Long Period Gratings in Standard Telecommunication Optical Fibers for Fuel Quality Control

Rosane Falate, Márcia Müller, José Luís Fabris, Hypólito José Kalinowski

Centro Federal de Educação Tecnológica do Paraná
rfalate@cefetpr.br

Abstract

In this work, we describe the application of a LPG (Long Period Grating) to measure changes in the refractive index of gasoline when solvents are added to it. We report the experimental setup used in the writing process of LPG, besides the equipments employed for gasoline and solvents characterization. The results point to the possibility of using the developed system for fuel quality control measurements.

Introduction

Refractive gratings in fiber optic present a large variety of applications both in optical communications and as reliable fiber optic sensors. Optical communications devices like, e.g., wavelength filters, gain equalizers or dispersion compensation modules can be assembled from Bragg gratings. For sensors applications the gratings are mainly used to measure physical parameters like temperature, strain or refractive index [1]. Particularly for applications in Oil and Gas Industry, fiber optic sensors can be remotely operated over a fiber link that can be several kilometers long. This avoid bringing electrical signal to the sensors, reducing potential hazards derived from electrically induced fire or explosion of the combustible products.

Research in the particular class of long period gratings (LPG) attracted much attention in the past years [2]. In comparison with standard Bragg gratings, that have spatial period in the order of a micrometer, the LPG present a longer spatial period for the refractive index modulation, in the order of hundreds of micrometers. The LPG operate by coupling the fundamental mode in the core of the fiber to co-propagating cladding modes. The resonant wavelength of a particular coupling to a cladding mode is given by [2]:

$$\lambda_{\mathrm{m}} = \left(n_{co} - n_{cl}^{m}\right)\Lambda \tag{1}$$

where λ_{m} is the peak wavelength of the resonance band between the core mode and the cladding mode, n_{co} and n_{cl}^{m} are, respectively, the effective refractive index of the core mode and of the m-th order cladding mode and Λ is the grating pitch. The interaction of the guided mode in the optical fiber with a cladding mode is strongly affected by fiber imperfections, by micro and macro bending and by the boundary condition at the cladding - external medium interface. Consequently, light coupled from core mode leaks out the fiber, leaving several dips in the transmission spectrum, each one corresponding to a specific coupling governed by Eq. 1.

LPG are very useful as sensor when the refractive index of the external medium changes. If the parameter to be measured affects the refractive index, this will also change the matching condition expressed by Eq. 1 and will lead to a wavelength shift of the resonance dip in the LPG transmission spectrum. That occurs because the effective indexes of cladding modes are dependent on the refractive index of the core, cladding and external medium. For comparison, in the case of Bragg gratings the effective index of the mode in the fiber's core depends on the core and cladding refractive index, so that a change on the external medium index only is perceived when the cladding is almost entirely removed, to expose the evanescent field of the core mode to the external index. As LPG have fast response to external medium changes [2-4], their use as sensors of refractive index is far more interesting than Bragg gratings based sensors. Another advantage is that the cladding does not need to be removed, a fact that drastically affects the mechanical properties of the optical fiber [4].

In this work we show the use of a LPG as a sensor for measuring the refractive index of a mixture of ethanol and gasoline. In Brazil this mixture has legal validity for an anhydrous ethanol proportion of 20 %. However, as the ethanol has lower price (about 60 %) than gasoline, a common malpractice is to increase ethanol concentration in the mixture that is sold to car owners. Procedures to verify the contents of ethanol in the mixture are required to assure the legal limit and to protect consumer's rights. Although we describe that particular sensor application, its use can be extended to any other kind of contaminant in the gasoline mixture (including other hydrocarbon based products that enter in the final composition of the commercial gasoline).

Experimental Setup

The LPG are produced using a technique similar to that described by [5]. A bare fiber with its protective coating removed is inserted between the electrodes of a commercial splicing machine. A small weight is suspended in one of the fiber's extremities to keep a constant longitudinal tension. The other extremity of the fiber is mounted on a computer controlled translation stage. An electrical arc is applied with the splicing machine, using adequate current and time duration settings. After the discharge, the fiber is moved by the required period of the grating, before another arc is applied. After a suitable number of point-to-point discharges, a periodic pattern is engraved in the fiber's refractive index profile, due to heating activated processes. An optical set-up is used during the writing process to monitor the transmission spectrum through the fiber. When the measured spectrum shows adequate characteristics to the intended application, the process is interrupted. The advantage of using the electrical arc is that no special fiber (hydrogenated of pre sensitised one) is required.

