LPG-based sensor for curvature and vibration

I. M. Nascimento[a,b*], G. Chesini[c], J. M. Baptista[d], Cristiano M. B. Cordeiro[c], P. A. S. Jorge[a,b]
[a]INESC TEC, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal.
[b]Department of Physics and Astronomy, Faculty of Sciences of University of Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal.
[c]Institute of Physics Gleb Wataghin, University of Campinas, UNICAMP, Campinas, Brazil
[d]Faculty of Exact Sciences and Engineering of University of Madeira, Funchal, Portugal.

ABSTRACT

A long-period grating (LPG) written on a standard single mode fiber is investigated as a curvature and vibration sensor. It is demonstrated a high sensitivity 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 an intensity based interrogation scheme with the LPG sensor operating in the curvature regime. Results have shown a reproducible frequency discrimination in the 30 Hz to 2000 Hz, with resolutions between 11 mHz and 913 mHz. Frequency retrieval could be performed independent of temperature up to 86 ºC.

Keywords: long-period fiber grating (LPG), vibration sensor, fiber optic sensor, intensity modulation scheme.

1. INTRODUCTION

Fiber optic vibration sensors have been subject of great interest due to its relatively small dimension, inherent insolation provided by the fiber itself and immunity to electromagnetic effects[1]. Nowadays, a large diversity of vibration sensors are being used in real-time structural health monitoring for civil infrastructures and engineering systems, namely bridges, buildings and railway tracks[2]. In the case of large-scale structures like bridges, low frequency vibrations are the most commonly monitored. In this range of operation, however, traditional electromagnetic vibration sensors are usually very limited and inadequate while operating in the presence of high magnetic fields, or subjected to corrosion, giving rise to faults.

Low frequency signals give information about the presence of small cracks and discontinuities. For an old arch bridge, that vibration frequencies in the range of 6 Hz to 44 Hz are the most suitable for the detection of signs of structural degradation[3]. Furthermore, for a centenary iron arch bridge[4], bending and torsion of the structure present vibration frequencies within the 0.9 Hz and 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 as bearing, eccentricity, end ring faults and broken rotor bars[5].

According to the working principle, vibration fiber optic sensors can be implemented using different sensing elements such as fiber Bragg gratings (FBG)[6] or long-period gratings (LPGs)[7].

In this paper, a simple approach is presented using a single LPG fabricated in a standard single mode fiber (SMF), exciting a low order mode, keeping its sensitivity to external refractive index relatively low. The sensor operates with amplitude modulation of a narrow spectral signal, enabling the frequency retrieving capability to be maintained over a relatively large temperature range. The sensor was characterized and demonstrated as suitable for a high sensitivity curvature or vibration measurement applications.

2. PRINCIPLE OF OPERATION

A long period grating consists of a refractive index perturbation inscribed along the fiber with a periodicity of hundreds of microns. The amplitude and periodicity defines the coupling between the propagating core mode and co-propagating cladding modes. The high attenuation of the cladding modes, results in a series of attenuation bands, in the transmission spectrum, where each peak corresponds to a different cladding mode[8]. For this experiment, the LPG sensor was inscribed in a single mode fiber using a CO_2 laser with a periodicity of 600 μm. Typically, this fabrication technique creates a LPG

*ivomac88@gmail.com; phone +351 22 040 2301;

Sixth European Workshop on Optical Fibre Sensors, edited by Elfed Lewis, Proc. of SPIE Vol. 9916,
99162D · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2237041

which excites asymmetric modes, LP_{1m}, in this case the 3rd mode, corresponding to the 1570 nm wavelength. The use of a high period grating was chosen in order in order to couple energy to lower-order modes and deliver lower refractive index sensitivity, ensuring a reduced cross-sensitivity to this parameter.

