VIBRATION IDENTIFICATION OVER 50KM SSMF WITH POL-MUX CODED PHASE-OTDR

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Abstract

We demonstrate multi-detection and recognition of mechanical events over 50km of SSMF with coherent homodyne phase-OTDR using novel Pol-Mux orthogonal interrogation codes. Pattern identification of an engine noise is highlighted, paving the way for numerous smart-city/industrial monitoring applications over already deployed telecom fibers.

1. Introduction

Exploiting fiber based networks with optical sensing is emerging as a hot topic to enable smart-city monitoring applications [1]. Nevertheless, the used technology based on a measure of the change in the intensity of Rayleigh backscattering usually comes with a limited sensitivity and is inherently not linear to the vibration event, resulting in a restriction of the fiber distance over which perturbations may be detected and a limitation of their event identification capability. The standard fiber probing technique used for Distributed Acoustic Sensing (DAS) systems is based on single-pulse interrogations that can be – but not necessarily – frequency-swept. The intra-pulse beating patterns are then captured with simple photodetection or SNR-enhancing coherent detection at the receiver side [2].

Recent progress in DAS schemes, exploiting the phase information of the backscatter signal [3] instead of the sole intensity, offers better sensitivity and linearity, and helps envisage identification of complex mechanical events featuring large bandwidth and dynamic range. However, various issues such as polarization fading effects, non linearities induced by pulse probing, or laser source phase noise make practical realizations highly challenging. We introduced in [4] a new probing technique to tackle these limitations through a polarization and phase sensitive interrogator. At the transmitter side (Tx), two mutually orthogonal Golay binary pairs mapped to binary- or quaternary- phase-shift-keying (BPSK/QPSK) symbols jointly and continuously modulate two orthogonal polarization states of a narrow-linewidth laser source. At the receiver side, through a self-homodyne configuration, a dual-polarization coherent receiver (Rx) captures the backscattered optical field which is then correlated with the transmitted coded sequences. A perfect estimation of the fiber response is obtained in the form of Jones matrices from which optical phase variations in time are derived per fiber segment. The method was experimentally validated with large bandwidth acoustic signals over a 100m long fiber equipped with Fiber Bragg Gratings to enhance the backscattered intensity [5].

The present paper aims to extend the scope of this novel probing method to long distances over non-sensing-dedicated fibers, typically standard single mode fibers (SSMF), where the detected light comes from the inherent Rayleigh backscattering. In doing so, we potentially target distributed sensing onto the widespread networks of deployed telecom fibers, hence addressing detection and identification of a wide range of mechanical events in smart city monitoring applications (transportation, industries, security…).

Section 2 details firstly the probing method enabling perfect channel estimation and secondly the Rayleigh backscatter static model used to determine the distance limit over which mechanical events can be captured in an SSMF. Section 3 describes the experimental setup while Section 4 highlights the ability to detect and identify a synthetic engine noise signal along a 51km SSMF up to the fiber end.

2. Fiber response estimation

2.1. Probing method

In an SSMF, the Rayleigh backscattered signal captured at the dual-polarization coherent Rx after correlation with the transmitted sequence is expressed as $\boldsymbol{E_r} = \boldsymbol{H}.\boldsymbol{E_t}$ where $\boldsymbol{E_t} = \begin{pmatrix}\boldsymbol{E_{tx}}\\ \boldsymbol{E_{ty}}\end{pmatrix}$ and $\boldsymbol{E_r} = \begin{pmatrix}\boldsymbol{E_{rx}}\\ \boldsymbol{E_{ry}}\end{pmatrix}$ stand for the polarization-division-multiplexed (PDM) transmitted and dual-polariation received optical fields respectively. The 2×2 Jones matrix $\boldsymbol{H}_{i,j}$ is the dual-pass impulse response from the start of the fiber to the i^{th} fiber segment at time index j. $\boldsymbol{H}_{i,j}$ is estimated for each fiber segment index i whose length $d=c_f/(2F_{symb})$ is given by the symbol rate F_{symb} of the transmitted probing sequence, c_f standing for the velocity of light in the SSMF core. The interrogating code duration T_{code} is N_{code}/F_{symb}, where N_{code} stands for the number of symbols that compose the code. N_{code} is typically a power of 2 and the generation of a set of orthogonal codes for jointly probing each polarization axis is detailed in [4]. The code is repeated with a period equal to the code duration T_{code}, leading to periodic estimations of $\boldsymbol{H}_{i,j}$ at time index j with a period of T_{code}. The associated mechanical bandwidth of the system is thus $BW=1/(2.T_{code})$.

