Long-Period Gratings Dynamic Interrogation With Modulated Fiber Bragg Gratings and Optical Amplification

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***Abstract*—It is reported a long-period grating (LPG) dynamic interrogation technique based on the modulation of fiber Bragg gratings located in the readout unit of the system. It permits to attenuate the effect of the $1/f$ noise of the electronics in the resolution of the LPG-based sensing head. The concept is tested to detect variations of the external refractive index and a resolution of 2.0×10^{-4} *NIR* was achieved without system optimization. Additionally, the effect in the sensor resolution when introducing Erbium and Raman optical amplification is experimentally investigated.**

***Index Terms*—Fiber Bragg gratings (FBGs), long-period gratings (LPGs), optical fiber sensors, sensor interrogation.**

I. Introduction

The concept of long-period gratings (LPGs), where the light guided in the core is coupled to several cladding modes at specific resonant wavelengths, appeared in 1996 [1]. They are devices which share the intrinsic characteristics of optical fiber sensors, such as electrically passive operation, immunity to electromagnetic interference and multiplexing capability, and show some specific features such as low back reflection and low insertion loss. The low back reflection characteristic occurs because LPGs operate in transmission configuration owing to the coupling of the fundamental guided mode to co-directional cladding modes. The coupling between forward modes occurs when the phase matching vector is short, which corresponds to a refractive index spatial modulation period of some hundreds of micrometers that means a fabrication advantage compared with fiber Bragg gratings [2].

Since LPGs deal with radiation that propagates in the cladding region, its resonance loss band is sensitive to changes in the fiber structure induced by torsion, transverse load, and, in particular, when bending is applied to the section of the fiber containing the grating. They are also prone to changes in the surrounding medium, mainly to changes on its refractive index. These devices are also sensitive to strain and their temperature sensitivity can be substantial. Therefore, LPGs are tunable band-rejection filters that find a wide range of applications as optical sensors [3]. More recently, LPGs have been fabricated in photonic crystal fibers and their use as sensing elements is an active area of research [4]–[6].

Due to its principle of operation and spectral characteristics, LPGs as sensing elements are mostly used to detect variations of quasi-static parameters. Their interrogation is normally achieved with optical spectrum analyzers or by detecting the optical power changes at one or more wavelengths located on the edges of the LPG transmission spectrum. If two wavelengths, one in each edge of the LPG, are selected (for example using selective filters such as fiber Bragg gratings-FBG), and if the detected optical power in these wavelengths are P_1 and P_2, respectively, then processing of the type $(P_1-P_2)/(P_1+P_2)$ gives a signal proportional to the measurand induced LPG shift and independent of the optical power fluctuations along the system [7], [8]. Considering the associated photodetection, amplification and processing are in most of the cases in the DC or quasi-DC regime, the measurand readout resolution can be substantially affected by the $1/f$ noise of the electronics. Therefore, it would be advantageous to set-up a LPG interrogation approach compatible with signal photodetection and amplification at higher frequencies.

In this paper, first results are reported of a LPG interrogation technique based on modulation at different frequencies of the Bragg wavelengths of two FBGs, spectrally located in the edges of the LPG. The amplitudes at these modulating frequencies of the signals reflected by the FBGs are detected. These amplitudes are proportional to the slopes of the LPG spectral response at the FBG wavelengths, which change with the relative spectral movements of the LPG to the FBGs, permitting

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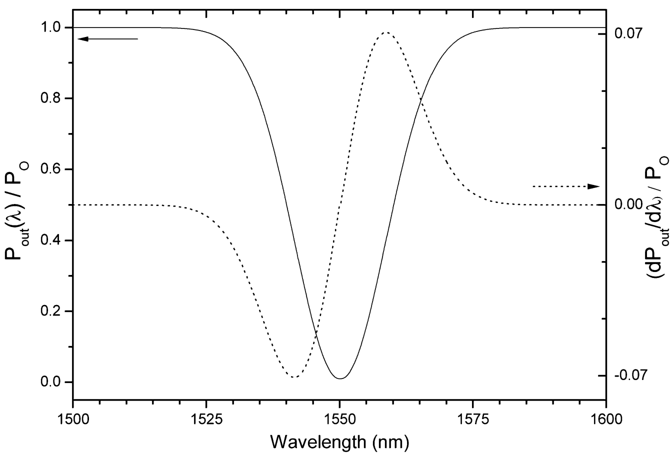

