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One-year analysis of road condition using FBG arrays

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ABSTRACT

In this work, it is presented an analysis of FBG arrays installed in a public road. The arrays were installed in a newly paved urban road and were monitored for more than one year. The study evidences the permanent deformation of the wearing course and the degradation of the reflected spectra of the sensors.

Keywords: Fiber Bragg grating, asphalt, structural health monitoring, weigh-in-motion.

1. INTRODUCTION

The development of an efficient and sustainable mobility scheme is one of the main concerns nowadays due to the repercussion in the life quality of the population, but also, it has an important economic and environmental impact. In urban areas, the rapid population increase results in an unprecedented amount of urban traffic, from heavy freight to personal vehicles. This implies more traffic congestions, air and noise pollution, accidents, infrastructure degradation, etc. From a broad scope, it has a detrimental impact on the wellbeing of the citizens. New mobility schemes are being developed to overcome this challenge, with new policies, but also including the new technology advances such as the related with smart cities. In this regard, new high-performance traffic-monitoring systems allow to get a deeper comprehension of mobility, from real-time monitoring of a key road/street to the development of accurate mobility models based on more quantity and higher quality information. Those systems can also carry out lighting control for traffic regulation and derivation or speed monitoring, among others [1], [2].

Optical fiber sensors show appealing characteristics that make them suitable to help palliating the aforementioned issues. To cite some related with Smart Cities, they have demonstrated their multiplexing and distributed sensing capability, the ability to measure different physical or biochemical parameters over long distances; and the full distributed sensing operation (Raman, Brillouin and Rayleigh scattering), among many others [3], [4]. In particular, optical fiber sensors have been successfully installed in asphalt structures showing high performance and versatility in comparison with other technologies [5-9]. In this way, this technology presents characteristics enough to achieve weigh-in-motion in normal traffic conditions [10].

In this contribution, it is presented an experimental demonstrator of a fiber optic sensor network for traffic monitoring, installed in asphalt in a real environment. Two arrays of 20 fiber Bragg gratings (FBG) each were installed in February 2021 on a newly paved road section. The scheme was originally designed for traffic monitoring, but degradation information has been extracted from the long-term measurements. These results evidence a progressive non-elastic deformation of the pavement after the installation, and evidence the degradation of the FBG reflecting spectra due to non-uniform deformations. Those aspects are crucial to stablish the first steps for high resolution weigh-in-motion and asphalt degradation monitoring.

2. METHODOLOGY

In previous communications, we have reported a simple FBG installation process suitable for asphalt structures, aimed to traffic monitoring applications [5]. However, in this study, the data retrieved from the installation is analyzed from the degradation perspective instead from the traffic detection. As shown in Fig. 1(a), the experiment consisted of 2 arrays separated 50 cm consisting of 20 FBGs each, separated 7.5 cm, covering 1.5 m length of asphalt in total. The sensor arrays were installed in a two-lane road (same direction) near the laboratory. The location of the sensors was connected to the monitoring station in the Optical Fiber Laboratory by means of ~100 m of standard single-mode fiber. The sensor fibers were installed by digging a small trench of 1 cm deep (0.5 cm wide) in the asphalt, placing the fiber inside and protecting it with an epoxy resin. Each trench is conducted to a manhole where the connecting fibers to the lab are located.

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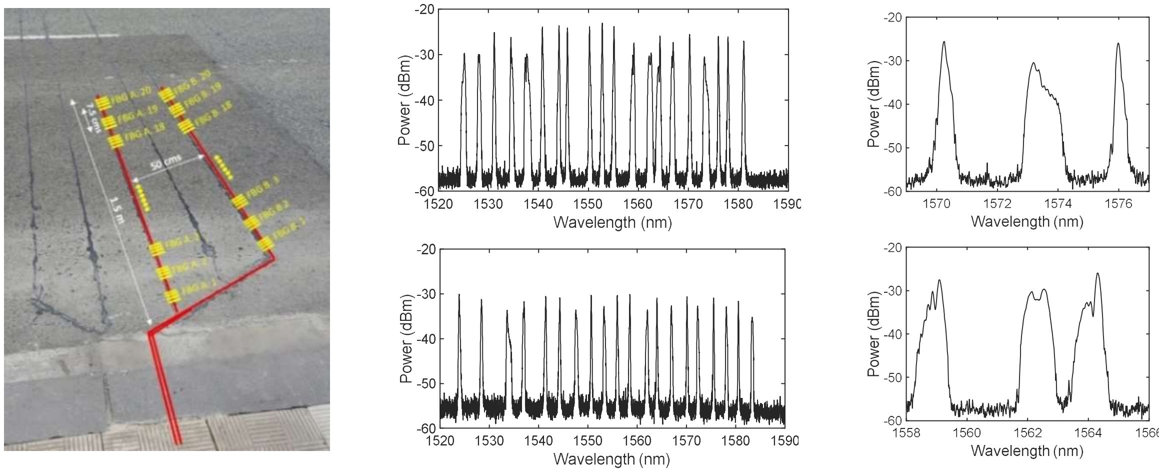


(a) (b) (c)

Figure 1. (a) Schematic diagram of the FBGs arrays distribution in the road (b) reflection spectra of both arrays and, (c) detail of the degraded spectrum of the FBGs due to inhomogeneous strain.

