A Dual-polarization Rayleigh Backscatter Model for Phase-sensitive OTDR Applications

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Abstract: A dual-polarization model of Rayleigh backscattering for telecom fibers is developed. The noise standard deviation over distance estimated from phase-OTDR simulation matches experimental results when accounting for the laser source phase noise.

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1. Introduction

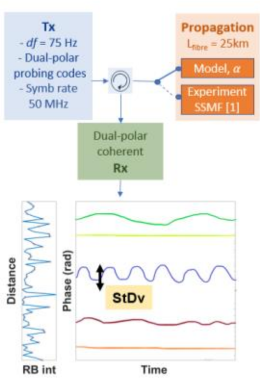
Coherent phase-OTDR has recently improved the sensitivity and dynamic range when detecting mechanical events using a Standard Single Mode Fiber (SSMF) compared with intensity-based sensing. In [1], the fiber is probed jointly over the two polarization axes, and a dual-polarization coherent receiver captures the backscattered signal, from which dual-pass Jones matrices for each fiber segment are estimated. The differential optical phases extracted from the Jones matrix estimates are linearly related to local mechanical perturbations inducing fiber extension in the nm range.
There is little background on the use of both polarization and phase of Rayleigh Backscatter (RB) in the literature. To further study the observed sensitivity limit, we build a dual-polarization model of the Rayleigh backscattered optical field including a spatial discretization of the SSMF to reflect the fiber segmentation induced by the above-mentioned probing method.
When comparing simulation results based on dual-polarization probing codes obtained from our model to experimental ones, we show similar distortion profiles over the fiber length. The spatial evolution of the observed distortion is shown to be mainly induced by the laser phase noise.

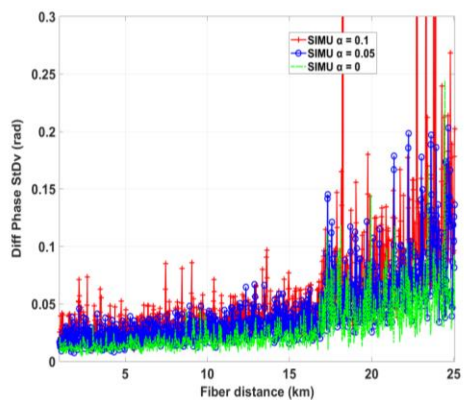
2. A dual-polarization model for Rayleigh backscattering

A single-polarization model was developed for the use of Rayleigh backscatter in distributed sensing [2]. It predicts the phase and intensity of the backscattered optical field by modeling the statistical distribution of Rayleigh scatterers along the fiber in the case of coherent OTDR sensing. The Rayleigh scatterers are defined by their spatial coordinate z_m randomly distributed along the fiber and their scattering amplitude a_m, m being the index of the scatterer, with $z_m > z_{m-1}$.
State and Degree of Polarization (SOP & DOP) of the Rayleigh backscattered light were characterized in [3], in case the coherence length L_{coh} of the source was smaller than the fiber length L_f. This analysis of Rayleigh backscattering polarization is updated in [4] to highly coherent light sources ($L_f \ll L_{coh}$) as those used in phase-OTDR and considers the backscattered field from each scatterer.
In practical implementation cases, the fiber is implicitly discretized into consecutive segments of length equal to $T.cf/2$; c_f is the light velocity in the fiber and T stands for the pulse time width in case of pulse interrogation [2] or for the symbol period in case of probing with codes [1]. Then, capturing the integration of Rayleigh backscattering over each segment allows to come up with an estimated local optical field. DOP and SOP after each fiber segment can be extracted from these local fields.
We integrate the scatterers over distance to simulate the implicit segmentation of the sensing implementation case. The modeled dual-pass Jones matrices of the fiber from $z = 0$ up to the i^{th} segment are of the form $H_i = \mu\, e_i\, U^\dagger\, M(\alpha)\, U$, with μ as a common attenuation ratio and † standing for the conjugated-transpose operator. The backscattered field is characterized by a phasor e_i [2], derived for each fiber segment i. A general elliptic retarder U is used to model the evolution of polarization [4] up to the i^{th} fiber segment. We introduce a virtual global reflection M at the end of each fiber segment i that encloses the polarization-dependence of all the elementary scatterers present in the current fiber segment.
The phasor is derived as in [2]: $e_i = \sum_{m \in segment_i} a_m . \exp(j\, 4\, \pi \lambda^{-1} z_m n_f)$ with n_f assumed constant along the fiber. λ is the probing wavelength. The global reflection is modeled as $M(\alpha) = \begin{bmatrix} \sqrt{1-\alpha} & -\sqrt{\alpha} \\ \sqrt{\alpha} & -\sqrt{1-\alpha} \end{bmatrix}$, α being the backscattering transfer coefficient from one polarization to the other one.

