Real-Time Urban Sensing by In-Fiber Interferometric System over Field-Deployed Uncoupled 4-Core Fiber Cable

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Abstract: We demonstrate urban anthropic events monitoring through a sustainable and cost-effective interferometer sensor built by exploiting two cores of an uncoupled 4-core fiber in the first deployed multi-core fiber cable in L'Aquila, Italy. © 2024 The Authors.

1. Introduction

Multi-core fibers (MCFs) can be exploited not only for high capacity space-division multiplexing (SDM) transmission, but also for sensing applications, for example by using separate cores for simultaneous distributed vibration and temperature sensing by independent Raman optical time-domain reflectometry in one core and Rayleigh-scattering-based distributed acoustic sensing (DAS) in another one [1]. Fiber distributed-curvature and 3-D shape sensing were demonstrated by employing the bending dependence of Brillouin frequency shift in off-center cores of an MCF [2]. In a recent field trial, a standard-cladding 4-core uncoupled-core (UC) MCF deployed in L'Aquila, Italy [3], was used for a field-demonstration of advanced DAS based on coherent detection in a looped-back configuration, where the output of one core was looped back to the input of another core [4].

In this contribution, we demonstrate that the same 6.3-km MCF cable deployed in L'Aquila can become sensitive to the urban environment thanks to the adoption of a very simple interferometric approach, exploiting a pair of cores of an UC- MCF. No distributed fiber sensing techniques based on optical backscattering phenomena, such as Rayleigh and Brillouin scattering, requiring high operating power and complex and expensive digital signal processing (DSP) and storage of the acquired data, are considered. Two uncoupled cores inside the same fiber provide two separated optical paths in the field trial, operating as the arms of a Michelson interferometer (MI) embedded in the single MCF itself, making the deployed cable sensitive through a cost-effective and power-saving implementation, suitable for extensive and sustainable applications. Perturbations inside the underground tunnel and anthropic events caused by cars or pedestrians over the manhole covers are detected, allowing the monitoring and the surveillance of the integrity of the optical network infrastructure itself.

2. Experimental field trial based on sensing MCF

The deployed urban fiber infrastructure used to experimentally assess the effectiveness of the proposed in-MCF MI sensor consists of a 6.3-km multi-fiber optic cable housed in an anti-rodent micro-duct in a ring configuration, running in L'Aquila downtown area in a multi-service underground tunnel [5] (map in Fig.1).

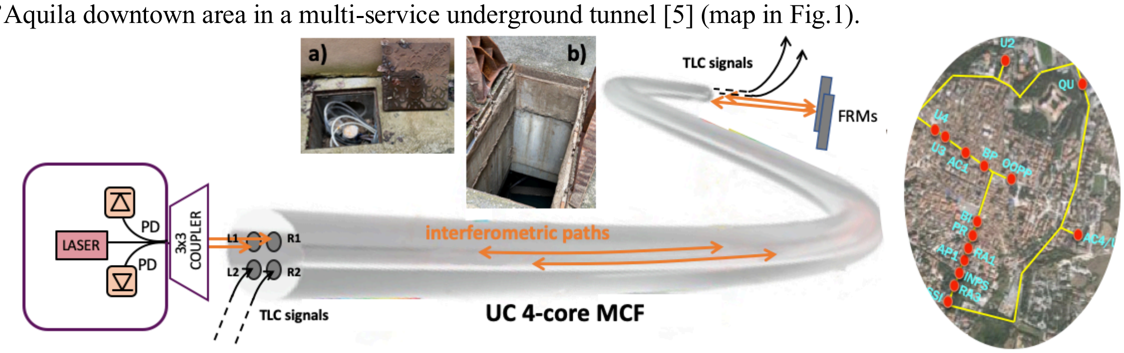

Fig. 1. Schematic diagram of the sensitive UC 4-core MCF based on the MI embedded inside the fiber. On the right: map of L'Aquila 6.3-km MCF testbed. In the inset a) typical manhole and in b) an entrance of the underground tunnel, where the MCF cable is deployed.