Measurements for the characterization of the LPG and to determine its sensitivity to external index changes are made using a halogen lamp, whose light is focused on the entrance slit of a monochromator. After the exit slit, light is modulated by a mechanical chopper and launched into the fiber using a 40X microscope objective. The light on the fiber's output is collected by another 40X objective onto an InGaAs photo detector. The electrical signal from the photo detector is fed to a lock-in amplifier, synchronized to the chopper's modulating frequency. A personal computer controls the fiber positioning system [6], the monochromator grating position and collects the resulting data through an Analogue to Digital Converter card. The gratings used in this work were written using a current of 12 mA in the electrical arc of the splicing machine, with a time duration of 0.5 s. The resolution of the translation stage is 5 µm.

To measure the response of the sensor to the external medium index, the fluid was kept in contact with the fiber covering all the region where the LPG resides. Then transmission spectra were recorded as a function of the liquid mixture, using the same equipment as described in the previous paragraph. Initially a few calibration measurements were taken using mixtures of several fluids whose refractive index were previously measured with an Abbe Refractometer. A grating with 53 periods (pitch of 649 µm) was used and the corresponding results are shown in Fig. 1. It can be seen that the larger change in the resonant wavelength occurs when the refractive index of the external medium is close to the cladding refractive index [3,4]. A spectral shift of 11 nm in the refractive index range from 1.36 and 1.44 is obtained, which translates as an average resolution of 0.007 nm^{-1}.

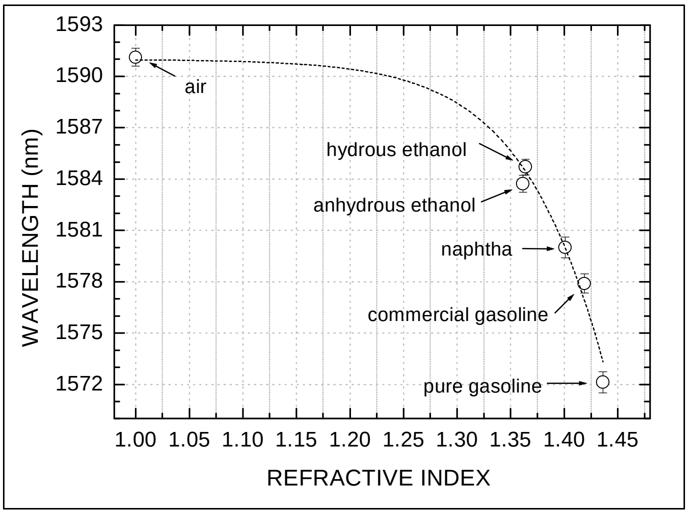

Figure 1: Peak position of the principal attenuation dip in the transmission spectrum of an LPG (Λ= 649 µm, 53 points) as a function of the refractive index of the external medium, in the range between 1.00 and 1.44 at 20°C (the dashed line is just a guide to the eyes).

Results and Discussions

Fig. 2 shows the peak position of the resonant band in the transmission spectrum of the same LPG when the fibre optic is immersed in a mixture of anhydrous ethanol and both, pure and commercial (Brazilian standards, 20% anhydrous ethanol proportion) gasoline. The graph shows the sensitivity of the LPG when used as a sensor for the proportion of the mixture, based on the fact that the refractive index of a mixture of two liquids has a value depending on their respective volumetric concentration [7]. It can be seen on that figure that the sensor is useful to determine ethanol proportions (in volume) even higher than 70 %, with a good sensitivity between 20 % and 50 %, a region that is particularly useful because most of the frauds and malpractices using higher concentration of ethanol are within such range (for higher concentrations the engine may not work properly, which attracts the attention of consumers). It is also important to notice that the absolute variation of the peak position of the resonance band is around 3 nm in that region, a dynamic range that assures the possibility of even better accuracy and resolution, when using LPG with narrower line widths.

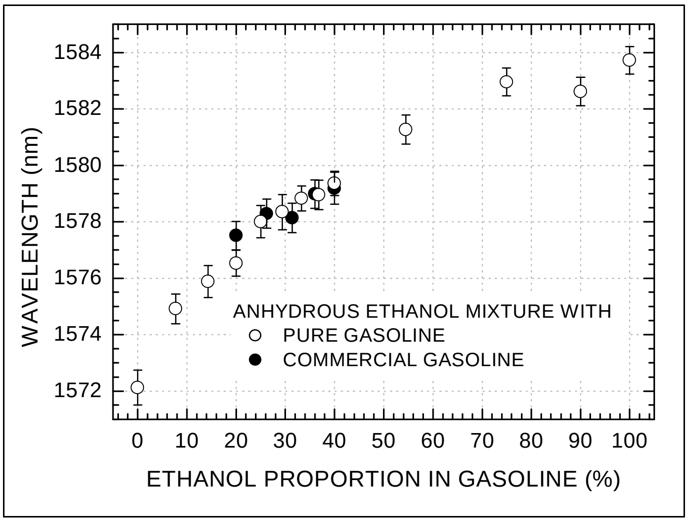

Figure 2: Peak position of the principal resonance band in the transmission spectrum of the LPG as a function of ethanol proportion (in volume) between 0% and 100% in pure gasoline, and between 20 % and 33 % in commercial (Brazilian standards, 20% anhydrous ethanol proportion) gasoline at 20°C.