Fig. 1. $P_{\mathrm{out}}(\lambda)/P_0$ and $(dP_{\mathrm{out}}/d\lambda)/P_0$ versus λ.

to generate an optical signal proportional to the LPG spectral shift and to be immune to optical power fluctuations along the system. This technique is tested for measurement of the refractive index variations of the surrounding medium. Also, the impact of introducing Erbium and Raman optical amplification is experimentally investigated.

II. Principle and Experiment

The feasibility of the proposed approach is dependent on the level of slope variation along the LPG spectral resonance. To a good approximation the LPG transfer function can be represented by the following expression [9]:

$$P_{\mathrm{out}}(\lambda) = P_o\left[1 - m\exp\left[-(4\ln 2)\left(\frac{\lambda-\lambda_{\mathrm{res}}}{\Delta\lambda_{\mathrm{LPG}}}\right)^2\right]\right] \tag{1}$$

where λ_{res} and $\Delta\lambda_{\mathrm{LPG}}$ are the LPG resonance wavelength and spectral width, respectively, and m indicates the resonance loss level. For a typical LPG with 20 dB of attenuation at $\lambda_{\mathrm{res}}, m = 0.99$.

Fig. 1 shows $P_{\mathrm{out}}(\lambda)/P_0$ as well as $(dP_{\mathrm{out}}/d\lambda)/P_0$ versus λ. It can be observed that the magnitude of the normalized slope variation along the full LPG response is approximately one order of magnitude smaller than the normalized optical power variation, which means a corresponding factor for the signal variations associated with $P_{\mathrm{out}}(\lambda)/P_0$ or $(dP_{\mathrm{out}}/d\lambda)/P_0$ with origin at a LPG spectral shift relative to fixed wavelength values (that can be defined by FBGs). Therefore, from this argument it seems that the preferable option should be to monitor $P_{\mathrm{out}}(\lambda)/P_0$, i.e., following the standard approach. However, this is a DC reading, consequently affected by low-frequency noise, which usually has a $1/f$ power spectral dependence (see Fig. 4). On the other hand, the slope approach is compatible with interrogation in a frequency range far from the $1/f$ noise region, which means the signal-to-noise ratio can eventually be favored by the reduction of the noise level, compensating the disadvantage of the reduction in signal amplitude.

