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Vibration and magnetic field sensing using a long-period grating

I. M. Nascimento, G. Chesini, J. M. Baptista, Cristiano M. B. Cordeiro, P. A. S. Jorge

Abstract— **A long-period grating (LPG) written on a standard single mode fiber is investigated as a fiber optic sensor for vibration and magnetic field sensing. It is demonstrated the high sensitivity of the device to applied curvature and the possibility to monitor vibration in a wide range of frequencies from 30 Hz to 2000 Hz. The system was tested using intensity based interrogation scheme, providing a frequency discrimination of 913 mHz. The goal of these tests was to evaluate the sensor as a passive vibration monitor in the detection of changes in resonant vibration frequencies of support infrastructures can provide information on its degradation. Furthermore, taking advantage of the intrinsic sensitivity to micro strain, alternating magnetic fields were also measured using an intensity-based interrogation scheme by coupling a Terfenol-D magnetostrictive rod to a pre-strained LPG sensor, providing a resolution below 5.61 μT$_{RMS}$/√Hz from 1.22 mT$_{RMS}$ up to 2.53 mT$_{RMS}$.**

Index Terms — **long-period fiber grating (LPG), vibration sensor, magnetic field sensor, intensity modulation scheme.**

I. Introduction

A large diversity of vibration sensors are being used for real-time structural health monitoring, in civil infrastructures and engineering systems, namely bridges, buildings and railway tracks [1]. In the case of large-scale structures like bridges, low frequency vibrations are the most commonly monitored. Vibration monitoring can immediately detect changes of structural integrity, leading to fast and reliable conclusions about the condition of the structure [2].

In this range of operation, however, traditional electromagnetic vibration sensors are usually very limited [3] and inadequate while operating in the presence of high magnetic fields, giving rise to faults. In contrast, optical sensors do not suffer from electromagnetic effects and therefore operate well in these environments [4].

Low frequency signals provide information about the presence of small cracks and discontinuities in the infrastructures [5]. For an old arch bridge, vibration frequencies in the range of 6 Hz to 44 Hz are the most suitable for the detection of signs of structural degradation [6]. Furthermore, for a centenary iron arch bridge [7], bending and torsion of the structure present vibration frequencies within the 0.9 Hz to 9 Hz range. On the other hand, higher frequencies in the range of 1 kHz to 1.5 kHz enable the early detection of potential problems in electrical machines such as bearing, eccentricity and broken rotor bars [8].

According to the working principle, fiber optic sensors to measure vibration can be based mostly on intensity or wavelength modulation schemes [9]. They can be implemented using different sensing elements such as fiber Bragg gratings (FBG) [10]–[12] or long-period gratings (LPGs) [13]–[15], mostly fabricated using conventional single mode fibers. Usually the former are interrogated in reflection and the later in transmission. However, FBGs and LPGs, fabricated in standard optical fibers, usually present a high cross-sensitivity to temperature. In LPGs, in addition, the refractive index (RI) of the external medium is also a major source of cross sensitivity, strongly affecting the sensor response [16], [17] and requiring the use of low refractive index coatings that impact on the overall sensor response.

Concerning the optical sensors based on FBGs, in 2010, Nan [18] developed a low frequency vibration sensor operating in the range from 0.24 Hz to 50 Hz. It employs two FBGs sensors, one acting as the sensor (works in reflection) and the other like a transmission filter. The first FBG is attached to an oscillating cantilever plate with a mass in the edge. The reflected signal then follows through the filter FBG which is attached to a second cantilever of the same material. This cantilever, however, is not free to oscillate and its position can be adjusted by a screw that is used to define a fixed curvature. By adjusting the screw, the spectrum of the second FBG is tuned in wavelength, in order for its slope match with the reflective peak of the first FBG. Therefore, when vibration is applied to the first FBG, a proportional power fluctuation is detected in the photodetector. When temperature changes, however, both peaks move alike. Their relative position does not change, and the transmitted power is therefore independent of temperature.

