Optical fiber sensors for petroleum hydrocarbon detection in pipelines

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Abstract

This work shows prospects of optical fiber grating sensors application to identify the hydrocarbons flowing in a pipeline. A fiber Bragg grating and a long period grating were used as sensor devices. Long period grating was written in a standard telecommunication optical fiber applying a point-to-point electrical arc discharge from a fusion splicer. The sensitivity of this grating to the refractive index of the medium surrounding the fiber allows its use as a sensor device in the detection of hydrocarbons that flows in pipelines. Samples of anhydrous alcohol, turpentine, paint thinner, naphta, kerosene and commercial gasoline were used in the experiments. It was observed an average grating sensitivity of $3.8x10^5$pm/RIU (refractive index units) for external refractive indexes ranging from 1.432 to 1.448. This sensitivity relates to a sensor resolution of $2.6x10^{-5}$ if the grating is used as a refractometer together with an OSA with ± 5 pm of wavelength precision. A maximum wavelength shift of 15.57 nm was detected in the kerosene presence with a short temporal response of 3 seconds. Fiber Bragg gratings written in hydrogen loaded single mode fiber by the inteferometric technique were applied as temperature sensors. The gratings were kept during one hour in a temperature of 190 ºC for thermal stabilization. The obtained sensor sensitivity ranged from 10.2 pm/ºC up to 11.4 pm/ºC.

Introduction

Along the last years, research in the field of optical fiber sensors showed an important increase, mainly due to the unique characteristics of such devices. Among these characteristics, low cost, size and weight, besides the electrical immunity, make these sensors a very attractive option for applications of distributed sensing, real time and fast response monitoring. In other hand, for the petroleum industry, the use of electrically passive sensors is very important to avoid the risk of fire or explosion. Moreover, fast response is very important when the sensor is intended to detect hydrocarbons leakage, what in turn can minimize the extent of the damages to the environment. Fiber Bragg Gratings (FBG) and Long Period Gratings (LPG) fulfill all requirements, easily allowing the measurement of stress, temperature and refractive index [1,2]. For FBG, the periodic modulation of the refractive index of the core fiber couples light from the fundamental propagating core mode to the contra-propagating one, resulting in a band in the fiber reflection spectrum centered at the Bragg wavelength, λ_B, given by:

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where n_{eff} is the effective refractive index of the core mode and Λ is the grating periodicity [3], close to 1 µm for this device. The grating sensitivity to the applied longitudinal strain (ε_z) or temperature (T) leads to a spectral shift $\Delta\lambda_B$ that can be written as:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha + \eta)\Delta T \qquad (2)$$

where p_e represents the effective coefficient for the photo-elastic effect, α is the thermal expansion coefficient and η is the thermo-optic coefficient. It is observed a shift in the central wavelength of FBGs written in hydrogen loaded fiber and a change in its reflectivity. The wavelength shift results from the hydrogen diffusion out of the fiber that reduces the effective refractive index n_{eff} (see eq. 1). The grating reflectivity given by eq. (3) is dependent on the effective refractive index n_{eff}, as well as the index modulation Δn [4].

$$R = tanh^2\left(\frac{\pi L \Delta n}{2\Lambda n_{eff}}\right) \quad (3)$$

In this equation, L is the grating length. For grating periodicities of hundreds of micrometers, the device is called an LPG. In this case, the grating couples light from the fundamental core mode to the cladding modes, leading to several dips in the fiber transmission spectrum given by:

$$\lambda_m = \left(n_{co} - n_{cl}^m\right)\Lambda \quad (4)$$

where λ_m is the central resonance wavelength of the m^{th} cladding mode, n_{co} is the effective refractive index of the core mode, n_{cl}^m is the effective refractive index of the m^{th} cladding mode and Λ is the grating periodicity. As the effective refractive index n_{cl}^m depends on the refractive index of the fiber surroundings, the device can be used to identify de external medium. Spirin et al [5] presented a polymer-coated FBG-based sensor to be used in the detection of hydrocarbon leakage, resulting in a sensor with response time of 20 minutes. Kamikawachi et al [6] showed the using of a LPG to monitor hydrocarbons leakage in water environment. In that work, it was shown the need for a temperature monitoring of the external medium to avoid a misinterpretation of the results due to the crossed grating sensitivity to temperature (70 pm/°C) and refractive index. In this work, FBG and LPG were produced and characterized as temperature and refractive index sensors of the fiber surroundings, respectively. The LPG sensor was successfully employed to identify several hydrocarbons samples flowing under controlled conditions. Moreover, a method for FBG defects stabilization was employed.

