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Simultaneous measurement of humidity and vibration based on a microwire sensor system using Fast Fourier Transform technique

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***Abstract*— This work presents a new sensor system for vibration and relative humidity measurements based on its interaction with the evanescent field of a microwire. The interrogation of the sensing head is carried out by monitoring the fast Fourier transform phase of one of the FFT peaks of the microwire transmission signal. This technique is not dependent of the signal amplitude and also eludes the requisite of tracking the wavelength evolution in the spectrum, which can be a handicap when there are multiple interference frequency components with different sensitivities. The point sensor is able to measure a wide humidity range (20%–70% relative humidity) with a maximum sensitivity reached of 0.14πrad/% relative humidity. This microwire sensor is also operated within a frequency range from 320 to 1300 Hz with a sensitivity of around 0.0051 nm^{-1}/Hz. Finally, due to the system uses an optical interrogator as unique active element, the system presents a cost-effective feature.**

***Index Terms*— fast Fourier transform, humidity sensor, vibration sensor, simultaneous measurement, nanosensors, microwires, relative humidity.**

I. INTRODUCTION

THE use of micro/nanowires has been growing steadily over the last years. They are usually manufactured by the flame-brushing technique [1] where an optical fiber is heated and pulled to monotonically reduce its diameter to the range of the propagated wavelength. Therefore, tapered optical fibers with a uniform waist in the micro/nanometer range can be obtained [2]. Furthermore, a precise control of the taper profile is achieved through the pulling rate parameters. The optical properties of these devices include a large evanescent field, which is particularly important for optical sensing. Thus, the interaction of such strong evanescent field with the surrounding medium can be measured through changes in either intensity or phase of the transmitted light [3].

These kinds of nanostructures, such as nanotubes, nanoribbons or nanowires, have been used as physical, chemical or biological sensors [4]-[7]. Optical sensor systems offer great potential for immunity to electromagnetic interference, high sensitivity, fast response, and safe operation in dangerous atmosphere (explosive and combustive areas). In addition to this, they offer a great number of choices for signal retrieval from different parameters such as intensity, spectrum, polarization, or phase of the measured light [8].

Fiber-optic vibration sensors can be classified in three main types: intensity [9]-[12], interferometers [13]-[18], and gratings [19]-[23] based sensors. In areas such as tribology [24], [25] and structural health monitoring [26], humidity and vibration measurement are essential issues. Simultaneous measurement of these parameters can significantly decrease the cost and complexity of currently sensing systems [27].

Intensity-based sensors have been extensively employed due to the fact that they can be used to detect vibrations just by monitoring the power variations [28]. This type of sensors also offer low cost and are easily produced, however the measurement accuracy is limited. Interferometric sensors, such as Fabry–Perot, Mach–Zehnder, or Michelson interferometers, provide much higher resolution and accuracy, but its construction is a complex process.

In this work, a new method for simultaneous measurement of relative humidity (RH) and mechanical vibration is presented. This method is based on the fast Fourier transform (FFT) of the microwire optical power transmission spectrum. For the RH measurement, the evolution of the phase of one interference is measured [29], and on the other hand, for the vibration measurements, the special frequency value for the interference is tracked. Both measurement process are insensitive to the signal amplitude variations, increasing the robustness of the system.

This technique also avoids the necessity of tracking the wavelength evolution in the spectrum simplifying the measurements. In addition, the system uses an optical interrogator as unique active element, presenting a cost-

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effective feature (in comparison with the economic cost of a classic interferometric interrogation setup).

II. OPERATION PRINCIPLE AND EXPERIMENTAL SETUP

The manufacture of the microwires has been done by the flame-brushing procedure as shown in [28]. Following this procedure, a standard optical fiber (single-mode standard Corning SMF-28) has been tapered from its nominal outer diameter of 125µm until get an adiabatic taper 4µm uniform waist diameter that means a tapering ratio of 31.25.

The transition between the unperturbed optical fiber and the uniform waist is exponential. With this system, a uniform waist around 20mm length for total taper length of about 110mm is fabricated in a single step. Afterwards, the microwire has been carefully fixed on a semi-rigid cylindrical substrate for easy handling purposes. This microwire renders a λ/r value of 0.775 with a normalized frequency V of about 8.4 as is was previously carried out in [29]. Even with these relative high values, the evanescent filed is strong enough to interact with the outer medium.

