Vibration Sensing for Deployed Metropolitan Fiber Infrastructures

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Abstract: A counter-propagating coherent vibration sensing approach is exploited in a 32km deployed fiber ring network, proving its feasibility in early detection of critical events that may damage and put out of service the optical infrastructure.

1. Introduction

Nowadays, optical metropolitan networks are often organized on optical ring topologies used, for example, as the primary link of active access networks, where the interconnection between the different network sections takes place through switching devices (e.g. Optical Add Drop Multiplexer) [1]. The ring layout opens the possibility of new sensing applications that can run on a dedicated wavelength in parallel to all the other DWDM wavelengths carrying telecom traffic, providing added value to the fiber optic infrastructure. Recently, the authors of this paper demonstrated the possibility of using a deployed passive optical network (PON) infrastructure for structural vibration monitoring in smart city applications with the simultaneous downstream of a 10-Gb/s NRZ signal [2]. In that case, a coherent (i.e. interferometric) sensing approach was proposed for vibration monitoring at locations known a priori at the optical network unit (ONU) side, that is, in correspondence of one of the final PON splitter terminals, where selected fibers were dedicated to sensing purposes. In the present work, thanks to a counter-propagating layout along the metro ring, we propose a coherent sensing technology allowing to detect and even localize along the entire link the onset of vibrations or dynamic stress applied to the fiber.

Experimental demonstration is presented for a deployed 32-km ring cable running in the city of Turin, Italy and devoted to telecommunication applications. The mechanical stress events monitored and localized by the proposed sensor can be caused, for example, by road works too close to the deployed fiber cable. Damages or breakages of optical telecommunication infrastructures is in fact a current topical issue that can cause prolonged out of service, requiring time-consuming and high-cost repairs. In this frame, the sensing system proposed in this work provides a simple and reliable solution for optical network surveillance, able to identify in advance potentially dangerous situations that can affect the integrity of the optical metro link, without resorting to complex and expensive phase-OTDR (Optical Time Domain Reflectometer) distributed solutions [3,4].

2. Experimental layout

The proposed experimental layout is shown in Fig. 1. A 32 km SMF fibre ring deployed in the city of Turin, Italy (belonging to one of the Italian FTTH operators), was used to prove the feasibility of metro fiber infrastructure for sensing purposes, e.g. for monitoring the structural integrity of the fiber itself. The proposed scheme is basically a

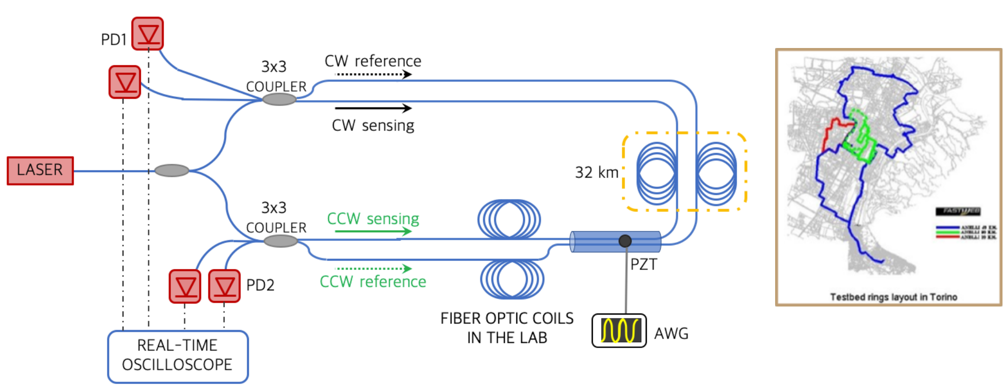

Fig1. Experimental layout comprising a 32 km fiber ring deployed in the city of Turin.