The conditions for perfect estimation of $\boldsymbol{H}_{i,j}$ when the sensing fiber is probed with PDM-BPSK codes [4] is $T_{code}>4.T_{ir}$ where $T_{ir}=2L/c_f$ stands for the time spreading of the channel response

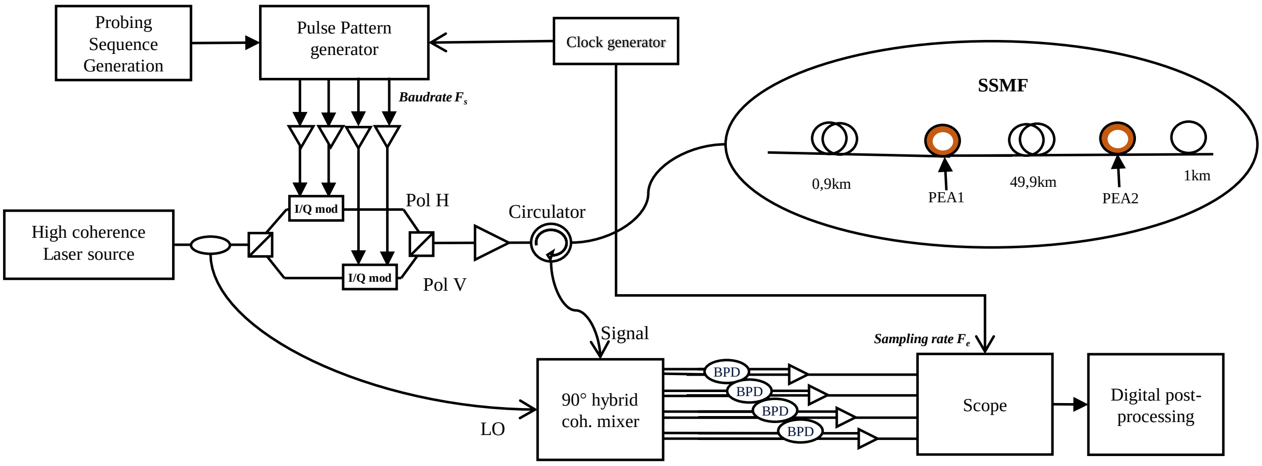

Fig. 1 Experimental Setup (PEA: Piezoelectric actuator, Pol: polarization, BPD : balanced photodetectors).

for a fiber of length L. The symbol rate and the code length are chosen accordingly to come up with a T_{code} value that complies with the above condition.

The optical phase is extracted from $\boldsymbol{H}_{i,j}$ as $\boldsymbol{\varphi}_{i,j}=0.5angle(det(\boldsymbol{H}_{i,j}))$ where *det()* stands for the determinant operator. Differential phase in the space dimension is then computed to obtain the evolution of the optical phase in time for each spatial segment. The phase standard deviation (StDv) in time is used as a metric for monitoring the interrogated fiber: mechanical events perturbing the optical line will be detected and localized from the magnitude and position of peaks emerging in the differential phase StDv along the fiber segments.

2.2. *Rayleigh backscattering model*

We developed a dual-polarization numerical model of Rayleigh backscattering in SSMF which proved that the sensitivity of phase OTDR with the above-mentioned probing method was mainly limited by the laser phase noise contribution [6], leading to a maximum probing distance with regard to the estimated coherence length of the used laser source.