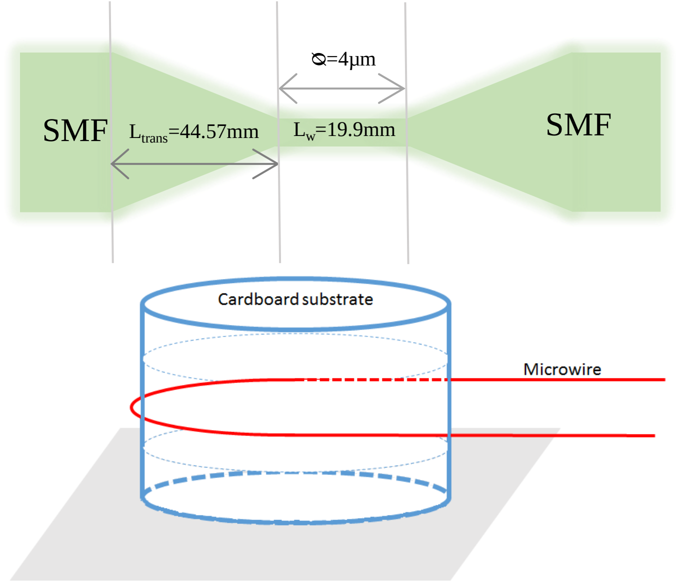

Fig. 1. Schematic illustration of the microwire for RH and mechanical vibration sensor and its disposition with the substrate.

As schematically illustrates Fig. 1, the fiber taper drawn from a single-mode fiber (SMF) with a diameter of 4µm and a nanowire length of about 20mm has been used as sensor. Due to the fact that this microwire has been developed only by using SMF there is no need of making any splices. With the help of nanoscale optical fiber tapers, the light is efficiently launched into and picked up from the single microwire using evanescent field interaction [4], [30]. In addition to this, it was not needed any kind of chemical coating to develop the sensor´s sensitivity. This nanowires used as point vibration sensors could be multiplexed along a network through the FFT analysis. In this work, the microwire sensors are employed as transducers to measure mechanical vibrations.

Fig. 2 illustrates the experimental set up of the proposed microwire for RH and mechanical vibration sensing system. As it was presented in [29] a commercial interrogating sensor device was used to illuminate the network and also to analyze the spectrum of the signal guided through the microwire sensor. This equipment was originally commercialized for FBG sensors monitoring and allows us to interrogate sensors in real time (scan frequency of 1Hz) [31]. An optical circulator was employed to couple the light towards the sensing unit. This sensor unit was inserted into a humidity chamber where humidity ranges from 20% to 70% (at constant temperature) were applied to evaluate its response to this parameter.

The experimental set up of the proposed microwire for mechanical vibration sensing system is shown in Fig. 3.

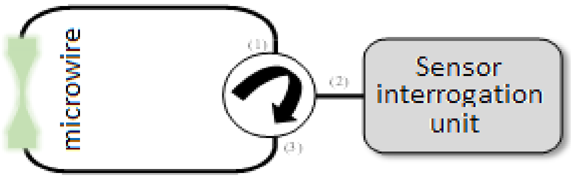

Fig. 2. Experimental setup of the proposed humidity sensor system.

A variable frequency mechanical wave driver was employed to induce transversal vibration on the sensing fiber as can be seen in Fig. 3. This device allows to create a continuous sinusoidal vibration between 0.1 Hz and 5 kHz with an amplitude of 7 mm for a vibration of 1Hz and decreasing with increasing the frequency.

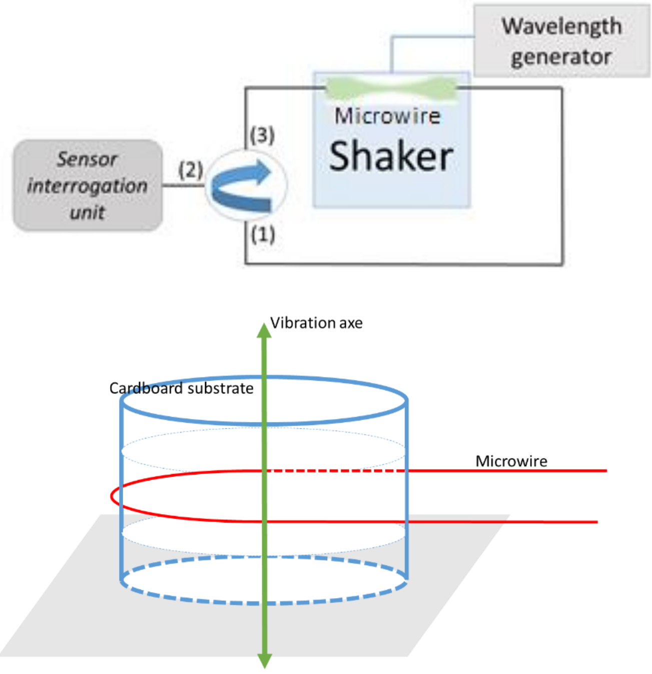

Fig. 3. Experimental set up for mechanical vibration measurements.