dual Mach-Zehnder interferometer arranged in a loop configuration, where counter-propagating clockwise (CW) and counterclockwise (CCW) optical signals travel along two fibers inside the same deployed optical cable [5].
The two fibers acts as the sensing and reference arm of each Mach-Zehnder interferometer. When a mechanical or acoustic vibration acts on the fiber loop, an additional phase modulation $\Delta\phi$ is generated in the optical signals, which, as well, propagates in the two opposite directions. Vibration localization is achieved by evaluating the time delay ΔT between the two counter-propagating phase modulations $\Delta\phi_{CW}$ and $\Delta\phi_{CCW}$ at the receivers. In particular, $\Delta\phi_{CW}$ and $\Delta\phi_{CCW}$ are separately retrieved by means of coherent receivers constituted by a simple 3x3 optical coupler providing the in-phase I and quadrature Q components of each interferometric signal [6]. The four optical signals are simultaneously detected by 125 MHz photoreceivers (NEP=25pW·√Hz), sampled by a 20MS/s real-time oscilloscope (13bit) and post-processed to recover $\Delta\phi_{CW}$ and $\Delta\phi_{CCW}$ and evaluate the relative time delay ΔT [5-7]. Although the frequency band of mechanical and acoustic vibrations is in the order of kHz, a 20MS/s sampling rate is required to guarantee a 10-meter spatial resolution in event localization. We believe this is a good compromise between a reduced DSP complexity (20 MS/s can today be implemented on extremely cheap programmable electronic boards) and a spatial accuracy in fault location that is more than adequate for metro network.

3. Vibration monitoring characterization and experimental results

Typically, interferometric sensors have their reference arm kept separated from the measurement area [5,7]. Considering that in a deployed fiber network the phase noise contributions caused by the city environment are significantly strong, the reference and sensing arms were chosen along the same path. In this way, the common mode noise is reduced, at the expense of a reduction of the actual detected vibration signal. Initially, in our experiment a 5 kHz vibration, generated by a piezo transducer (PZT), was applied the fiber cable to emulate a dynamic stress event. Fig. 2 shows the time behaviour and the spectral content of the recovered phase signal $\Delta\phi$ for the case of a 32km reference fiber placed inside the lab compared to the configuration depicted in Fig.1 with reference and sensing fibers coupled in the same cable.

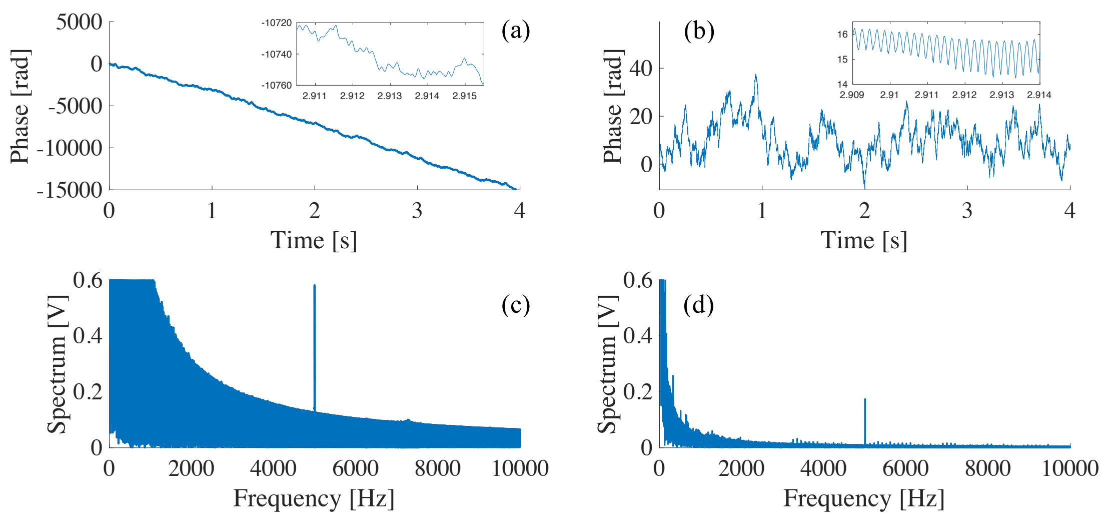

Fig2. Example of recovered phase signals in case of a) lab reference b) coupled fibers in the ring. Corresponding frequency spectra in case of c) lab reference d) coupled fibers in the ring.

