHz}$$  \hspace{1cm} (1)

A similar measure was taken for the AM channel, as shown in fig. 6: there is a rise time of about 10 $\mu$s such that, using the relation (1), it is possible to obtain a bandwidth $BW_{AM} \approx 35$ kHz.
Figure 5. Measurement of the rise time on the transition of a fringe of the FM channel.

Figure 6. Measurement of the rise time on the transition of a fringe of the AM channel.

The sensitivity performance of this kind of instruments are typically described by the Noise Equivalent Displacement (NED), which would represent the uncertainty on the displacement measurement caused by the instrument noise [2]. Considering that each fringe corresponds to a shift of $\frac{\lambda_0}{2}$, the NED can be calculated through the following proportion:

$$\text{NED} : \frac{\lambda_0}{2} = V_{n,\text{rms}} : V_{\text{pp}}$$

(2)

where $\lambda_0$ is the wavelength of the laser, $V_{n,\text{rms}}$ is the noise coming out of the signal reading circuit and $V_{\text{pp}}$ is the amplitude of the signal corresponding to an interferometric fringe.

With regard to amplitude modulation, the Noise Equivalent Displacement is equivalent to:

$$\text{NED}_{\text{AM}} = \frac{\lambda_0}{2} \cdot \frac{V_{n,\text{rms}}}{V_{\text{pp}}} = \frac{\lambda_0}{2} \cdot \frac{1}{\text{SNR}_{\text{AM}}} = \frac{1550 \text{nm}}{2} \cdot \frac{1}{298.51} \approx 2.59 \text{ nm}$$

(3)
While for the frequency modulation, the "Noise Equivalent Displacement" is equivalent to:

\[ \text{NED}_{\text{FM}} = \frac{\lambda_0}{2} \cdot \frac{V_{\text{rms}}}{V_{\text{pp}}} = \frac{\lambda_0}{2} \cdot \frac{1}{\text{SNR}_{\text{FM}}} = \frac{1550\text{nm}}{2} \cdot \frac{1}{833.33} \approx 0.93 \text{ nm} \]  
(4)

From the calculations we have just carried out, we see how the two values apparently have the same order of magnitude. In practice, thus, “NED” is usual to be reported normalized on measurement bandwidth. In particular, for AM reading channel:

\[ \text{NED}_{\text{AM}} = \frac{2.59 \text{ nm}}{\sqrt{35 \cdot 10^6 \text{Hz}}} \cong 14 \text{ pm/}\sqrt{\text{Hz}} \]  
(5)

while for FM reading channel:

\[ \text{NED}_{\text{FM}} = \frac{0.93 \text{ nm}}{\sqrt{43 \cdot 10^9 \text{Hz}}} \cong 0.14 \text{ pm/}\sqrt{\text{Hz}} \]  
(6)

This level of noise allows for high-resolution measurement also at very-high speed. For example, figure 7 shows the measurement of vibration at 10 kHz with peak-to-peak amplitude lower than 1 nm (full bandwidth 43 MHz, 64 averages)

![Figure 7](image)

**Figure 7.** Measurement of a 10 kHz vibration of a piezoactuator. Upper trace is the driving signal; middle trace is the signal from AM channel; lower trace is the signal from FM channel. rise time on the transition of a fringe of the AM channel.

### 6. Conclusions

In this work we presented an inexpensive, compact and high-performance instrument which, using the innovative FM self-mixing laser interferometer technique, is able to perform measurements as with the same level of precision and accuracy of the traditional expensive and bulky vibrometers commercially available.

During the prototyping phase of the instrument, in addition to the choice of electronic components, particular attention was paid to the realization of its mechanical structure, so as to optimize the available space as much as possible and to make easy to adjust any parts or components.

After verifying the correct sizing of the instrument, the signal-to-noise ratio of the AM modulation was compared with that of the FM modulation from the acquired vibration measurements and it was possible to observe how, despite its small size, the latter is still larger than the former, even though it has a bandwidth than about 3 orders of magnitude larger.
Furthermore, the minimum measurable signal expressed as Noise Equivalent Displacement, by exploiting the frequency modulation, was about 0.14 pm/√Hz, on a bandwidth not limited by the internal monitor photodiode.

In conclusion, the actual prototype is ready for field tests, for different demanding applications, like those of Laser Ultrasonic technique.

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