Experimental Setup

The LPG (Λ= 600 µm, 60 interaction points) was recorded in a single mode fiber using the point-to-point electrical arc discharge method with a fusion splicer (Siemens, S46999-M7A3), in a technique similar to described by [7]. The grating sensitivity characterization for changes in the refractive index of the surroundings was carried out allowing the LPG to be in contact with the fluid under analysis in a plastic pipe. To avoid influence of curvature, stress and temperature in the grating response, the LPG was glued on the internal pipe wall, and the temperature was monitored to be constant within 19.5 °C ± 1 °C. After the insertion of the desired sample, the flow was interrupted and the grating spectrum was measured under static conditions. As the measurement was completed, the fluid was drained, a new sample was injected and the process was repeated. A LED (Superlum, Pilot 2) was used as a light source, and the grating spectrum was analyzed with an optical spectrum analyzer – OSA (Anritsu, MS9710B, 0.1 nm resolution, ± 5 pm of wavelength stability). Samples of alcohol, turpentine, thinner, naphtha, kerosene and gasoline were used in the experiment. FBG was also produced in a single mode fiber loaded with hydrogen, during 2 weeks at 150 psi, to increase the fiber photosensitivity. The writing setup used a phase mask interferometer with two mirrors computer controlled, with an angular resolution of 0.001 degrees, and a 266 nm Nd-YAG laser (NewWave, Tempest 20). The thermal characterization of the gratings was carried out with the aid of a thermopar and a thermoelement Peltier in three heating and cooling cycles. The thermal treatment for the grating stabilization was done in an electrical oven.

Results and Discussion

Results of the LPG sensitivity to the external medium refractive index are presented in Figure 1, for two complete cycles. Each cycle corresponds to the grating characterization for alcohol, turpentine, thinner, naphtha, kerosene and gasoline, in this sequence. The wavelength shift $\delta\lambda$ of the grating resonance was measured regarding to the grating resonance in the air. During the second cycle, the resonance wavelengths nearly recover the wavelengths of the last cycle. The small differences detected are within the OSA wavelength stability. The temporal response of the sensor (close to 3 seconds) is mainly determined by the data acquisition time of the equipment. The wavelength shifts ranged from –3.82 nm to –15.57 nm (for alcohol and kerosene, respectively), corresponding to the samples with refractive indexes in the lower and higher sensitivity zones of the grating. This sensitivity is showed in Figure 2, where the wavelength shift $\delta\lambda$ of the grating resonance is displayed as a function of the sample refractive index. The closer the refractive index to the cladding one (1.458), the higher the wavelength shift and consequently the grating sensitivity. In the range of refractive indexes between 1.432 (thinner) and 1.488 (kerosene), which corresponds to the higher sensitivity zone, the average grating sensitivity was 3.8×10^5pm/RIU (refractive index units).

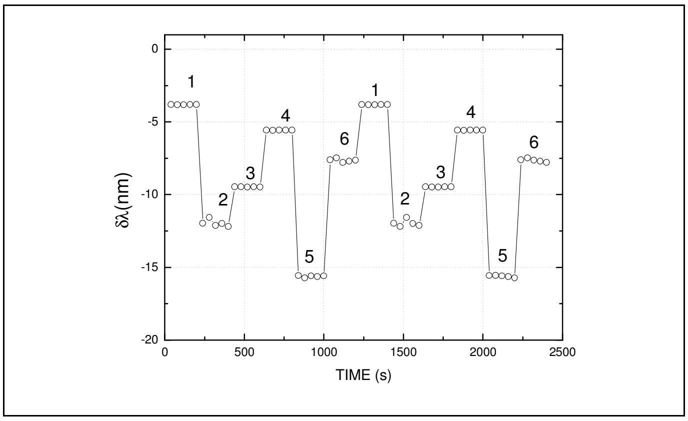

Figure 1: Wavelength shift $\delta\lambda$ for the used LPG along the temporal cycles, when the grating is in contact with alcohol (1), turpentine (2), thinner (3), naphtha (4), kerosene (5) and gasoline (6).

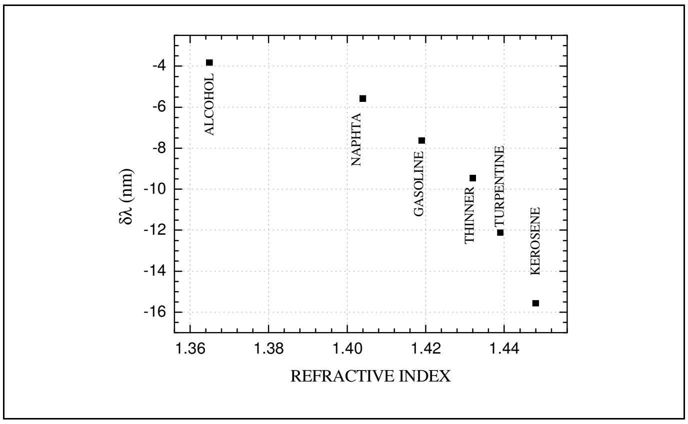

Figure 2: Wavelength shift $\delta\lambda$ for the used LPG as a function of the sample refractive index.