On the other hand, LPG sensors for vibration measurement

This paper was submitted for review in 11 March 2017. This work is financed by the ERDF – European Regional Development Fund through the Operational Programme for Competitiveness and Internationalisation - COMPETE 2020 Programme within project «POCI-01-0145-FEDER-006961», and by National Funds through the FCT – Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) as part of project UID/EEA/50014/2013.

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were also investigated in 2009 by Tanaka et al. [14]. The sensor consists of a symmetric LPG, exciting the 8^{th} order mode, and attached to a piezoelectric transducer. The sensor is illuminated by a laser source, coincident with the transmission slope of the LPG attenuation band, and when strain is applied to the piezoelectric transducer (using a 10.22 kHz modulation signal), the LPG only changes in wavelength, maintaining its spectral shape. At the output, a photodetector is used to detect the amplitude changes. Still, the LPG is dependent on the temperature and the external refractive index.

Regarding optical current sensors, distinct sensing mechanisms, including Faraday effect, magnetostriction and magnetic fluid can be employed for current sensing. Nevertheless, Faraday effect is the preferable one among the high power industry, where the sensing medium is a bulk glass rod [19], [20] or an optical fiber [21], [22].

More compact solutions typically include sensors based on magnetostriction effects, with magnetostrictive materials, expanding in the presence of a magnetic field. Typically, Terfenol-D is one of the preferable materials, due to its high magnetostriction. This material when coupled to an optical strain sensor, such as an FBG, can provide a sensitivity of $(2.31 \pm 0.05) \times 10^{-10}$ nm/($A^2.m^{-2}$), with fields up to 59 mT [23]. Thin films were also investigated by Yang et al. [24], exhibiting a sensitivity of 0.95 pm/mT, for an etched FBG with 85 µm diameter. Withal, optical fiber lasers was also subject of study [25]. The sensor is an erbium doped optical fiber laser, whose wavelength emission is modulated according to the magnetic field. With the use of a passive interferometer, the wavelength changes are read, with errors below 0.79 %, for magnetic fields higher than 2.26 mT_{RMS} and up to 13 mT_{RMS}.

Nevertheless, the use of magnetic fluid, a fluid whose refractive index changes according to the applied magnetic field, was also explored. In 2015 a Michelson interferometer provided a sensitivity of 65 pm/mT with fields up to 200 mT [26].

In this paper, a simpler approach, based on the previous configuration, is presented using a single LPG fabricated in a standard single mode fiber (SMF). Since the LPG was fabricated with a relatively long period, thus exciting lower order modes with a more internal power distribution, its sensitivity to external refractive index is low. On the other hand, it sensitivity to vibration is preserved. The sensor device is therefore characterized and demonstrated as suitable for a high sensitivity vibration measurement applications and also for magnetic field sensing.

II. Working Principle

A long period grating consists of a refractive index perturbation inscribed along the fiber with a periodicity of hundreds of microns. The periodicity and amplitude of this refractive index variation determine the coupling of light between the guided core mode and the cladding modes, through the phase-matching condition. For long period gratings, the energy typically couples from the fundamental core mode to discrete forward-propagating cladding modes. The cladding modes are quickly attenuated and this results in a series of loss bands in the transmission spectrum of the grating.

The LPG used in the experiment was fabricated by a CO_2 laser, heating the fiber with the desired periodicity. For this particular experiment a LPG with a period of 600 µm was produced and its transmission spectra is present in Fig. 1. This fabrication technique creates LPGs which excites the asymmetric modes, in this case the LP_{13}, the third order mode. The refractive index modulation was introduced by closing and opening a shutter positioned in front of the laser, according to the period, while the pulsed beam was being focused along the fiber.