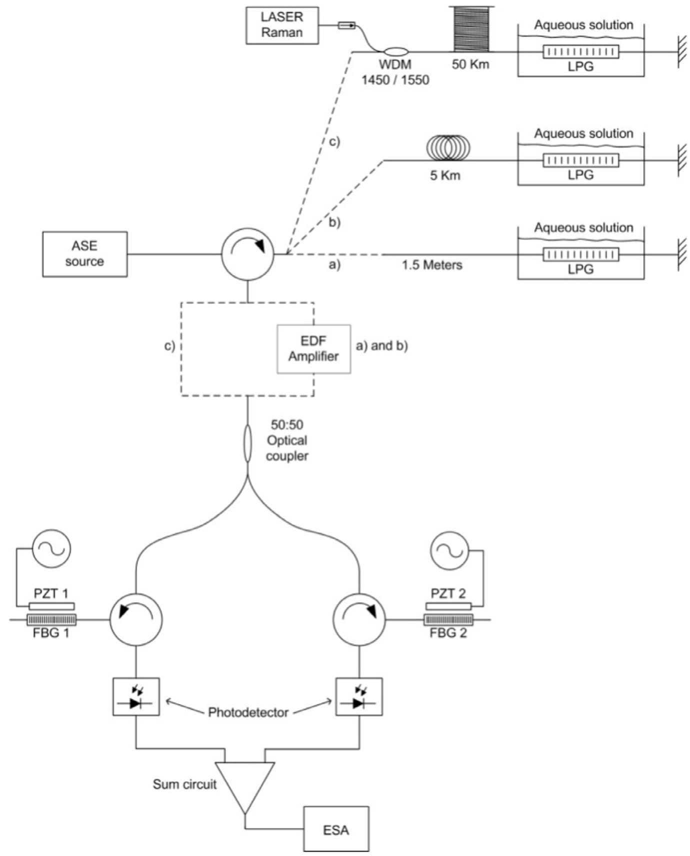

Fig. 2. Experimental setup for different configurations (a) for 1.5 m with and without EDF amplifier, (b) for 5 km with and without EDF amplifier, and (c) for 50 km with and without Raman amplifier.

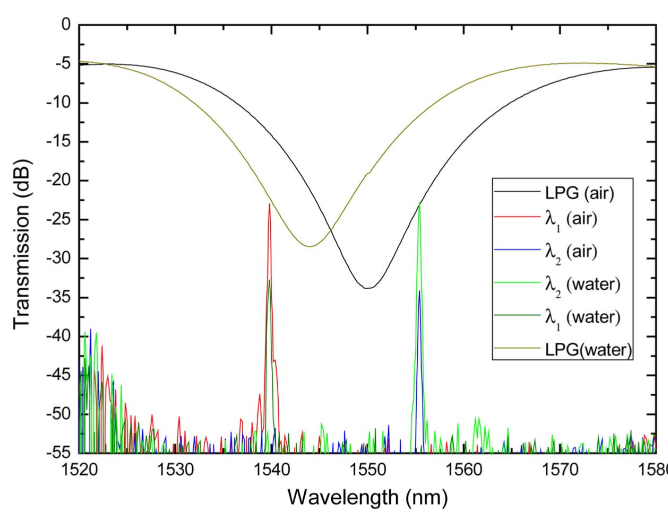

Fig. 3. Optical spectra of the FBGs and LPG in air and immersed in water.

In order to evaluate the feasibility of the proposed interrogation approach the setup presented in Fig. 2 was implemented. An LPG with a strong resonance centered at 1550 nm (Fig. 3) was fabricated using the electric arc technique (period of the refractive index modulation: $\Lambda = 395\ \mu$m; coupling to a fifth-order cladding mode). The LPG was placed into a recipient

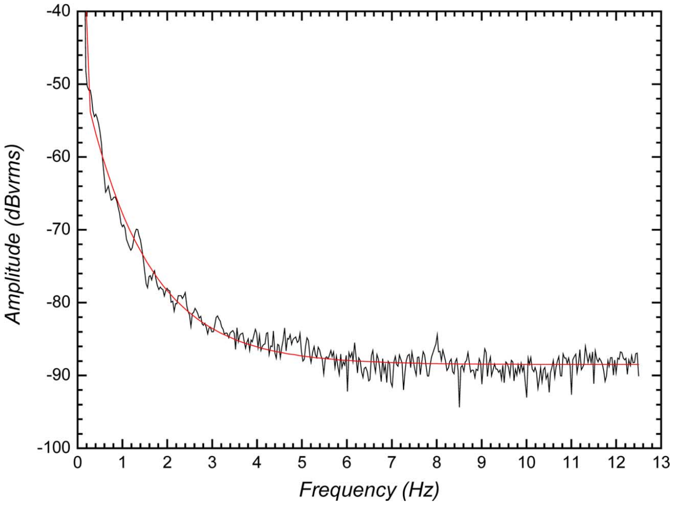

Fig. 4. Noise level of the electronics at low frequencies.