In this model, the fiber is described as an array of randomly distributed scatterers along a $\boldsymbol{z}$ axis (uniform distribution along the fiber), with random backscattered amplitudes (normal distribution around the mean Rayleigh backscattering coefficient). This distribution of scatterers leads to a scalar response in amplitude and phase $\boldsymbol{e}$ of the fiber, depending on the position and amplitude of the scatterer on which the light is reflected [7]. The fiber model is split into spatial fiber segments, for which a Jones transfer matrix $\boldsymbol{U}_{\boldsymbol{forward}}$ is defined. $\boldsymbol{U}_{\boldsymbol{forward}}$ stands for a general unitary matrix (det($\boldsymbol{U}$)=1). Since the optical fiber is reciprocal, the backward path of light in the fiber segment verifies $\boldsymbol{U}_{\boldsymbol{backward}} = \boldsymbol{U}^{\dagger}_{\boldsymbol{forward}}$, where † is the complex conjugate operator, and $\boldsymbol{M} = \begin{bmatrix} \sqrt{1-\alpha} & \sqrt{\alpha} \\ \sqrt{\alpha} & \sqrt{1-\alpha} \end{bmatrix}$, with $\alpha \in \left[0,\frac{1}{2}\right]$ being a polarization transfer coefficient [6] which modelizes the reflection on the Rayleigh scatterers inside a fiber segment. A round-trip in a fiber segment thus transforms polarized input light $\boldsymbol{E}_{\boldsymbol{in}}$ such that $\boldsymbol{E}_{\boldsymbol{out}} = \boldsymbol{e}.\boldsymbol{U}^{\dagger}_{\boldsymbol{forward}}.\boldsymbol{M}.\boldsymbol{U}_{\boldsymbol{forward}}.\boldsymbol{E}_{\boldsymbol{in}}$. Finally, the model yields the Jones matrices for every fiber segment. The full backscattered field is then $E_{out} = \sum_i e_i U_i^{\dagger} M U_i \, E_{in}$ where i is the index of the segments. Once the fiber is modeled, the emission and reception process is emulated in order to add the laser phase noise to the input light and to the local oscillator, and to take all receiver noises and losses into account at the receiver side. The estimated Jones matrices are processed to capture relevant information such as phase variations along the line.

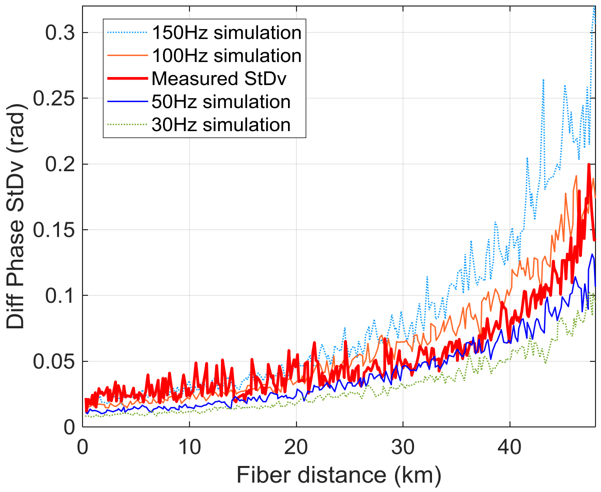

Fig. 2 Optical phase standard deviation as a function of fiber distance; simulations for different laser linewidths $\Delta\nu$ versus experimental results, no perturbation.

An exponential growth of phase standard deviation in time is observed after 50km of simulated fiber, which forecasts a noisy phase signal, thus bringing issues to correctly identify any mechanical event after such a distance. Fig. 2 compares the phase StDv of simulated fibers with different laser linewidths Δν to experimental results for differential phase StDv measured over a 1s time period in a 50km SSMF for which the setup is described in the following, without any disturbance (static mode) on the line. We observe that experimental phase StDv over the fiber distance is well fitted by the model when simulating a laser phase noise in the 50Hz to 100Hz linewidth range.

This static mode measurement defines the sensitivity limit of our interrogator for perturbations detection and identification.

3. Experimental setup

The full interrogation setup is presented in Fig. 1. An overall 52km-long SSMF is under test, on which mechanical perturbations are applied after 1 km and 51 km by means of piezoelectric actuators (PEA). The first actuator (PEA1) has 55cm of fiber coiled around it while the second one (PEA2) has 133cm. These actuators are excited with an audio signal made of a combination of three sinewaves at 50, 105 and 145Hz selected to emulate an engine noise. Its Power Spectral Density (PSD) is shown in Fig. 4 (dotted line).

An OEwaves^{TM} highly coherent laser is used for the experiment, which linewidth is given around 1 Hz in a 10µs window. However, the bandwidth of the mechanical events to be detected in sensing applications calls for working with codes having low repetition rates, in the range [100:1000]Hz typically. With such long observation periods, laser sources show a much larger linewidth, estimated here between 50 and 100Hz for our OEwaves^{TM} source.