3. EXPERIMENT AND RESULTS

3.1 Temperature and refractive index characterization

As known from literature, LPG sensors are susceptible to temperature and refractive index changes. The sensor was firstly characterized in temperature using an oven, where the LPG was fixed carefully without torsion and maintained with a constant strain. A change between 30 ºC and 90 ºC showed a positive linear wavelength shift of 57.67 ± 0.26 pm/ºC. The LPG cross-sensitivity to the external refractive index was also evaluated following a procedure where a change of -1.074 ± 0.02 nm was calculated for a refractive index change between 1.0003 and 1.3355, measured at 589.3 nm.

3.2 Curvature

Evaluation of the sensor behavior as device for structural health monitoring was first performed by submitting the sensor to curvature and strain, using the setup of Figure 1 (a). The LPG was fixed between a static and a moving rod, where the latter was attached to a translation stage possessing 5 µm resolution. The initial distance was set to d = 326 mm and corresponds to ΔL = 0, the transition point between the fiber being submitted to curvature or strain. In Figure 1 (b) it is shown the LPG transmission spectra, obtained with an OSA (Optical Spectrum Analyzer) to small deformations applied to the sensor by turning the screw on the translation stage between -55 µm up to 80 µm. The LPG resonance shows a large change in the resonance depth (13.63 dB) for small increments of ΔL, with only 1 nm change in the central wavelength. The negative and positive values of ΔL correspond to curvature and strain, respectively.

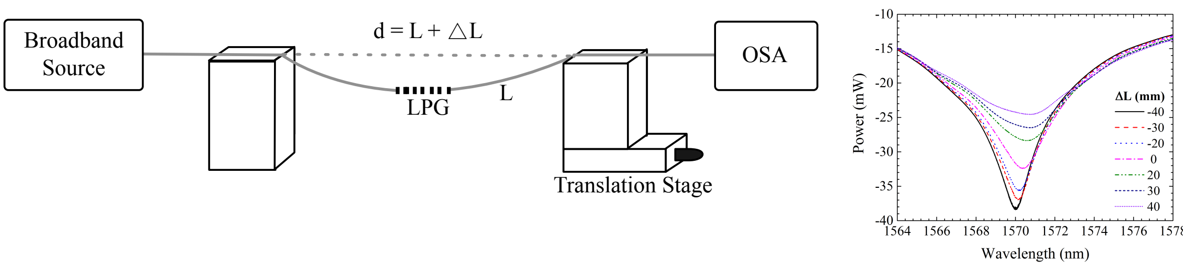
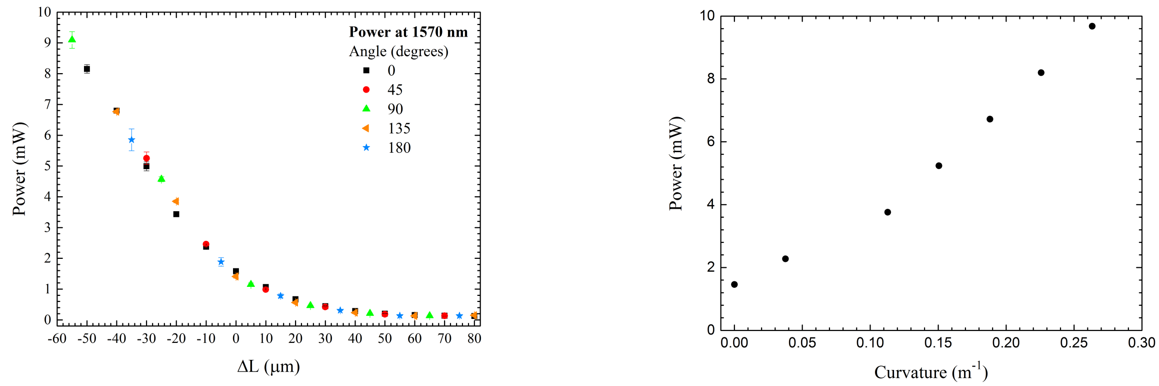


Figure 1. (a) Setup used for characterization of the response to curvature and in (b) the transmission spectrum of the LPG as function of ΔL.