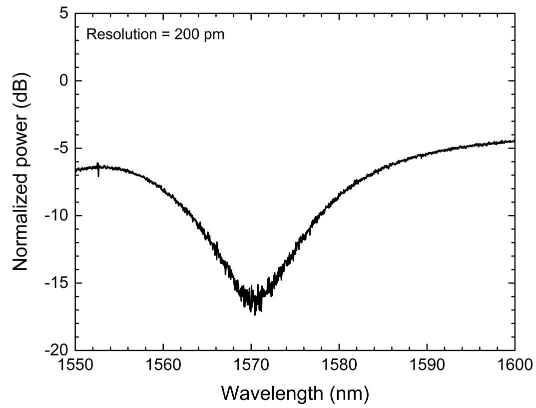

Fig. 1. LPG spectrum measured with a white light source.

III. Experiment and Results

A. Temperature and refractive index

The LPG was firstly characterized in temperature using an oven, with a setup as depicted in Fig. 2.In order to prevent any twisting, two marks were placed on each end of the LPG, to ensure that its placement inside the oven does not undergo any rotation. To guarantee the LPG is maintained with a constant strain, while increasing the temperature, one of the LPG's extremes was fixed at one point and the other one was left hanging and coupled with a 7 g weight.

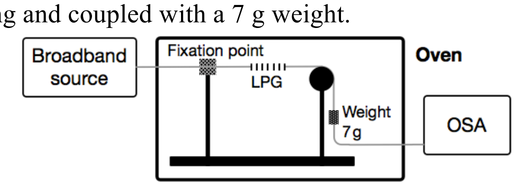

Fig. 2. Temperature characterization setup.

The sensor was submitted to a rising temperature between 30 ºC to 90 ºC. A linear red-shift was obtained in this range, from which it was possible to estimate a linear temperature sensitivity of 57.67 ± 0.26 pm/ºC ($R^2 = 0.99892$). The system was also let to cool down, and the sensor response registered during the lowering of temperature. No hysteresis was observed. This process was repeated two times with the results of both tests showing a good reproducibility.

In order to evaluate the cross sensitivity to refractive index, the response of the LPG to changes in the surrounding refractive index was also studied. Three independent experiments were carried out where the sensor was submitted

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to three measurements with refractive index changing between 1.0003 and 1.3355, measured at 589.3 nm and at 20 ^{o}C. The sensors showed a maximum change of the resonance peak of -1.074 ± 0.02 nm while changing from air to water, indicating a first order sensitivity of 3.2 nm/RIU. This is a value that is typical of low order modes and is quite low when compared with typical standard refractometer LPG where higher order modes are used (usually 5th or 6th) with 50 nm/RIU and 100 nm/RIU [27], [28]. This feature contributes to minimize cross-sensitivity arising from surface contamination. Furthermore, the use of low refractive index coatings can also be employed to further reduce the sensor refractive index sensitivity. This RI change is also equivalent to a positive temperature variation of 18.62 ºC. Besides the observed wavelength shifting behavior of the resonance, its features remained otherwise preserved. Indeed, during temperature and refractive index tests, the shape and magnitude of the resonance transmission loss was preserved.

B. Curvature

In a preliminary stage, the sensor was characterized in curvature using the setup of Fig. 3. The LPG was fixed carefully with no torsion (fiber markers were inserted and lined up with the rotation stage 0-degree trace) between a fixed pole and a moving pole, set on a micrometric translation stage with ΔL = 5 µm displacement resolution, where the fiber was stretched from the initial distance of d = 326 mm (L = 326 mm, ΔL = 0). A rotation stage in each pole allows to spin the fiber, enabling testing the sensor response with curvature applied at different angles. The relation between the fiber length (L) and the distance between both fiber fixation points (d), is given by $d = L + \Delta L$.

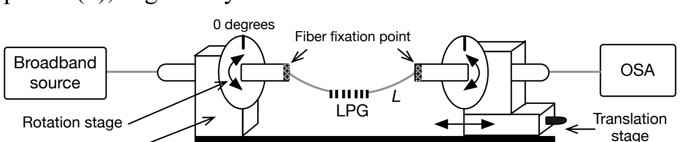

Fig. 3. Setup used for applying curvature to the LPG sensor at different angles by adjusting a rotation stage in each fixation pole.