III. EXPERIMENTAL RESULTS

A. *Relative Humidity sensor*

In order to verify the proper operation of the sensing head,

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the humidity-sensing performance of the nanowire in the atmosphere of different RHs at room temperature (about 25ºC) was experimentally carried out. Fig. 4 (a) shows the transmission spectrum of the sensing head which presents different frequency components due to the multiple modes interference.

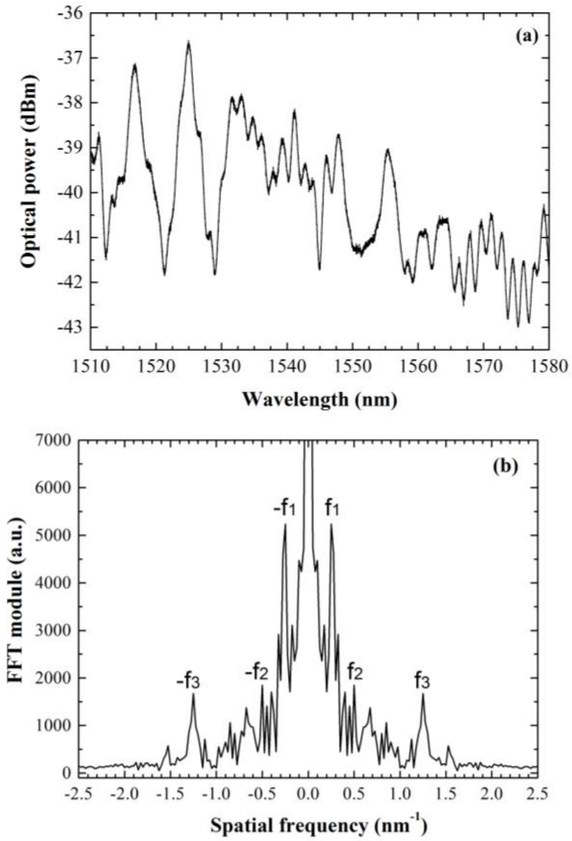


Fig. 4. (a) Optical transmission spectrum of the sensor at 25ºC and 20% humidity, and (b) its fast Fourier transform spectrum.

As it was presented in [29], performing the FFT analysis to the optical spectrum interference and tracking the evolution of the FFT phase (directly related to wavelength shifts of the optical spectrum), it avoids the need of tracking the spectrum displacement with the measurement. Fig. 4 (b) shows the FFT of the microwire transmission spectrum. This figure evidences three frequency components f_1, f_2 and f_3 which corresponds with 0.25 nm-^{1}, 0.5 nm^{-1} and 1.25 nm^{-1}, respectively. The three frequency components phase evolution were characterized in order to determinate their sensitivities to the RH.

The characterization was carried out by using a climatic chamber in the humidity range from 20% to 70%, 25ºC constant temperature, and taking samples each minute for about 3 hours. Fig. 5 shows the evolution of the phase of each frequency interference with humidity. In this figure, f_3 presents the maximum phase sensitivity and range, followed by f_2. However, f_1 presents a behavior that can't be used for measuring. The sensitivity of f_2 and f_3 was about 0.045 rad/%humidity and 0.14 rad/%humidity, respectively.

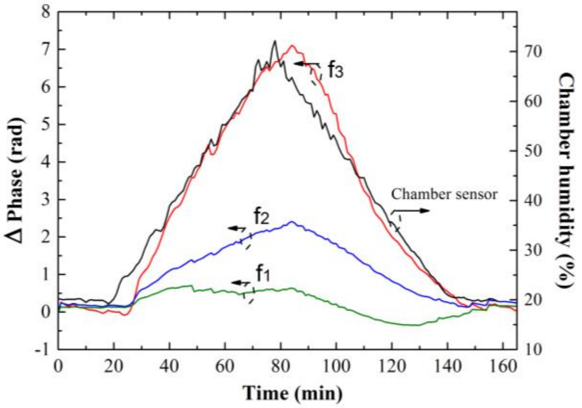
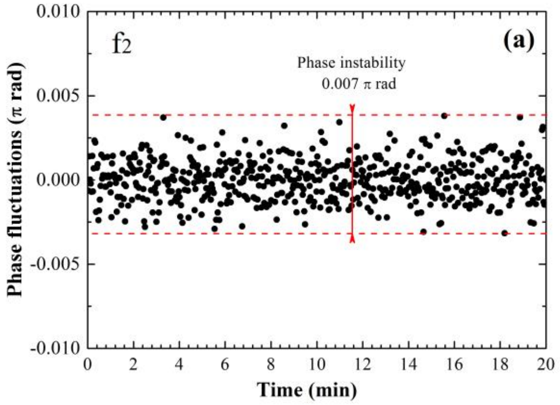


Fig. 5. Representation of the phase shift of each frequency component as a function of humidity.