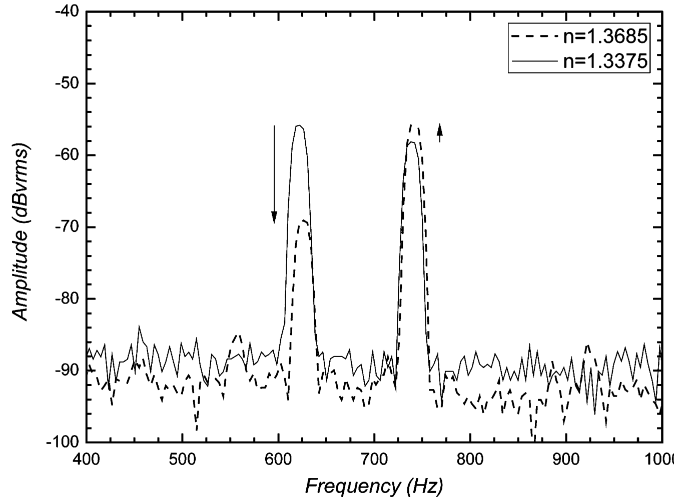

Fig. 5. Electrical spectra when modulating FBG1 and FBG2 with $f_1 = 620$ Hz and $f_2 = 740$ Hz, respectively, for the LPG immersed in solutions with different refractive indexes.

with an aqueous solution of ethylene glycol and illuminated by means of an ASE broadband source. The optical fiber at the LPG right side was mirrored with silver nitrate allowing the sensing head to operate in reflection. Two fiber Bragg gratings $(\mathrm{FBG}_1, \mathrm{FBG}_2)$, designed to be spectrally located on each edge of the LPG (λ_1, λ_2; Fig. 3), had their Bragg wavelengths sinewave modulated with a fixed amplitude using two piezoelectric transducers (PZTs) driven by two independent signal generators (f_1, f_2). After photodetection of the optical signals reflected by the FBGs, the resultant electrical signals were added with an electrical circuit and visualized in an electrical spectrum analyzer (ESA) with adequate impedance matching. The modulation of the FBG resonance originates a relative spectral movement with reference to the LPG transfer function, with a consequent optical power modulation at the modulation frequencies. The amplitude of this power modulation for each FBG would be constant if the LPG response were linear, which is not the case. Therefore, this amplitude is function of the LPG spectral position, which changes due to the measurand variation. This effect can also be observed in Fig. 3 for the LPG in air and in water, where it can be seen that the wavelength shift of the LPG resonance at 1550 nm is transformed into an amplitude variation of the two peaks observed in the ESA, each one corresponding to the frequency in which each FBG is being modulated. Due to an adequate previous selection of the FBGs Bragg wavelengths, the corresponding reflected optical power amplitudes will change in phase opposition, a useful feature for readout sensitivity enhancement.

The FBG_1 was modulated at $f_1 = 620$ Hz and FBG_2 at $f_2 = 740$ Hz, both in a frequency region where the system noise level stabilized at ~ -90 dBVrms (see Fig. 5). The processing adopted was $V_{\mathrm{proc}} = (V_1 - V_2)/(V_1 + V_2)$, where V_1 and V_2 are the rms voltage amplitudes of the signals at frequencies f_1 and f_2, respectively.

The dynamic electrical interrogation concept previously described was implemented with six different schemes that were presented in Fig. 2. Firstly the system was tested with 1.5 m with and without an EDF Amplifier with a flat optical power

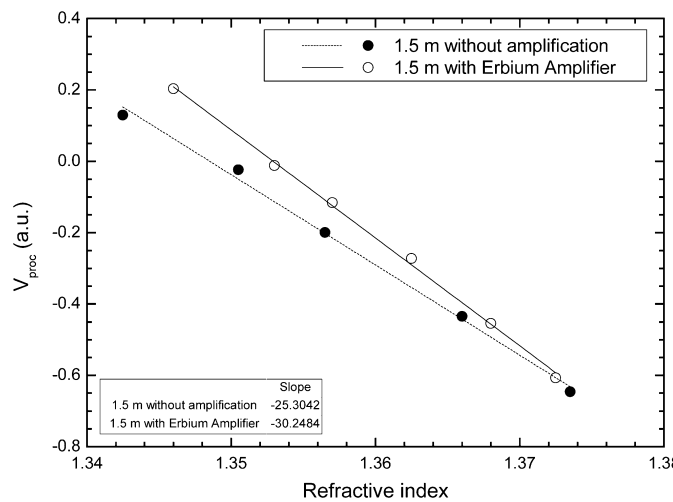

Fig. 6. System output versus refractive index for the case of not using and using EDFA amplification. Fiber length to the sensing head: 1.5 m.

response that operates in C+L bands. Second, the process was repeated for 5 and 50 km simulating a remote detection system. In the 50-km remote detection scheme Raman amplification was applied.