Small curvatures were applied to the sensor by turning the moving screw of the translation stage in the micrometer range between -50 µm and 125 µm, while recording the transmission spectrum with an optical spectrum analyzer (OSA) with 20 pm resolution. In Fig. 4 it is only shown the behavior of the resonance peak with the fiber at 0 degrees, since for other fiber orientations (45, 90, 135 and 180 degrees), similar results were obtained. The negative and positive ranges of ΔL correspond to applied curvature and strain, respectively (from now on referred as curvature mode and strain mode of operation). In addition, the transition point between these two regimes was established to have ΔL = 0 µm, and is the limit where the fiber is stretched but has no applied strain. Results show that the position of the peak wavelength of the resonance dip is not affected but its depth changes significantly, with peak loss ranging between -38.0 dB and -20.9 dB.

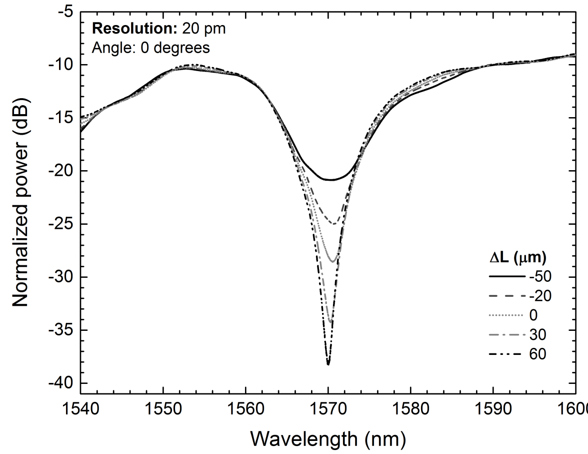

Fig. 4. LPG spectra obtained when the sensing region was submitted to different displacement values.

Variation of the transmitted optical power at a fixed wavelength, 1570 nm, was observed while changing the displacement with the fiber oriented at 0, 45, 90, 135 and 180 degrees. This test was performed in order to evaluate possible asymmetric behaviors of the LPG curvature response. In Fig. 5 it is shown the recorded average power variation and the corresponding standard deviation value, obtained from three repeated tests, in a linear scale for each angle, while increasing the displacement. Results showed very good reproducibility, with very small deviations registered between tests. Furthermore, while decreasing the displacement to the initial value no hysteresis was observed. As noticed earlier, much higher power variation is observed in the region where curvature is applied to the LPG, i.e. for negative values of ΔL. Therefore, it is expected that any small perturbation in the curvature will be translated into a linear power fluctuation in the transmitted power. In particular, from the recorded data could be estimated a change of -148 ± 3.5 µW/µm (R^2 = 0.99396) between -55 µm and -10 µm. A logarithmic curve was also fitted to the data in the range between -40 µm to 50 µm with -0.17877 ± 0.00279 dB/µm (R^2 = 0.99781). A strain displacement sensitivity of 3.077 µε/µm was calculated for positive values of ΔL and the behavior of the transmitted power.

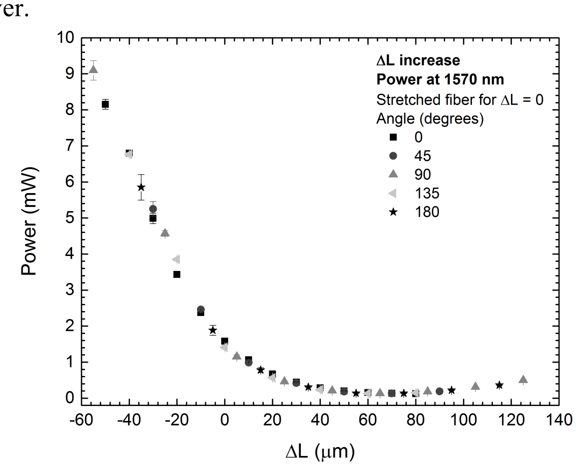

Fig. 5. LPG power change at 1570 nm while increasing ΔL between -55 µm and 125 µm

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The behavior of the peak wavelength position was also characterized in the same range, showing a maximum change of 1 nm in full scale measurement and a linear dependence with ΔL, between 0 µm and 125 µm.