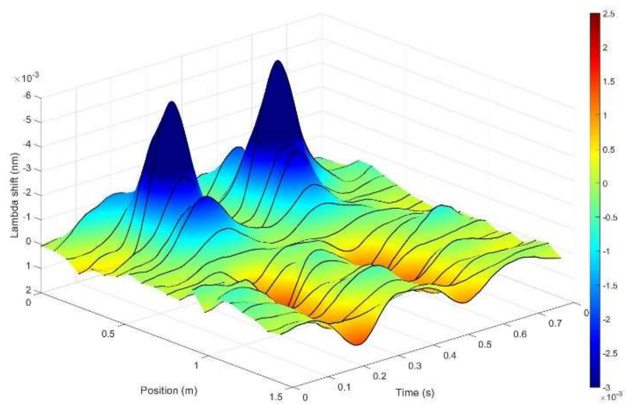


Figure 2. Surface 3D plot representing the lambda shift measured for a vehicle passage as a function of the road position and time. Black lines represent the recorded FBG signals, where each FBG corresponds to a specific road position.

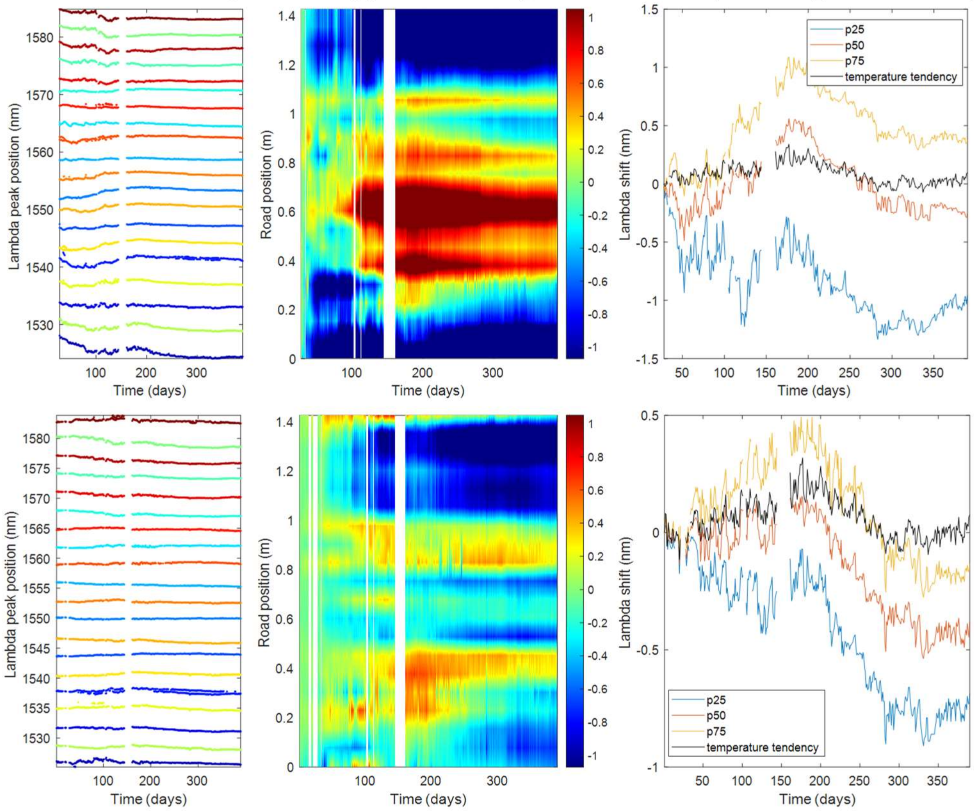
Figure 1(b) presents the spectrum of both arrays where the reflection peak of each FBG is shown. It was detected right after the installation, that during the curing of the epoxy, some distortion appeared in the reflected spectrum of the FBGs. That behavior, evidenced in Fig. 1(c) matches with a non-uniform strain along the FBG itself [11]. This could happen due to a strain variation during the curing or the creation of some bubbles along the FBG. Moreover, after the initial spectrum degradation, it was observed that the variation of these spectral distortion evolved with time. Thus, this can be an indication of asphalt degradation or deformation and could be studied to correlate the degree of distortion with the asphalt degradation. Moreover, this degradation could lead to wrong vehicle detections using an automated detection algorithm.

As an example of the measurements provided by this setup, Fig. 2 depicts the wavelength shift evolution regarding time and position of a vehicle passage. In the experiment, the FBGs separation was calculated to be able to reconstruct the strain distribution perpendicular to the traffic flow. Thus, the events created by vehicles can be accurately measured, which can lead to subtract information about degradation and weight of the vehicle after a correct modelling of the structure.