III. Results

The setup depicted in Fig. 2 was used to estimate V_{proc} in several situations: with and without optical amplification considering local [Fig. 2(a)] or remote sensing [Fig. 2(b) and (c)]. The obtained responses with the dynamic interrogation approach are shown in Figs. 6–8, respectively to 1.5 m, 5.0 km, and 50.0 km of fiber length, when the refractive index of the environment changes. It can be seen the proposed interrogation scheme permits to read refractive index variations, exhibiting V_{proc} versus n as a linear relationship. Also, as can be observed in Figs. 6 and 7 the slopes are not substantially different, which is understandable in face of the way V_{proc} is defined. On the

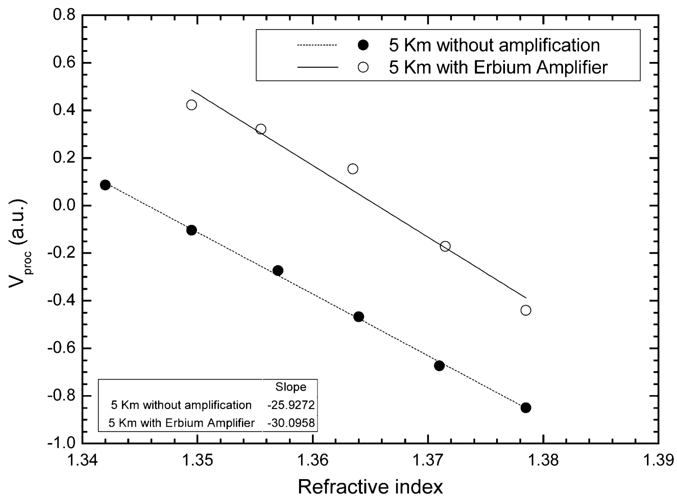

Fig. 7. System output versus refractive index for the case of not using and using EDFA amplification. Fiber length to the sensing head: 5 km.

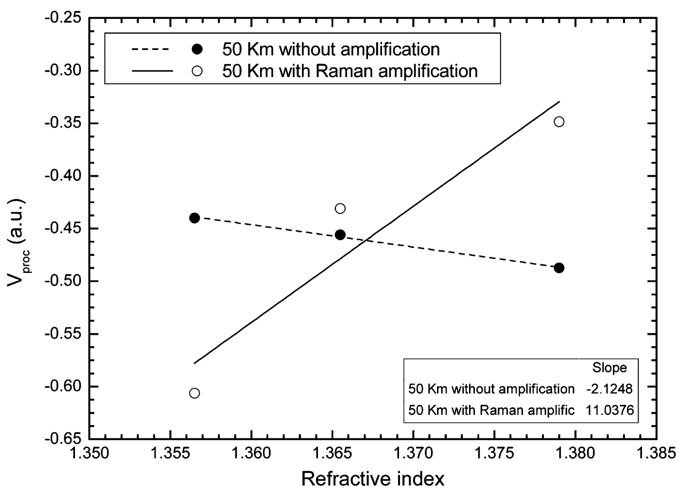

Fig. 8. System output versus refractive index for the case of not using and using Raman amplification. Fiber length to the sensing head: 50 km.

other hand, the amplification has real impact in the readout resolution when the sensing head is located far away. To further test this point, 50 km of fiber were located between the sensing head and the processing region, simulating therefore the situation of a long haul remote sensor [Fig. 2(c)]. In this case, the Erbium amplification was replaced by a Raman amplification stage.