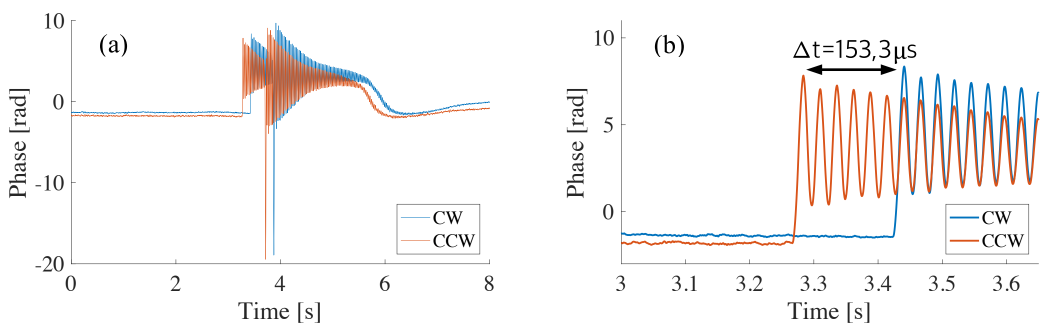

Fig3. a) Recovered $\Delta\phi_{CW}$ and $\Delta\phi_{CCW}$ signals in case of PZT impulse applied after 1km fiber coil attached to the 32km fiber ring network. b) Detail of the onset of the detected impulsive event.

The measurements highlight how the use of coupled fibers drastically reduces to only a few tens of radians the integral noise accumulated along the link, while, at the same time, the slightest difference in the geometric arrangement of the fibers in the cable is sufficient to allow to reveal the vibration signal with a good SNR, thanks to the high sensitivity of coherent detection.

Afterwards, by exploiting two coherent systems coupled in the counter-propagating configuration of Fig.1 we verified the possibility of localizing an impulsive dynamic event (e.g. an intrusion or a sudden damage). Different coil lengths, namely of 100m, 1km and 4km were connected to one side of the deployed ring network and an impulsive event was generated with the PZT near the junction. The PZT was excited with square pulses of 450μs which in turn caused a natural damping response of the PZT itself. Fig. 3 shows the corresponding recovered signals $\Delta\phi_{CW}$ and $\Delta\phi_{CCW}$ measured for the case of a 1 km coil attached to the ring network, resulting in a delay ΔT=153,3μs in agreement with a ΔL=31 km (fiber refractive index n=1.483). Repeated measurements confirmed an accuracy of ±15m of the proposed approach in dynamic event localization.

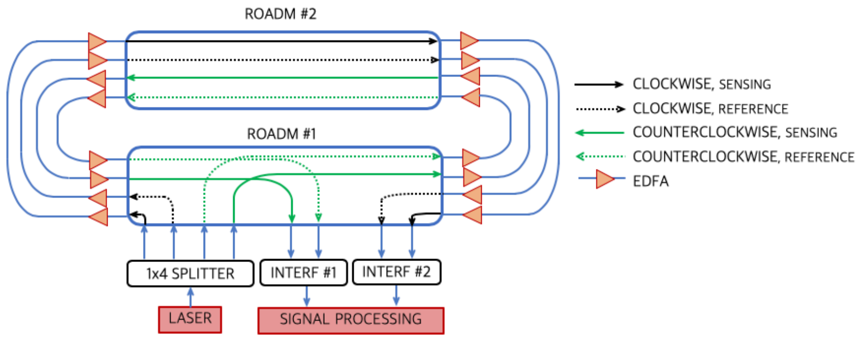

Fig 4. Extension of the proposed architecture in a ROADM-based ring network

4. Discussion for the implementation in a ROADM-based ring network and conclusions

In this paper we have shown and experimented in a 32-km fiber ring deployed in Turin city a coherent sensing solution, based on counter-propagating paths along the ring, to detect and localize mechanical stress applied to the network cable. The system capabilities in vibration monitoring are demonstrated, proving a 15-meter spatial accuracy in event localization guaranteed by a simple interferometric approach combined to off-the-shelf 20MS/s sampling boards, without recourse to complex and expensive phase-OTDR based techniques. The proposed sensing solution thanks to its ring topology and typical operation distances, is potentially suitable for modern metro ring networks, where distributed monitoring would be particularly interesting for early detection of anomalous conditions, that can induce damages or breakages of the fiber infrastructure. The experimented solution described in Fig.1 uses the two ring fibers in a bidirectional way. Today reconfigurable optical add-drop multiplexer (ROADM)-based dense wavelength-division multiplexed (DWDM) ring metro networks employ isolators in the optical amplifiers making each fiber path strictly mono-directional [1,8]. To apply the same experimented sensing architecture, four mono-directional fiber paths are required (as shown in Fig. 4), exploiting two pairs of sensing and reference fibers (one pair for clockwise and one for counterclockwise propagation). The architecture in Fig. 4 would dedicate to sensing only one wavelength (in each of the four paths), leaving all the other wavelengths (not shown in the Figure for the sake of clearness) in the DWDM comb available for the normal data traffic transmission and routing inside the metro ring.

5. Reference

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