The sensor response presented a hysteresis effect (see Fig. 5) observed at high humidity in the descent cycle (the climatic chamber uses a digital humidity probe to check the real humidity value). This is due to part of the water molecules are trapped in the porous surface of the cardboard substrate used during the fabrication process for a longer time than in the chamber´s atmosphere. This effect could be minimized only by using another kind of hydrophobic substrates in the fabrication process.

The stability of the system was also analyzed. The phase variations of frequencies f_2 and f_3, were tested during 20 minutes for a 30% RH and 22ºC, showing an instability of around 0.007π rad and 0.012π rad in that order, as Fig. 6 illustrates.



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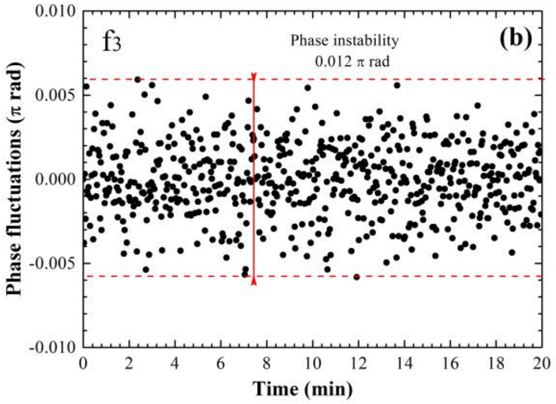

Fig. 6. Phase fluctuations of frequencies f$_2$ (a) and f$_3$ (b) along 20 minutes for a 30% RH and 22ºC.

B. Mechanical vibration sensor

Mechanical vibration sensors using fiber-optic tapers as transducers, are usually based on the detection of power variations generated by the bending change radius [32]. However, in this work, the analysis of the vibration is carried out by using the relation between the vibrations with the position of the peaks in the FFT module. Fig. 7 illustrates four examples of these peaks in the FFT module due to the vibration induced by a mechanical shaker. As it can be seen, these spatial frequencies do not overlap with the intrinsic nanowire peaks (in the frequency range 300-1300Hz). Those nanowire intrinsic peaks appear due to the mode beat of the fiber and are located at lower spatial frequencies (below 1.5 nm^{-1}) than the peaks which correspond to external vibration (over 1.5 nm^{-1}).

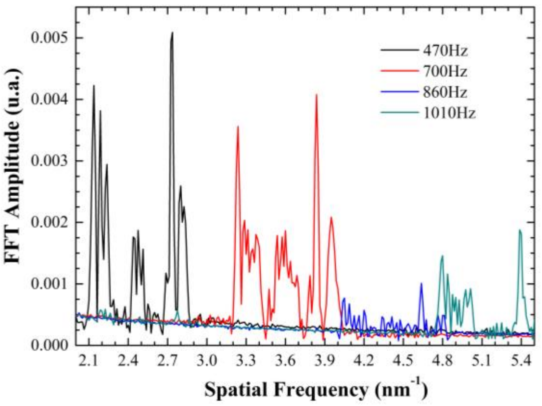

Fig. 7. FFT magnitude peaks for 470 Hz, 700Hz, 860 Hz and 1010 Hz induced sinusoidal vibration.

The spatial frequency position (maximum peak) for each vibration frequency in the range of 320 Hz – 1300 Hz was carried out. As Fig. 8 illustrates, the peak position presents a linear behavior with the vibration frequency with a sensitivity of 0.0051 nm^{-1}/Hz. The sensor system was tested in conditions of 42% RH and constant 24ºC.

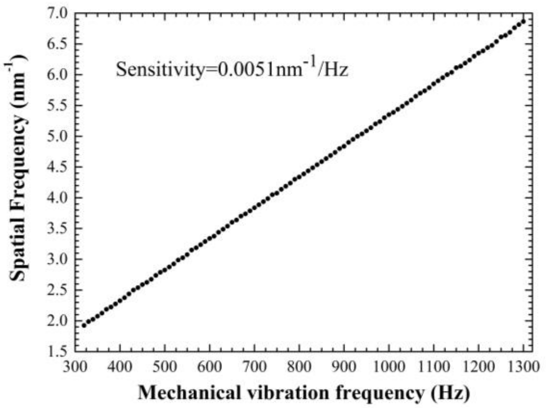

Fig. 8. Characterization of the spatial frequency peaks location with the vibration frequency.