3. RESULTS

For this study, a measurements campaign of over a year was carried out. The FBG data was collected during the period between February 1st 2021 and March 4th 2022 (14 months). It must be considered that FBGs are both sensitive to strain and temperature. Therefore, to prevent sunlight from inducing uncontrolled effects on asphalt temperature, the data was collected at night, at ~12:00 a.m. Every day, five consecutive measurements were recorded with one second interval between them. This redundancy was aimed to be avoid any artifact that could be caused by vehicle perturbations.

The central wavelength of each FBG was recorded and was then processed to obtain physically interpretable information about the asphalt degradation. First, temperature compensation must be done to extract possible deformation of the structure. For this purpose, daily temperature changes were obtained for each recording day. Then, the central wavelength values for each FBG were compensated by subtracting an estimated wavelength shift component associated to temperature variations. To estimate this wavelength shift, a typical FBG temperature sensitivity of 0.13 pm/Cº was employed.



(a) (b) (c)

Figure 3. Results obtained for the FBGs arrays A and B (upper and lower subfigures). a) Wavelength values obtained for each FBG as a function of time; b) heatmap representing the wavelength shift as a function of the position of the fiber in the road and time; c) 25th, 50th and 75th wavelength shift percentiles and wavelength shift tendency component associated to temperature variations (in black).

Next, it was to estimate a density data distribution along the central wavelengths for each recording day. For each day, every peak of the estimated density distribution corresponds with the average wavelength value of an FBG. Thus, this procedure allows not only to identify each FBG individually, but also to average the five data measurements to avoid particular artifacts. The experimental results obtained after this processing step along the overall period are represented in Figure 3(a). Note that in the figure, the different FBGs are shown with colors. It can be inferred from the figure that the non-uniform strain distribution on the FBGs changes with time, implying a variation in the mechanical conditions of the pavement. This effect is so important that at some point some FBGs present two peaks that are detected individually (e.g.: FBG at 1532 nm in the array 2 of Fig. 3(a)). Initial experiments discarded stress-induced birefringence changes. In addition, Fig. 3(a) evidences that permanent deformations are taking place during the initial months after setting the new pavement, as expected. Due to punctual unavailabilities of the interrogation unit, there are some gaps in the measurements.

In a last step, the FBGs were mapped with their corresponding position on the road. Thus, the measured data can be represented in three-dimensions: the first one is the recording time axis; the second one, the position of the road, where for each wavelength datum, the position is assigned based on which FBG the datum belongs to (note that the spatial disposition of all FBGs are known); and the third dimension is the lambda shift value, referenced respect to the wavelength value of the first recording day. The resulting three-dimensional data structure is linearly interpolated along the road position dimension in order to fill in the gap between the FBGs sampling positions. The resulting three-dimensional map can be seen in Fig. 3 (b), representing the asphalt deformation as a function of time and road position. It can be observed certain discrepancy between both FBG arrays. On the other hand, there are areas in which there is systematically a negative value of the lambda shift, and others that are positive, suggesting that a systematical deformation of the pavement. Also, note the high strain changes induced to the FBGs, with strain changes in the milistrain order.

In order to determine the component of the wavelength shift tendency common to all FBGs the compensation-free data was used. For each recording day, the 25th, 50th and 75th percentiles of the lambda shift FBG values were computed. Fig. 3 (c) shows the results where all FBGs share a tendency that is common to all of them. This common tendency can be compared with the estimated wavelength shift contribution of the temperature (black lines in Fig. 3 (c)). It can be observed that there are multiple sharp variations that present a similar behavior both in the common FBG tendency and in the temperature tendency. That is, there is a significative correlation between both. This seems to indicate that: 1) the temperature compensation has been performed correctly and b) slow variations not related to the temperature are present. This occurs on both FBGs arrays, verifying that there is a component of asphalt degradation that is common to all FBGs.

4. CONCLUSIONS

In this contribution, a long-term study of asphalt structure deformation using a dense FBG sensor setup is presented. This demonstrator, initially designed for traffic detection, allows the strain characterization perpendicularly to the traffic direction with the aim of assessing both pavement and FBG degradation. The results of more than one year measurement campaign in a newly paved road have been presented and analyzed. The study shows the degradation of the FBG sensors due to non-uniform strain happening first during the installation and later, progressively, during the year. Also, signal processing has been applied to determine the deformation trend with time. After the proper temperature compensation, permanent deformation of the structure can be observed, which differs between sensors, with wavelength displacements in the nanometer-order. Thus, an asphalt degradation was observed, mainly in the most common vehicle-passing section. Therefore, it has been demonstrated that advanced strain monitoring in asphalt can be done with FBGs, obtaining crucial information that can be used towards degradation estimation and ultimately, for weigh-in-motion applications.

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