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Multicore fiber sensors for strain measurement towards traffic monitoring

Arturo Sanchez-Gonzalez*[a], Javier Pradas[a,b], Iñigo Corera[a], Mikel Bravo[a], Daniel Leandro[a], Romain Dauliat[c], Raphael Jamier[c], Philippe Roy[c], Rosa A. Perez-Herrera[a], Manuel Lopez-Amo[a]
[a]Institute of Smart Cities (ISC), Dpt. of Electrical, Electronic and Communication Engineering, Public University of Navarre (UPNA), Campus de Arrosadia, 31006 Pamplona, Spain; [b]Menditech S.L., Tajonar 22, 31006 Pamplona, Spain; [c]XLIM UMR CNRS 7252, University of Limoges, F-87000 Limoges, France

ABSTRACT

In this work, two new interferometric sensors based on multicore optical fibers for the measurement of strain with the ultimate goal of traffic monitoring are presented. The operating principle of each sensor relied on the monitoring of the phase shift difference accumulated between the supermodes of the structure of the multicore segment in a full round trip. The strain characterization for both sensors resulted in a linear response, with sensitivities of $-4.073\cdot10^{-3}$ rad/με and $-4.389\cdot10^{-3}$ rad/με for the aligned and V-shaped cases respectively, and one-hour instabilities below $4.6\cdot10^{-3}$ rad with a 95% confidence level. These results suggest its feasibility in applications requiring high sensitivities over very wide strain ranges, such as heavy-vehicle traffic monitoring. To corroborate the hypothesis, both sensors were integrated into the pavement and their response to the traffic was analyzed.

Keywords: Fast Fourier Transform, fiber sensor, few-mode fiber, multicore fiber, traffic monitoring

1. INTRODUCTION

Fiber optic communications using multicore fibers (MCFs) is nowadays an emerging technology, having undergone a great development in the last decade [1]. In this regard, the space division multiplexing (SDM) allowed by this type of fibers has emerged as one of the main strategies for expanding the capacity of optical transport networks, enabling concurrent parallel data transmissions on dozens of cores in a single cladding. However, SDM usually comes at the expense of crosstalk, being one of its main drawbacks in terms of data transfer. Consequently, MCF manufacturing has moved toward minimizing this impairment, with increasing the distance between cores as one of the main solutions applied [2]. However, from the point of view of fiber optic sensing, crosstalk can be an important source of information, since it is usually the way in which a physical magnitude affects various propagation modes differently, and that can be measured and evaluated. Hence, the MCF manufacturing trend differs from the sensing interests. Moreover, as the distance between cores is increased, the interrogation schemes increase in complexity, as it becomes progressively more challenging to simultaneously illuminate the different cores of the fiber. As a result, commercial MCF are becoming progressively less suitable for this application, with the development of MCF sensing technologies falling rather behind. However, multiple examples of the sensing capabilities of MCF can be found, highlighting in recent years the design of fast-response temperature sensors [3], long-range displacement sensors [4], and high-sensitive bending sensors [5]. However, its implementation in mobility applications remains, as far as the authors are concerned, unexplored. In this regard, in addition to distributed schemes [6], point systems for traffic measurement are still mainly addressed by rather classic interferometric structures [7] or wavelength-selective fiber sensors [8].

In this work, preliminary results showing the response of MCF sensors for the detection of traffic are presented. Two MCF sensing elements were installed in a public road, evaluating the correct detection of passing vehicles by measuring the phase displacement in the Fast Fourier Transform (FFT) spectra.