C. Simultaneous RH and vibration sensor

A characterization of the sensor system as a simultaneous sensor for RH and vibration was carried out. The fringe characterization depends on the parameter to be measured: for RH the study was focused on the peak f$_3$ located at 1.25nm^{-1} (see Fig. 4 (b)) by following its FFT phase. Likewise, as can be seen in Fig. 7, new FFT peaks appear when vibration is applied to the sensor. As it will be shown, vibration frequency shifts can be easily evaluated by following those new peaks. For the characterization as simultaneous sensor, the crosstalk between peaks was experimentally analyzed. Fig. 9 shows the phase stability of f$_3$ at 40% RH with vibrations ranged 300 Hz – 1300 Hz with 100 Hz steps between them. Ten measurements were attained for each vibration frequency, obtaining a phase instability of 0.006π rad in the worst scenario.

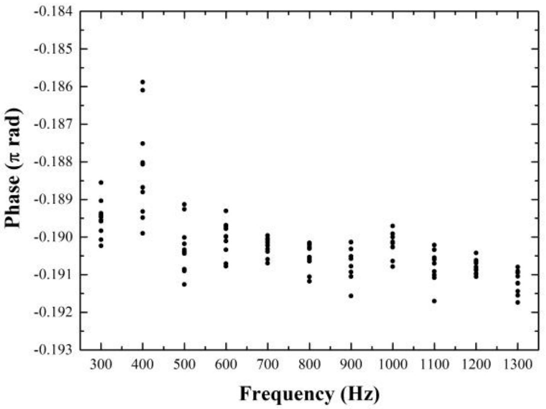

Fig. 9. f$_3$ component phase stability (40% RH) for different vibration frequencies.

In order to test the crosstalk with constant frequency vibration and variable RH the system was introduced inside the climatic chamber to induce variable-controlled RH changes. In Fig. 10 the results of the crosstalk are shown. The independence between measures of RH and vibration is probed. Applying RH variations from 20% to 70% with 10% steps a stability of 0.0125 nm^{-1} was achieved. This instability is given by the interrogating sensor device resolution.

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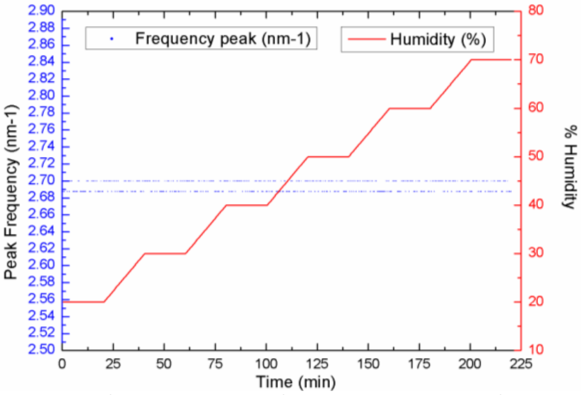

Fig. 10. Spatial frequency stability for a 470 Hz vibration frequency with variable RH.

IV. CONCLUSIONS

To summarize, a new sensor system for relative humidity and mechanical vibration measurements based on its interaction with the evanescent field of a microwire has been proposed and experimentally demonstrated. It has been experimentally demonstrated that this sensor is able to measure mechanical vibration regardless of the relative humidity and vice versa. The interrogation of the sensing head for RH measurements has been carried out by monitoring the FFT phase variations of one of the microwire interference frequencies. This method is independent of the signal amplitude and also avoids the necessity of tracking the wavelength evolution of the spectrum, which can be a handicap when there are multiple interference frequency components with different sensitivities. The sensor has been operated within a wide humidity range (20%–70% RH) with a maximum sensitivity achieved of 0.14rad/% RH.

For mechanical vibration measurements another technique, based on the generation and tracking of new FFT peaks when mechanical vibration is applied, has been used. A linear response, with a sensitivity of 0.0051 nm^{-1}/Hz, has been experimentally obtained when this microwire was made to operate in the range of 320 Hz – 1300Hz.

The feasibility of simultaneous of RH and mechanical vibration measurement with resolutions of 0.006π rad and 0.0125 nm^{-1}, respectively have been attained. To conclude, due to the system uses a commercial optical interrogator as unique active element, the system presents a cost-effective feature.

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