As it can be seen, Raman amplification enhances the sensing unit sensitivity. The system resolution with Raman amplification was also estimated by applying a refractive index step change of 0.023 RIU, determining the corresponding signal change and rms noise fluctuations as well. It is interesting to observe that the Raman amplification affects the behavior of $V_{\rm proc}$ versus Refractive index once the output slope gets the opposite signal. Although it seems weird, it happens due to the fact of the Raman gain curve change the reflected shape of the LPG that will be interrogated by the two modulated FBGs. Due to this effect on the signal inversion points of the LPG resonance slope$-(dP_{\rm out}/d\lambda)/P_0$ versus λ (as can be seen in Fig. 1)—the FBGs will not be placed exactly in the same location and thus the processing adopted made $V_{\rm proc}$ gets a different behavior.

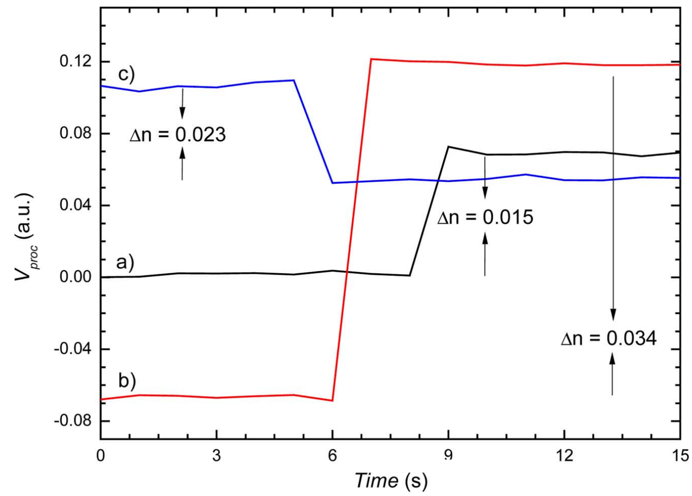

Fig. 9. System output for a refractive index step variation for the different configurations. (a) Sensing head located 1.5 m away with an EDF amplifier. (b) Sensing head located 5 km away with EDF amplifier. (c) Sensing head located 50 km away with Raman amplification.

TABLE I
REFRACTIVE INDEX RESOLUTIONS OBTAINED WITH THE DYNAMIC INTERROGATION TECHNIQUE FOR THE STUDIED CONFIGURATIONS

Length of the Fibre to the Sensing Head	Configuration	$\delta n_{\min}$
1.5 m	Without amplification	2.5×10^{-4}
	Erbium amplification	2.4×10^{-4}
5 km	Without amplification	4.3×10^{-4}
	Erbium amplification	2.2×10^{-4}
50 km	Without amplification	4.5×10^{-3}
	Raman amplification	7.4×10^{-4}

Fig. 9 shows the obtained refractive index step variation of the dynamic interrogation system for the three amplified previously described setups.

From the refractive index step variation the resolution of the interrogation system can be calculated. Table I summarizes the resolutions obtained with the proposed interrogation technique in all situations considered. An interesting result is the one obtained for the long haul remote sensing head and from it comes out a resolution of 7.4×10^{-4}, which is a factor of $\sim$6 better compared with the situation of no amplification.

These results permit to state the technique proposed based on signal reading outside the $1/f$ noise level is effective for refractive index measurement with a resolution that compares favorably with the obtained using the standard DC approach (which is typically around 10^{-3} [8]). Moreover, the amplification associated with the processing employed provides a combination that permits to get high resolutions when the sensing head is remotely located. These two characteristics route to the critical aspect of operating far from the low-frequency noise. Indeed, from Fig. 4 comes out that the noise level present in these experiments was ∼25 dB lower than the one shown at 1 Hz, which far compensates the lower signal variations associated with the proposed slope readout technique. Further work is going on to explore the potential of this interrogation technique, which can be applied not only to LPGs but also for other structures used for measurement of DC or quasi-DC measurands, such as SPR devices.

IV. Conclusion

In this paper, a dynamic LPG interrogation technique was presented. It was based on the analysis of the electrical spectrum of two modulated fiber Bragg gratings located in the LPG edges. This concept permits to attenuate the effect of the $1/f$ noise of the electronics when determining the refractive index measurement resolution. The system resolution for a long haul remote detection, based in dynamic electrical interrogation, was improved by a factor of ∼6 considering Raman amplification.

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