The laser source emits at λ=1536.6nm, it is used both to generate the interrogation signal and as a local oscillator at the reception. The probing signal is sent on two orthogonal polarizations through a dual-polarization Mach-Zehnder modulator (F_{symb}=50MHz) to modulate the optical wavelength. It is then amplified and sent through a circulator into the fiber under test. The Rayleigh backscattered optical signal returns through the circulator to a dual-polarization coherent mixer and is captured by balanced photodiodes, prior to a 12 bits resolution scope acquisition with a sampling rate equal to 2.F_{symb} and then off-line signal processing.

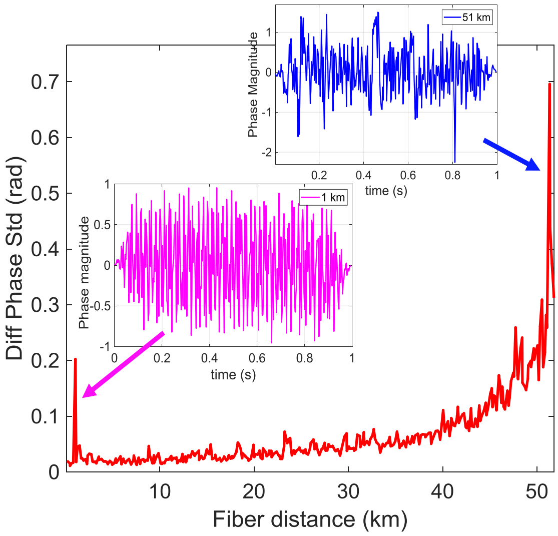

Fig. 3 Measured optical phase standard deviation along the fiber with an engine noise perturbation injected at 1 and 51km.

4. Results

We apply the same audio signal to perturbate the fiber thanks to the two actuators located 1km and 51km from the fiber start. After estimation of the Jones matrices of the fiber segments, we derive the differential phase StDv between a subset of segments separated by 150m to detect and localize the events along the line. Fig. 3 shows the measured phase StDv as a function of the fiber distance. The two mechanical events appear as two StDv peaks, actually present at the expected locations. The phase evolution over the 1s measurement window is also displayed in Fig. 3 for each of the two detected peaks locations.

Fig. 4 shows the power spectral density (PSD) of the differential phase at these two locations and displays also, for comparison purpose, the PSD of the audio signal that was injected into the actuators. The spectral signature of the engine noise at the first piezo location (1km) is well preserved, with a SNR of 30dB approximatively. After 51km, the lesser laser source coherence reduces the SNR to roughly 10dB, but the three frequency components of the mechanical noise emerge clearly, still enabling recognition of the mechanical event after such a long fiber distance. Notice the higher peak power level detected at 51km, in line with the greater coiled fiber length (133cm, versus 55cm at 1km).

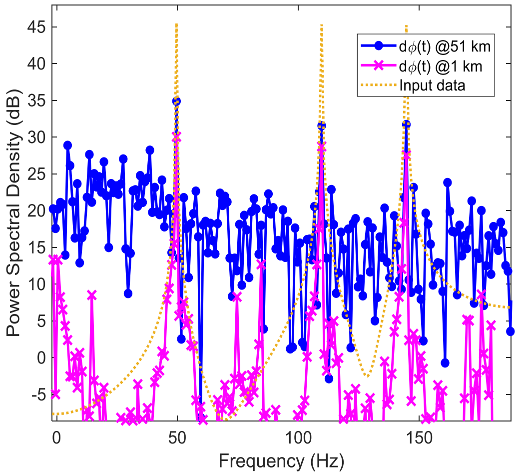

Fig. 4 Power spectral density of phase variations at detected event locations compared to input perturbation signal.

5. Conclusion

We demonstrated long distance sensing capabilities of a pol-mux code probing method enabling, through a coherent receiver, a perfect estimation of Jones matrices per fiber segment backscattered in a SSMF. A mechanical event, made of a sum of three sinewaves that synthesizes an engine noise, was detected, localized and then identified from a spectral analysis over a fiber distance that exceeds 50km. These results push back the distance limits of fiber sensing over telecom infrastructures for smart city monitoring applications.

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