For the produced FBG, the thermal behavior showed a hysteresis in the range of temperatures from 7 ° C to 60 °C. This hysteresis is characterized by small shifts in the Bragg wavelength (< 40 pm) towards lower wavelengths for consecutive heating and cooling cycles, what in turn can lead to a non-correct temperature determination when the device is used as a thermometer. To minimize this behavior, the gratings were kept under 190 °C during one hour; after this time, the grating resonance presented a shift of 0.435 nm towards lower wavelengths (Figure 3a), besides a small decrease of 0.86 dB in the reflectivity (Figure 3b).

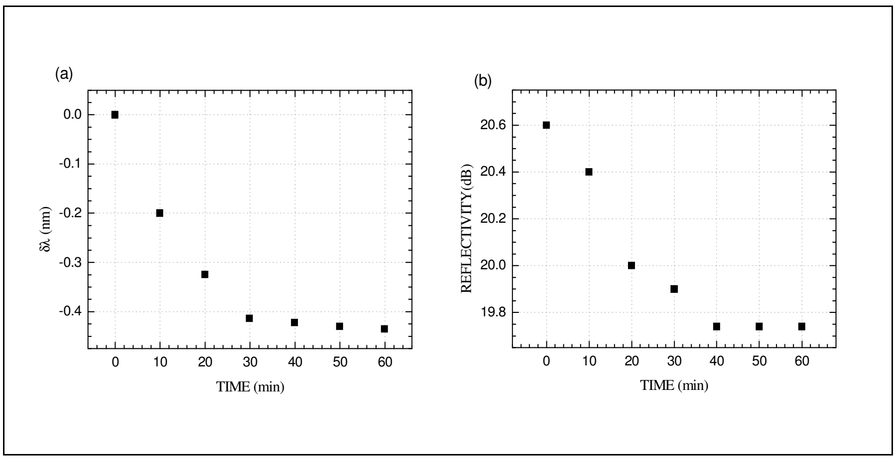

Figure 3: FBG (a) wavelength shift $\delta\lambda$ and (b) grating reflectivity along the time, while the grating was kept at 190 °C.

These parameters presented a fast decrease during the first 30-40 minutes of the thermal treatment, and a tendency to stabilize in the remaining time. After the treatment, the gratings nor presented the early observed hysteresis. The thermal grating sensitivity was in the range from 10.2 pm/°C to 11.4 pm/°C.

Conclusions

The results presented in this work show that the LPG based sensor can be used to identify the hydrocarbons flowing in a pipeline, with an average sensitivity of 3.8×10^5pm/RIU for samples with refractive indexes ranging from 1.432 and 1.448. This sensitivity relates to a sensor resolution of 2.6×10^{-5} if the grating is used as a refractometer together with an OSA with ± 5 pm of wavelength precision. Even in the lower sensitivity zone, the smallest wavelength shift measured ($\delta\lambda$= 3.824 nm for alcohol) can be easily detected by the instrument, as in this zone the grating sensitivity was 4.5×10^4 pm/RIU, corresponding to a resolution of 2.2×10^{-4} for a refractive index measurement. The wavelength reproducibility for a given fluid in different cycles of the sample identification shows the sensor reliability. The very fast sensor response time (~3 seconds) makes it adequate for many applications, like leakage monitoring or fluid identification in pipelines. The LPG temperature sensitivity can be compensated with the use of a FBG to measure this parameter. One advantage of using an FBG temperature sensor is the possibility of multiplexing it in the same fiber link where the LPG is installed. However, this FBG must be stabilized before its use by means of the thermal treatment to assure a good performance of the sensor. The effects observed in Figure 3 can be associated with the presence of hydrogen in the fibers, previously introduced to increase the photo-induced changes in the core fiber refractive index during the grating production. The shift in the resonance dip to lower wavelengths while the grating is under high temperature leads to a decrease in the n_{eff} of the core fiber due to the diffusion of loaded hydrogen out of the fiber (see equation 1). This decrease in the n_{eff} also contributes to the increase in the grating reflectivity. However, the thermal structural relaxation of the defects reduces the index modulation Δn, what contributes to decrease the grating reflectivity (see equation 3). The combined effect is responsible by the observed decrease in the grating reflectivity during the thermal treatment [8, 4]. It must be emphasized that the grating is stabilized for operation in temperatures below the temperature of the thermal treatment.

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