2. SENSOR DESIGN AND EXPERIMENTAL SETUP

To conduct the experiment, two 3-core fibers were designed and manufactured by means of the stack-and-draw technique. With respect to the number of cores, they were limited to three in agreement with recent designs reported in the literature

* arturo.sanchez@unavarra.es
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for bending sensors [9]. Concerning core diameters and distribution, two fundamentally analogous approaches were chosen. In both cases, the cores were made as small and as close together as attainable in order to achieve single mode cores and a good coupling between them. The structure showed good guidance in the 1500 to 1600 nm spectral range of interest. As a result, 6 µm diameter cores with a core-to-core pitch of 18 µm were achieved, in agreement with [10]. The difference between the both lied exclusively in the arrangement of their cores. Hence, in one of the MCF manufactured the three cores were arranged according to the vertices of an isosceles triangle with an unequal angle of 110º and whose corresponding vertex coincides with the longitudinal axis of the fiber (3V), as illustrated in Figure 1 (a). On the opposite, in the remaining one they were aligned (3L), with one of them matching the longitudinal axis of the fiber, as can be seen in Figure 1 (b).

Using the manufactured MCF, the designed sensors consisted of 45 cm-long segments, with one end cleaved and mirrored and the other spliced to a single-mode fiber. This length was found long enough to achieve the path difference between propagation modes needed to obtain multiple periods in the interferogram. Additionally, the mirroring is done in order to operate in reflection. Regarding the splice involved, a specialty fiber fusion splicer (Fujikura FSM-100P) was employed. Thus, by properly correcting fiber alignment as well as adjusting the electrode location, gap between fiber ends and discharge intensity, it was possible to compensate the effect that small asymmetries in the MCF manufacturing process could have caused in the inhomogeneous coupling of modes between SMF and MCF as well as in the occurrence of spurious reflections at this interface.

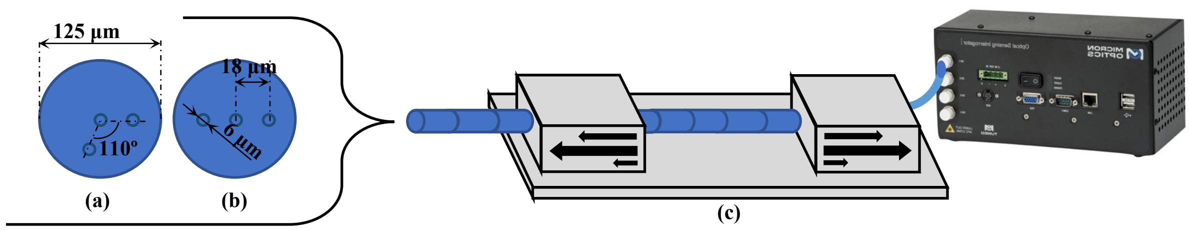

Figure 1.Geometry of the aligned (a) and V-shaped (b) multicore fibers employed, and their strain characterization setup (c).

The setup employed in the study is illustrated in Fig.1 (c). The operating principle of each sensor is based on the reduction in core diameter and core-to-core pitch with its elongation, which results in a change of the coupling coefficient and a shift of the wavelength dip in transmission spectrum [10]. In order to characterize this strain dependency, the fiber was attached to a motorized custom station equipped with two opposing clamps with a spacing that can be controlled with a minimum step of 17 nm. Once in place and slightly preloaded, each sensor was subjected to an increasing strain up to 1750 µε at regular intervals of 0.5 µε. At every step, an optical sensor interrogator (OSI, Micron Optics sm130) with a spectral resolution of 2.4 pm was employed to register the response of each structure in the 1510 to 1590 nm range. These spectra were then investigated in the spatial frequency domain by means of the FFT algorithm. Considering the specifications of the interrogator used, spatial frequencies over 200 nm^{-1} with a resolution of $1.25 \cdot 10^{-2}$ nm^{-1} could be resolved in the transformed domain.

3. RESULTS AND DISCUSSION

The spectral response of both fibers under test (FUTs) can be seen in Figure 2 (a). It is possible to appreciate a remarkable interference pattern in both cases, consequence of the beating produced between the different fundamental modes of each core in the multicore segment. Moreover, these patterns present no high-frequency carrier components, as would be expected if a faulty fusion occurred between the single-mode and multicore fibers, resulting in the formation of a Fabry-Perot cavity between this interface and the mirrored surface of the fiber end.