Variation of the transmitted power at a fixed wavelength of 1570 nm was also recorded, as function of ΔL with the fiber oriented at 0, 45, 90, 135 and 180 degrees and the data obtained is shown in Figure 2 (b). Results showed very good reproducibility, with very small deviations registered between tests, for all angles tested, showing no asymmetries in the sensor response. Furthermore, while decreasing the displacement to the initial value no hysteresis was observed. As noticed earlier, much higher power variation are 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/nm (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 and the corresponding radius of curvature is present in Figure 2 (b).



(a) (b)

Figure 2. LPG resonance power change at 1570 nm as function of the (a) *ΔL* between -55 µm and 80 µm or in (b) as function of the curvature.

3.3 Vibration

The high sensitivity to very small applied curvatures indicates that the LPG should also be responsive to acoustic vibration, because pressure variations will induce micro curvatures and strain in the fiber surface. In order to evaluate this idea, an intensity-based system was implemented as shown in Figure 3 (a). It uses a tunable laser, Santec TSL-210V, tuned to the 1570 nm wavelength, (LPG resonance peak). The transmitted optical power fluctuation, dependent on the applied vibration was recorded using a photodetector and an analog digital-converter system (DAQ NI USB 6363). A computer with a specially developed control software (LabVIEW) was used to record the AC optical signal. In Figure 3 (b) it is shown a schematic of the laser tuned to the LPG resonance and the corresponding transmitted optical power detected by the photodetector, when a vibration signal is applied.

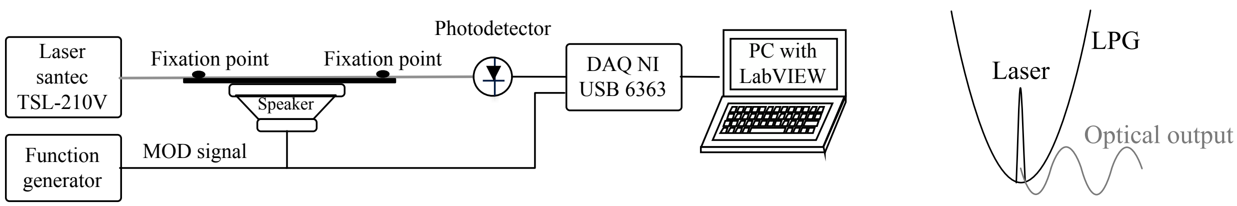
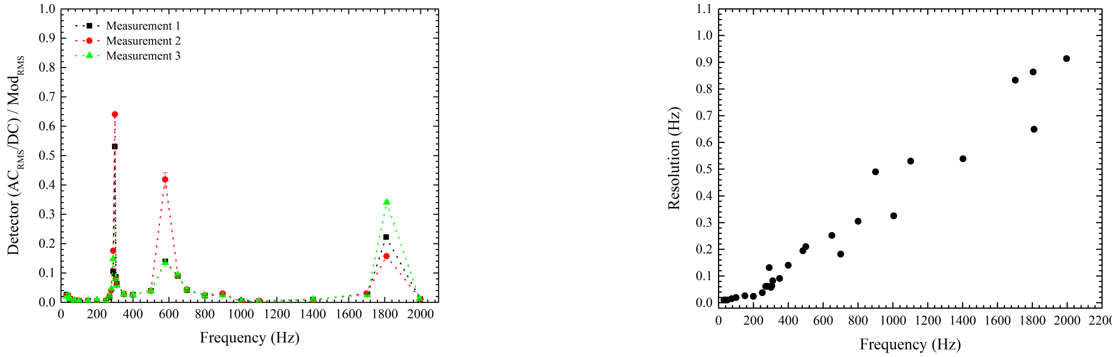


Figure 3. (a) Setup used for testing the sensor response to vibration and (b) a schematic of the relative position of the optical source and the resonance spectrum of the LPG.