C. Vibration

Foreseeing the possibility of using intensity-based systems in more practical applications, a tunable laser, was tested in the interrogation of the LPG vibration sensor with the setup shown in Fig. 6. The fiber is glued at both ends of the LPG to a solid acrylic plate (138 mm × 32 mm × 5 mm), which in turn is glued to the speaker diaphragm. This way, a signal applied to the loudspeaker is able to apply vibration to the LPG-Acrylic plate system. Using the OSA, the operation point was set by adjusting the initial curvature of the sensor in order to obtain a resonance dip corresponding to ΔL = -30 µm. The laser used has a line bandwidth of Δf = 1 MHz ($\Delta\lambda$ = ~0.009 pm) and 15 mW of peak emission power. In this setup, the sensor response to frequency is assessed using a tunable laser at a fixed wavelength, while recording the transmitted power using a photodetector, an analog-digital converter (DAQ NI USB 6363) system and a PC with appropriate LabVIEW software for signal acquisition and processing. The input channels of the DAQ had a resolution of 1.92 mV and the developed software was set to acquire the photodetector signal, searching for the most significant harmonic and recording its peak amplitude and frequency as a function of time. In the program, a vector of 10^5 samples and a sampling frequency of 10^5 Hz were defined. For each vibration frequency applied to the speaker, the AC optical signal, normalized by the DC value, was recorded during 60 s and its average and standard deviation values were calculated. This normalization makes the recovered signal independent of power fluctuations.

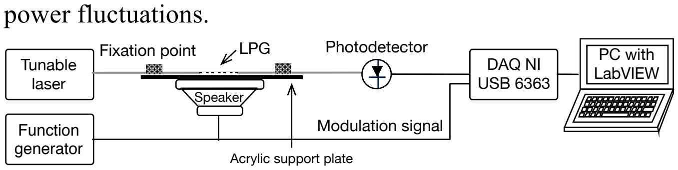

Fig. 6. Setup used for testing the sensor response to vibration.

Firstly, the sensor response was characterized in the curvature regime (ΔL = -30 µm) from 30 Hz to 2000 Hz by applying individual sine waves with an average vibration amplitude of 0.5 V_{RMS}. In Fig. 7 it can be observed the normalized amplitude modulation of the signal read in the photodetector for 400 Hz, 650 Hz and 1000 Hz, showing different modulation amplitudes. The amplitude and frequency is proportional to the support plate displacement. During the measurements, the power of the laser was maintained constant. The main reason for the sensitivity dependence with frequency is the fact that, depending on the particular vibration modes excited on the surface, different vibration patterns with nodes and maxima, can be imposed on the fiber that condition the sensor response. The optimization of the arrangement of the fiber plus support plate and speaker ensemble, to explore further this mutual dependence, is a research topic by itself and will be explored in future work.

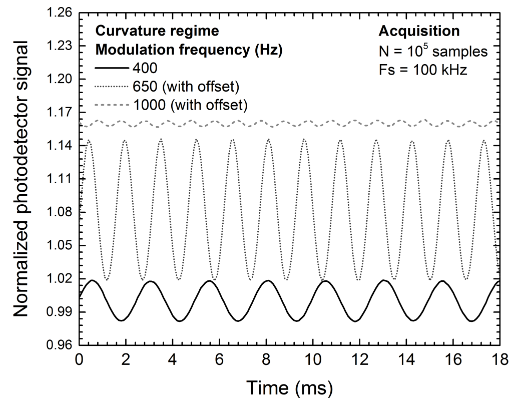

Fig. 7. Recovered optical output signals for several frequencies with the sensor operating in the curvature regime (ΔL = -30 µm).