As illustrated in the detailed view presented in Fig. 2 (b) and Fig. 2 (c), when the applied strain was increased, no disturbance of its functional form was noted, but a slight attenuation and significant shift of the spectrum was observed. This result is especially remarkable when studying the spatial frequency domain by means of the FFT. For this purpose, once the FFT is performed to the spectra of each sensor, the phase of the highest amplitude spatial component is monitored with respect to the applied strain. These components correspond to 0.4 nm^{-1} for the 3L-MCF sensor and 0.4375 nm^{-1} for de 3V-MCF sensor, with their phase evolution presented in Fig. 3. As it can be observed, the phase presents a strong linear evolution with the strain applied in the full range of study, retrieving a sensitivity of $-4.073 \cdot 10^{-3} \pm 2 \cdot 10^{-6}$ rad/µε and a coefficient of determination of 0.9996 for the 3L-MCF case, similarly to the 3V-MCF scenario with a sensitivity of -

$4.389 \cdot 10^{-3} \pm 3 \cdot 10^{-6}$ rad/με and a coefficient of determination of 0.9998. Moreover, their one-hour stability was also characterized, resulting in instabilities below $4.6 \cdot 10^{-3}$ rad with a 95% confidence level. It can be concluded that the different arrangement of cores in each fiber had no significant influence on their performance. Nevertheless, both results are comparable with recently reported sensors based on similar structures [11].

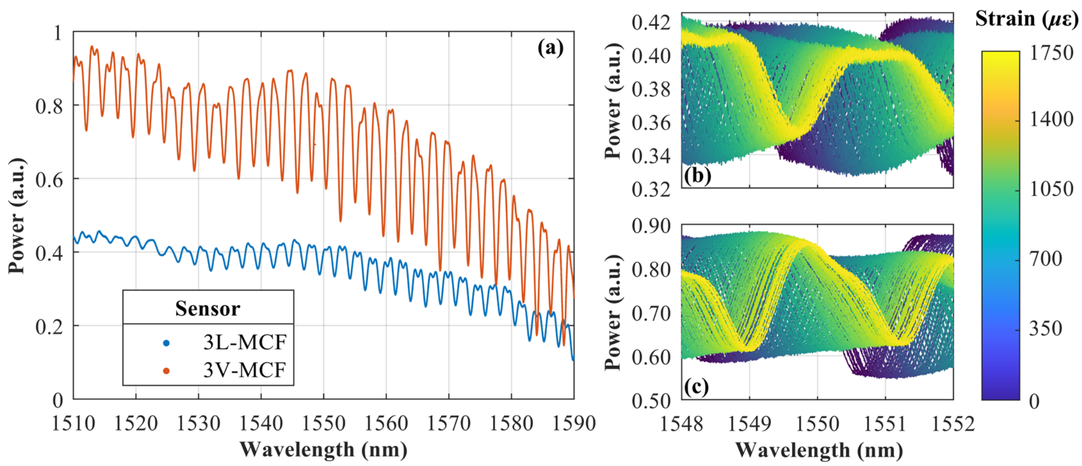

Figure 2. Sensor reflectance (a), and a detailed view of the evolution of the spectra around 1550 nm with strain for the 3L-MCF (b) and 3V-MCF (c) cases.

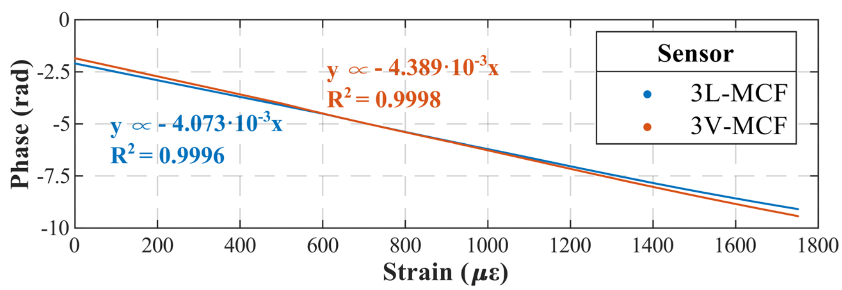

Figure 3. Phase variation of the main spatial frequency of each sensor with applied strain.