The sensor response was characterized in the curvature regime (ΔL = -30 µm), where the change in the optical power is higher, by applying an average vibration amplitude of 0.5 V_{RMS} to the speaker from 30 Hz to 2000 Hz as shown in Figure 4 (a). 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, 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 %. For the resonance at 580 Hz an amplitude increase of 200 % was observed between the first and the second measurements. This may be due to an unstable resonance condition of the sensor setup. In fact, off the resonances it can be observed that the sensors yielded very reproducible results. While temperature changes affect mostly the resonance wavelength, it introduces a reduction in sensitivity, affecting the detected modulation amplitude. However, results have also shown it was still possible to recover the modulation frequency, with a minimum signal variation $(AC_{RMS}/DC)/Mod_{RMS}$ of 0.0014 1/V even with temperature changes of up to 86 ºC.

To better characterize the sensor performance, the frequency resolution was estimated in different situations. These values were calculated as two times the standard deviation of the measured frequency in 60 s samples intervals and the largest error measured in three independent tests. In the whole frequency range tested, the resolution estimated was changing from the best resolution of 11 mHz at 30 Hz, to the worst value of 913 mHz at 2kHz.



(a) (b)

Figure 4. (a) Recovered AC amplitude and in (b) the frequency resolution as a function of the frequency generator.

4. CONCLUSIONS

In this paper an LPG was proposed for vibration and magnetic field sensing by recording the changes in the resonance peak amplitude with an intensity-based scheme. The sensor was tested by positioning the LPG sensor on the plate and operating it in the curvature regime. It was demonstrated the possibility to detect vibration in structures with frequencies ranging from 30 Hz to 2000 Hz with a maximum resolution of 11 mHz. Having into account the frequency resolutions attained, the optical sensor is suitable for applications in structural health monitoring only for frequency discrimination, in applications where the amplitude of modulation is not critical. In such case, frequency measurement can be performed independent of temperature for changes as high as 80 ºC.

5. ACKNOWLEDGEMENTS

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."

6. REFERENCES

[1] García, Y. R., Corres, J. M., Goicoechea, J., "Vibration detection using optical fiber sensors," J. Sensors **2010**, 10–17 (2010).

[2] Zheng, S., Zhu, Y., Krishnaswamy, S., "Temperature insensitive all-fiber accelerometer using a photonic crystal fiber long-period grating interferometer," Nondestruct. Charact. Compos. Mater. Aerosp. Eng. Civ. Infrastruct. **8347**, A. L. Gyekenyesi, Ed., 1–10 (2012).

[3] Bien, J., Kaminski, T., Kuzawa, M., Rawa, P., Zwolski, J., "Dynamic tests of two old masonry arch bridges over the Odra river in Wrocław," EVACES 2011 Proc. Int. Conf. Exp. Vib. Anal. Civ. Eng. Struct., 79–86, Varenna, Italy (2011).

[4] Gentile, C., Saisi, A., "Structural Health Monitoring of a centenary iron arch bridge: Ambient vibration tests and condition assessment," EVACES 2011 Proc. Int. Conf. Exp. Vib. Anal. Civ. Eng. Struct., 121–130, Varenna, Italy (2011).

[5] Toliyat, H. A., "Condition monitoring and fault diagnosis of electrical machines-a review," Ind. Appl. Conf. 1999. Thirty-Fourth IAS Annu. Meet., 197–204 (1999).

[6] Chang, J., Wang, Q., Zhang, X., Ma, L., Wang, H., Zhang, S., Wang, Q., Ni, J.., Wu, Y., "Fiber-optic vibration sensor system," Laser Phys. **18**(7), 911–913 (2008).

[7] Tanaka, S., Wada, A., Takahashi, N., "Highly sensitive operation of LPG vibration sensor using bending-induced spectral change," 21st Int. Conf. Opt. Fiber Sensors, Ottawa, Canada, 2011, pp. 1-4 **7753**, W. J. Bock, J. Albert, and X. Bao, Eds., 1–4, Ottawa, Canada (2011).

[8] James, S. W., Tatam, R. P., "Optical fibre long-period grating sensors: characteristics and application," Meas. Sci. Technol. **14**(5), R49–R61 (2003).

[9] He, Z., Zhu, Y., Du, H., "Effect of macro-bending on resonant wavelength and intensity of long-period gratings in photonic crystal fiber," Opt. Express **15**(4), 1804–1810 (2007).