From these tests resulted the data displayed in Fig. 8, for frequencies from 30 Hz to 2000 Hz. The modulation amplitude defined by the function generator is fixed. However, because the speaker has lower impedance than the function generator and its impedance dependents on frequency, the speaker modulation amplitude changed 9.3 % from 30 Hz to 2000 Hz. Having this effect into account, the results shown in Fig. 8 are also normalized as function of the function generator amplitude (Mod_{RMS}). Three independent tests were conducted, where some resonance peaks were detected at 300 Hz, 580 Hz and 1810 Hz, showing very high changes in amplitude.

While the same peaks were detected in all three repeated tests, it was observed a great variability of the detected amplitude, particularly in the vicinity of the resonances. For instance, the resonance neighboring 300 Hz showed from the first to the second measurement an amplitude increase of 20.7 %. Nevertheless, for the resonance at 580 Hz an amplitude increase of 200 % was observed between the first and the second measurements. On the other hand, off the resonances it can be observed that the sensors yielded very reproducible results. The frequency generator used during the experiment was manually configured, and although an effort was made to set the same frequencies in each measurement, very small changes and fluctuations could have taken place, inherent to the system limited resolution. As a result, slight changes in the frequency will result in amplitude differences, especially for the regions nearby the resonance where the rate of change of amplitude with frequency is much higher. Furthermore, changes in the laser input polarization may also affect the modulation amplitude of the optical signal. A change in the resonance dip of -3.2 dB (-52 %) was observed in the FS2200SA Braggmeter from FiberSensing (5 pm resolution), while varying the input polarization.

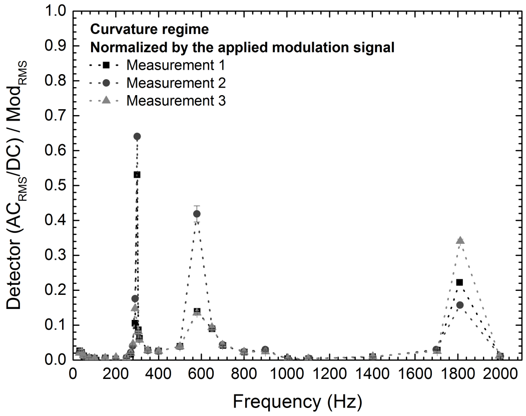

Fig. 8. Recovered AC amplitude as a function of the frequency generator for the sensor operating in the curvature regime (ΔL = -30 µm). Results are shown for three independent measurements.

Vibration of the structure was also simultaneously measured as function of frequency, using a microphone at 5 mm distance from the optical sensor. With this setup, a maximum positive variation of 2.4 % was observed at 580 Hz, much less than the one obtained with the optical sensor, with 200 %. This result indicates that the observed changes may be related with fluctuations of the resonant condition of the fiber-plate-speaker ensemble.

In order to better understand the sensor behavior, the LPG transmission spectra was recorded before and after the vibration test. This way it was possible to evaluate if there was some spectral change that could justify part of the changing response. The spectra of the LPG sensor acquired without applied vibration, before and after the vibration tests. The contrast of the LPG, given by the difference between the transmission at the base and at the peak of the resonance are 17.21 dB and 21.07 dB, before and after the test, respectively. This corresponds to a change in the depth of the resonance of -3.82 dB, implying a change in the optimum operation point and consequently affecting the overall sensitivity. This effect may be related with changes in the input polarization and in the curvature due to the fiber being slightly loose in the support plate.

In the curvature regime the poorest frequency resolution achieved in the three independent tests were 11 mHz for 30 Hz and 913 mHz for 2000 Hz.

D. Magnetic field sensing

The previous curvature tests, indicated the sensor operating in the strain regime, it could be used for magnetic field sensing, provided it is coupled with the right transducer element. In order to test this idea, the LPG was coupled to a rod of a magnetostrictive material (Terfenol-D). The sensor was pre-strained and glued in two fixation points, 52 mm apart. In these conditions, in the presence of a magnetic field, strain will be induced in the magnetorestritive rod which will modulate the LPG and impact the resonance dip accordingly.