The cable contains 4-core UC MCFs [3], characterized by four square-lattice arranged silica cores (core pitch 40.2±0.2 μm), and each MCF can be addressed by means of suitable fan-in/fan-out (FIFO) connections. The MI scheme [6] is illustrated in Fig.1: we choose two MCF cores to operate as interferometric arms and at the ending after the FIFO output they are terminated with Faraday Rotator Mirrors (FRMs) to back-reflect the optical sensing signals, retracing the state of polarization. In input a 3x3 coupler provides the passive homodyne demodulation of the signals, without the necessity of coherent detection and without additional data processing [7]. Although the event to be detected impacts in a very similar way on both cores, just the different geometrical arrangement of the two cores inside the same fiber is enough to detect the perturbation [8]. Furthermore, the strong noise induced by the urban environment, where the fiber cable is deployed, is the same for both the cores, so it can be minimized automatically in the demodulation after the 3x3 coupler as also shown in case of two fibers inside the same cable [9].

3. MCF core pairs characterization

A preliminary characterization of the perturbation sensitivity of the different pairs of cores in the employed 4-core UC MCF has been done, applying in the lab 5-kHz vibration generated by a piezoelectric actuator placed on an aluminum plate, where a 6-mm-diameter MCF cable was attacked. Fig. 2 a) shows the magnitude of the detected power spectrum: the geometrical arrangement of the cores and their relative distance are always enough to assure good evidence of the external perturbations, maximum in case of cores R1-L2 (according to the Fig.1 scheme numbering), which are more distant. On the other side, the noise is reduced more effectively when the distance between the two cores is minimum (in case of R1-L1), playing the role of a common-mode signal canceled-out after demodulation.

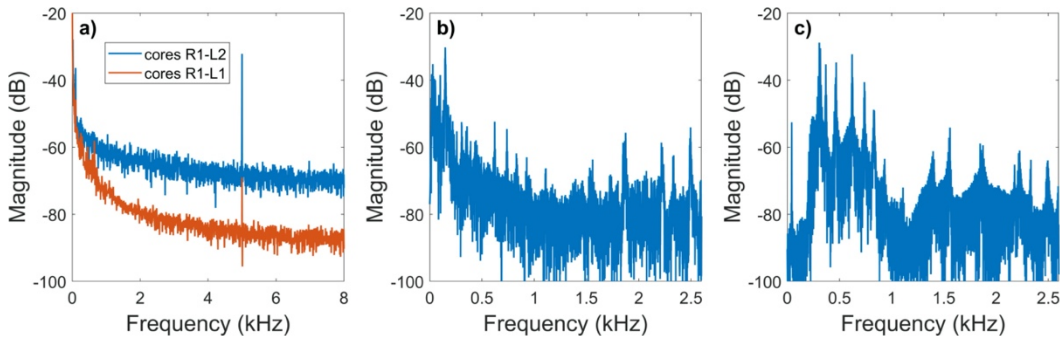

Fig. 2. a): Power spectra of the phase signal detected by the MCF cable in lab in case of 5-kHz vibration for the core pairs R1-L1 and R1-L2. b) Signal phase detected by the MCF cable inside the underground tunnel, whose entrance is reported in Fig.1 inset b), in case of cell phone ringing. c) Ringtone original spectrum.

3. Detection of events inside the underground tunnel and close to the manholes

We first characterized the capabilities of the proposed MI-based sensor embedded inside the deployed MCF cable to recognize intrusions and monitor the integrity of the network infrastructure by detecting different acoustic and mechanical events inside the underground multiservice tunnel, reported in the inset b) of Fig.1. Fig.2 b) shows the detected power spectrum corresponding to a cell phone ringing with the ringtone called “radiate”. From a comparison with the original spectrum shown in Fig.2 c), it is clear that the main tones are detected, with a limited distortion of the low frequency components, making the detected signal recognizable if acoustically reproduced. Moreover, the phase variation in time domain detected for a mechanical perturbation intentionally produced by hammer strikes of different strength on the wall and on a metal surface in the tunnel are reported in Fig.3 a) and b), respectively. Strong strikes on the metal surface are significantly evident, also thanks to the acoustic resonance induced by the strike on the metal surface. In a), not only the weak strikes on the wall are visible, but a background oscillation corresponding to talking people is also detected. The detection of urban events has been also demonstrated considering the two different manholes shown in the insets of Fig.1. Fig. 3 c) and d) report the phase variation in time domain detected for hammer strikes on the manhole cover of the inset a) with the MCF cable at about 20 cm below the ground and on the cover of the tunnel entrance of the inset b) with the MCF cable at about 1.5 m below the ground. Although the MCF cable is closer to the cover in the first case, the detected phase signal is weaker, probably owing to the reduced dimension of the cover well fitted with the hole, corresponding to a minor acoustic resonance. In any case, for both the covers the perturbations is identified, allowing to identify dangerous situations due to the road works, causing possible damages or breakages to the metro network. Finally, anthropic events over the manhole cover of the inset b) of Fig.1 have been also monitored. Fig. 4 a) and b) present the detected signal corresponding to pedestrian jumps and a pedestrian walking in close proximity to the slightly wonky cover, respectively (it is clearly visible in b) when the foot steps exactly over the manhole). In c) the passage of a car over the cover, characterized by lower frequency oscillations. Considering the events rate and their duration and power, the deployed MCF cable could give an indication of the road traffic.