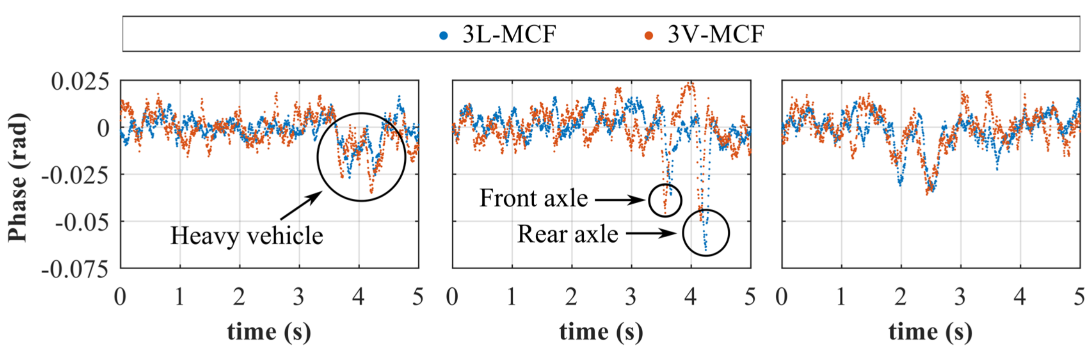

Figure 4. Three different examples of heavy vehicles crossing the developed sensors once embedded into the road asphalt.

4. PROOF OF CONCEPT

Once the strain response was characterized, both sensors were embedded into the asphalt pavement according to the process described in previous works [8]. The sensors were placed adjacent to each other so that the recording of events would be simultaneous, also avoiding the influence of disparities between them in environmental or pavement wear conditions. Hence, the comparability of their performance is ensured. Finally, the interrogator previously employed is replaced by a Micron Optics si155. The reason is that this model has a slightly broader spectral range, from 1500 to 1600 nm, at the cost of worsening its spectral resolution to 10 pm. However, taking into account that the analysis was performed in the transformed domain, the spatial frequency resolution is now enhanced to 10^{-2} nm^{-1}. Moreover, by properly modifying its application programing interface, the acquisition frequency of the full spectrum has been improved from 10 to 250 Hz, recovering a complete 10 ksamples-spectrum every 4ms. Thus, by dynamically applying the FFT in each measurement, a fine-tuned interrogation system compatible with high-speed applications has been developed.

Finally, the results of testing both sensors in the monitoring of heavy vehicles are analyzed. As shown in Fig. 4 for three different examples, the pitch of each axle over the sensors was detected by a significant perturbation in the phase stability. According to the results obtained from Figure 3, this perturbation was more significant for the case of the 3V-MCF sensor, given its higher sensitivity to strain. Likewise, in all cases it was noticeable how the perturbation associated with the rear axle was greater, as a consequence of the greater weight on it. Further work is being done to evaluate the stability of the measurements obtained, and the sensibility increase needed to detect a wider range of vehicles with enough accuracy.

5. CONCLUSIONS

This work has proposed two multicore fiber optic sensors for the measurement of strain with the ultimate goal of traffic monitoring. Their design was based on a 45 cm long 3-core fiber section fused to standard single-mode fiber in one end while the remaining one was mirrored. The manufacturing process was optimized to achieve substantial light injection to all existing cores, so that the difference in optical paths between the modes of each would result in a distinct interferometric response. This spectral response and its dependency with applied strain were analyzed in the Fourier transformed domain. For this purpose, the phase of the main spatial frequency of each sensor spectrum was monitored under increasing values of strain. The results obtained were linear trends in the full range of study, with sensitivities over $-4\cdot10^{-3}$ rad/με in both cases and one-hour stability lower than $4.6\cdot10^{-3}$ rad with a 95% confidence level. Finally, the feasibility of the proposed structure traffic monitoring sensor was suggested and verified.

ACKNOWLEDGEMENTS

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