The experimental setup implemented to test this idea is shown in Fig. 9 where the magnetic field is generated with an inductor with a relation of 9 mT/A, along the 52 mm extension of the sensor element. A specific LabVIEW program was designed for signal acquisition and processing. Due to electronic limitations of the current amplifier, the maximum alternating current that could be applied was of 3.5 mT$_{RMS}$ at 20 Hz (no bias magnetic field could be set). Acquisition was done with a sample frequency of 1 kHz and filtering was performed at the second harmonic resulting from the symmetric response of the magnetostrictive material as function of the magnetic field, with a Butterworth band-pass filter with a 5 Hz bandwidth.

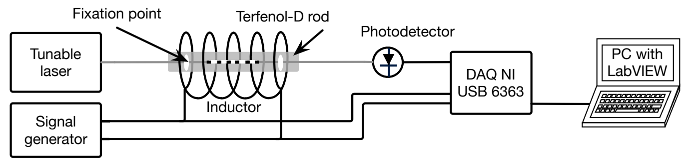

Fig. 9. Setup used to measure magnetic field with the LPG sensor glued to the magnetostrictive material.

Previous results showed that the sensitivity of the readout system to vibration is dependent on the relative wavelength position of the laser and the resonance dip. Hence the tests for the LPG based magnetic field sensor were carried out at two distinct wavelengths, near the resonance peak, at 1570 nm and 1569.7 nm, respectively.

The sensor was submitted to an increasing magnetic field between 0 and 3.3 mT$_{RMS,}$ by successively incrementing the applied alternating magnetic field with steps of approximately 0.25 mT with a duration of 30 s each. The waveform of the applied magnetic field and the corresponding photodetected sensor output for 3.28 mT$_{RMS}$ is shown in Fig. 10. The photodetected signal at 1570 nm presents a high level of distortion, with a SNR of 36.15 dB, measured with a 10 Hz bandwidth. The distortion is related with the magnetostrictive material response and primarily due to the LPG amplitude modulation dependence with wavelength. Nevertheless, at 1569.7 nm the recovered optical signal present much less noise, containing only the distortion due to the magnetostrictive material, also showing the frequency doubling. The SNR was also calculated yielding a value of 40.71 dB, which represents an improvement of 4.56 dB relatively to the previous test performed at 1570 nm.

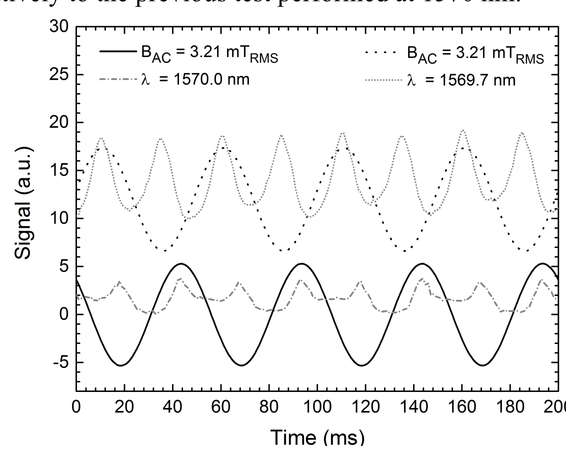

Fig. 10. Applied magnetic field and the corresponding photodetected signals (with gain and offset) obtained at 1570 nm and at 1569.7 nm.

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Three repeated measurements were performed. The results obtained can be observed in Fig. 11 showing a behavior that can be fit by a 3^{rd} order polynomial up to the 2.52 mT_{RMS} range. In this Figure, the average and standard deviation of the three measurements are also shown, revealing a good agreement between independent measurements. The same measurements were performed with the laser operating at 1569.7 nm where much better results could be obtained. A 4^{th} order polynomial curve provided a good fit ($R^2 = 0.99996$) to the experimental data where the maximum response registered was 4.2 times higher than at 1570 nm. The SNR was also calculated at 10 Hz bandwidth yielding a value of 40.71 dB, which represents an improvement of 4.56 dB relatively to the previous test performed at 1570 nm.