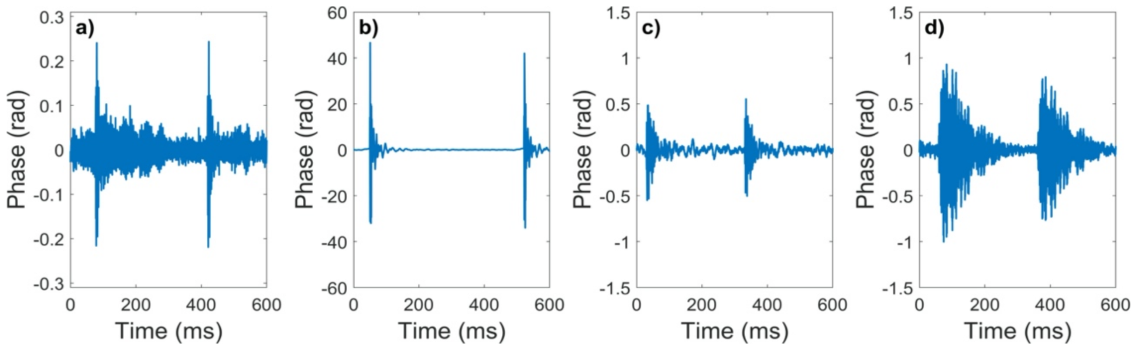

Fig. 3. Detected phase signal in time domain corresponding to hammer strikes: a) on the wall and b) on the metal face inside the tunnel reported in Fig.1 inset b); c) and d) on the manhole covers reported in Fig.1 inset a) and b), respectively.

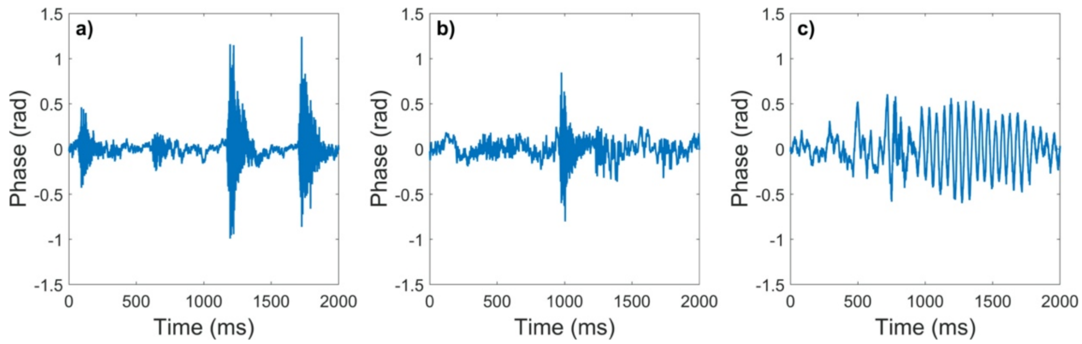

Fig. 4. Detected phase signals in time domain corresponding to urban anthropic events in proximity to the cover of the multiservice tunnel: a) pedestrian jumps; b) pedestrian walk; c) car passage.

4. Conclusions

The successful operation of an in-fiber interferometric sensor embedded in the field deployed UC 4-core MCF in L'Aquila was demonstrated, clearly monitoring acoustic and mechanical perturbations inside the underground tunnels, where the MCF cable is installed, and urban events (car crossing, human jump, pedestrian walking) close to the manhole covers. Preliminary assessment of the proposed interferometric approach was experimented with simple implementation supported by off-the-shelf low-cost instrumentations and without the necessity of coherent detection or complex and expensive DSP. Event localization is possible thanks to a so-called "dual" arrangement of the interferometric scheme [10]. The proposed in-MCF sensor provides a sustainable embedded solution for surveillance of the safety of telecom fiber infrastructure and for smart and pervasive monitoring of our cities in a large scale.

5. Acknowledgement

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6. References

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