Another solvent that can be added to gasoline is naphtha, a very explosive compound and which use can be dangerous for health and environment. Figure 3 shows the effect on two ressonances bands of LPG spectrum when naphtha proportion is raised up to 33 % in commercial gasoline. The absolute variation in the peak position of the two resonance bands is less than 1 nm, once the naptha refractive index is closer to the commercial gasoline refractive index than the anhydrous ethanol refractive index, as can be seen from figure 1.

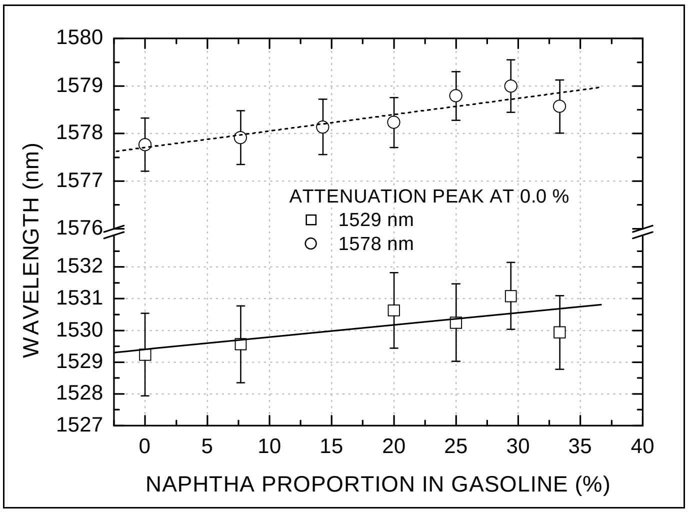

Figure 3: Peak position of two resonance bands in the transmission spectrum of the LPG as a function of naphtha proportion (in volume) between 0 % and 33 %, in commercial (Brazilian standards, 20 % anhydrous ethanol proportion) gasoline at 20°C (the lines connecting points are just guides to the eyes).

Conclusions

We report the measurement of ethanol proportion when mixed with gasoline, using a Long Period Grating based sensor. Calibration of the process has been checked by the use of liquids with known refractive index. The average resolution was 0.007 nm^{-1} when the refractive index varied from 1.36 to 1.44. For the anhydrous ethanol measurements the average sensitivity for the wavelength shift of the resonance band is 0.1 nm/%, for the region where the ethanol proportion changed from 20 to 50 % in the mixture with gasoline. For the naphtha measurements, this sensitivity is 0.03 nm/% for naphtha proportion ranging from 0 to 33 %. In spite of this lower sensitivity when compared to the ethanol sensitivity, the process can improved using an equipment with a better spectral resolution. Another possibility is to use a narrow line bandwidth LPG sensor, resulting in a better resolution accuracity. The achieved results point to the possibility of using this kind of LPG sensor in fuel quality control. The process can also be used with other hydrogen – carbon products that are mixed in the gasoline and that can suited to fraudulent uses.

Acknowledgements

This work received financial support from CAPES, CNPq, CTPETRO, Fundação Araucária (Brazilian Agencies) and from the Brazilian National Agency of Petroleum (PRH-ANP/MME/MCT 10 CEFET-PR). A patent application has been filled for the corresponding equipment and process.

References

[1] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, *J. Lightwave Technol.*, **Vol. 15 No. 8**, 1442 (1997).

[2] A. M. Vengsarkar, P. J. Lemaire, J. B. Judkins, V. Bhatia, T. Erdogan, and J. E. Sipe, *J. Lightwave Technol.*, **Vol. 14 No. 1**, 58 (1996).

[3] H. J. Patrick, A. D. Kersey, and F. Bucholtz, *J. Lightwave Technol.*, **Vol. 16 No. 9**, 1606 (1996).

[4] V. Bhatia, and A. M. Vengsarkar, *Opt. Lett.*, **Vol. 21 No. 9**, 692 (1996).

[5] G. Rego, O. Okhotnikov, E. Dianov, and V. Sulimov, *J. Lightwave Technol.*, **Vol. 19 No. 10**, 1574 (2001).

[6] J. L. Fabris, R. E. de Góes, R. Falate, e M. Muller, *Rev. Fis. Aplic. e Instr.*, **Vol. 14 No. 2**, 38 (1999).

[7] see, e.g., W. Bueno, J. F. C. Boodts, L. Degreve, F. A. Leone, *Alguns Conceitos e Soluções em Química Geral*, McGraw-Hill do Brasil, São Paulo (1978).