3. Simulation results

The dual-polarization model is further processed in the same way as for our experimental traces to retrieve the estimated matrices after propagation as shown in Fig.1. The simulation parameters are set to reflect the same conditions as in our experimental setup [1]: a simulated 25km long SSMF with Rayleigh backscatter derived from our model is probed using dual-polarization BPSK codes that modulate a laser source with a short linewidth *df*. The 1.31ms duration probing code is generated at 1/T=50MHz symbol rate and continuously transmitted with a period equal to that of its duration. The selected symbol rate yields 2m long fiber segments. The reception stage emulates a coherent receiver and captures, after signal processing, the Jones matrix estimates over time per fiber segment. The differential phase between adjacent fiber segments is finally calculated. We consider the differential phase standard deviation *StDv* per segment estimated over a 0.5s period to compare experiments to simulations.
A laser phase noise is emulated based on a Lorentzian model to cope with the OEwaves™ laser source used in our experimental setup, which linewidth *df* is estimated to 75Hz in a 3ms time frame. Fig.2 shows the StDv obtained along the 25km fiber for various values of the polarization transfer coefficient α around the standard 0.05 value [5], highlighting its impact on the phase noise.
Fig.3 compares the StDv simulation results from Fig.2 for α=0.05 and *df*=75Hz with experimental ones measured in our lab and with setup parameters identical to those entered in the simulation. The randomly distributed peaks correspond to segments with low backscattered intensity, leading to unreliable phase estimations. We observe a good match of the phase noise evolution over the fiber length, particularly in the second half of the fiber. The slightly higher noise level observed experimentally in the first half of the fiber may be imputed to environmental noise that impacts the setup in our laboratory, whereas it is gradually occulted by the laser coherence loss when getting close to the fiber end. We performed additional simulations with various *df* values around 75Hz (results not displayed in this paper), which confirmed that the phase noise observed experimentally in our dual-polarization phase-OTDR implementation over a long distance SSMF fiber is dominated by the imperfect stability *df* of the laser source.





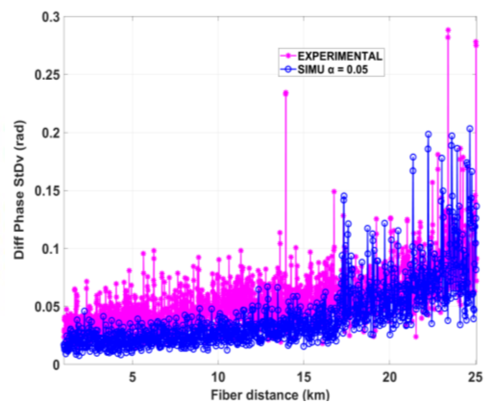


Fig.1 (left): Processing setup
Fig.2(center): StDv phase noise along the fiber obtained from simulation for various choices of α.
Fig.3(right): Experimental measurement versus simulation with α =0.05

4. Conclusion

A dual-polarization model of Rayleigh backscattering was developed to study the sensitivity limit in phase-OTDR when both fiber polarization axes are jointly probed by codes. The phase noise evolution simulated over a 25km SSMF was shown to match experimental traces, highlighting the major contribution of the laser phase noise in the observed sensitivity. This study helps estimate the maximal achievable SSMF distance when sensing already deployed telecom SSMFs for applications such as event detection in smart cities.

5. References

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