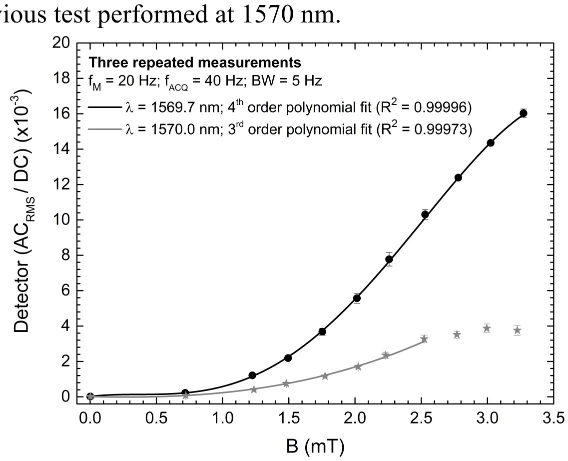

Fig. 11. Normalized photodetected AC response as function of the magnetic field

Resolutions were also analyzed as a function of the magnetic field and the values corresponding to maximum errors. As expected, better results were attained for the 1569.7 nm wavelength, because the sensitivity is higher. The best resolution values registered were 2.06 $\mu T_{RMS}/\sqrt{Hz}$ and 7.41 $\mu T_{RMS}/\sqrt{Hz}$ for 1569.7 nm and 1570 nm, respectively. Moreover, at 1569.7 nm, the resolution was below 5.61 $\mu T_{RMS}/\sqrt{Hz}$ from 1.22 mT_{RMS} up to 2.53 mT_{RMS}. Comparing this sensor with the magnetostrictive ones stated in the introduction, the optical fiber laser gave a slightly better error of 0.79 % (3.58 $\mu T_{RMS}/\sqrt{Hz}$), but for another operating range, between 2.26 mT_{RMS} and 13 mT_{RMS} [25].

IV. Conclusion

In this paper a LPG fabricated in a standard fiber was implemented and tested for vibration and magnetic field sensing. The sensor was shown to be highly sensitive to the applied curvature yielding a change in the resonant peak amplitude without affecting too much its peak wavelength position.

The sensor was tested in the curvature regime and interrogated using a laser source tuned to the resonant peak. Using the spectral scan laser source, it was demonstrated the possibility to detect vibration in structures with frequencies ranging from 30 Hz to 2000 Hz with a maximum resolution of 913 mHz. However, the recovered modulation amplitude was not stable, especially in the vicinity of the resonance peaks. In the curvature regime differences between measurements of up to 200 % were observed in the detected amplitude near a resonance peak, at 580 Hz. High errors were also found in the strain regime, at 1116 Hz with an increase of 424 %. Despite the instability observed in amplitude determination, the results suggest the sensor can successfully be used in identification of the vibration frequency.

The LPG was also tested in temperature where a sensitivity of 57.67 pm/°C in the resonant peak was found. Nevertheless, while the wavelength shift can reduce the sensitivity to applied vibration, it still allows retrieving the signal frequency in a broad range of temperatures. For the sensor operating in the curvature regime a change of 52 °C will reduce the sensitivity by 85 %, nevertheless, still enabling frequency identification. Overall the results indicate that the sensor is highly sensitive to the way it is coupled to the system under monitoring. This way, working on the optimization of material, shape and disposition of the fixation system, the sensor can be tailored to monitor specific frequencies with much higher sensitivity.

Finally, the LPG sensor was also tested in the detection of magnetic fields. A Terfenol-D rod was attached to the sensor and results presented resolutions below 5.61 $\mu T_{RMS}/\sqrt{Hz}$ from 1.22 mT_{RMS} up to 2.53 mT_{RMS} for 1569.7 nm.

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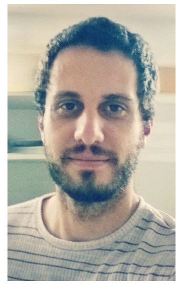

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2017.2743112, IEEE Sensors Journal

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