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Determination of the Measurement Accuracy of a Phase-sensitive OTDR

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Abstract: This paper presents the measurement accuracy of a phase-sensitive optical time-domain reflectometer (φ-OTDR) as a function of SNR and pulse width. A method to determine the absolute SNR of a φ-OTDR system is also proposed.

1. Introduction

Distributed Optical Fibre Sensing (DOFS) based on Rayleigh scattering can be interrogated by a number of methods, of which one of the simplest and easiest interrogation techniques is direct-detection frequency-scanned φ-OTDR. In such a system, the local quantification of external perturbation is carried out by appropriately compensating the refractive index change with respect to a reference by a frequency shift (FS) of the back-scattered light acting along the fibre through estimators such as cross-correlation.

Numerous studies on Rayleigh-based DOFS have been proposed to improve the system performance through the significantly important parameter, the signal-to-noise ratio (SNR) [1]. Enhanced SNR results in an enhanced measurement accuracy, which is the paramount parameter in any distributed sensing measurement. Despite that, a quantitative relationship pertaining the dependency of the measurement accuracy on SNR in a φ-OTDR system has not yet been addressed so far. However, it is ought to be remarked that the absolute value of the SNR of a φ-OTDR system is not straightforwardly calculated because of the noise-like jagged φ-OTDR intensity trace generated due to the stochastic fluctuations of refractive indices along the fibre.

In this work, a method to calculate the absolute value of the SNR of a φ-OTDR trace is discussed. Besides, an analytical model relating the SNR and the measurement accuracy is suggested, wherein the FS is calculated through cross-correlation. This is the first time to the best of our knowledge that such relationship is presented.

2. Experimental setup

The experimental setups employed in this work are shown in Fig. 1. The concept is to use an incoherent OTDR to determine the fraction of back-scattered power from the source along the fibre, while the coherent OTDR is the measuring setup itself. In the OTDR setup, the incoherent amplified spontaneous emission (ASE) from the erbium-doped fibre amplifier (EDFA) is shaped as a square pulse by an electro-optic intensity modulator (EOM), obtaining a 100 ns pulse. A tunable optical filter (TF) of 4 nm bandwidth is used to suppress the ASE noise from EDFA, followed by another EDFA, whose ASE noise is suppressed by another TF. The back-scattered power is directed through port 3 of the circulator to a 125 MHz photo-detector (PD). Finally, the electrical signal received at the PD is acquired by a fast oscilloscope. The φ-OTDR setup (Fig. 1 (b)) used in the present scenario is mostly similar to that of OTDR, except that the light source is a distributed-feedback (DFB) coherent laser and the input pulse is 10 ns (1 m spatial resolution).

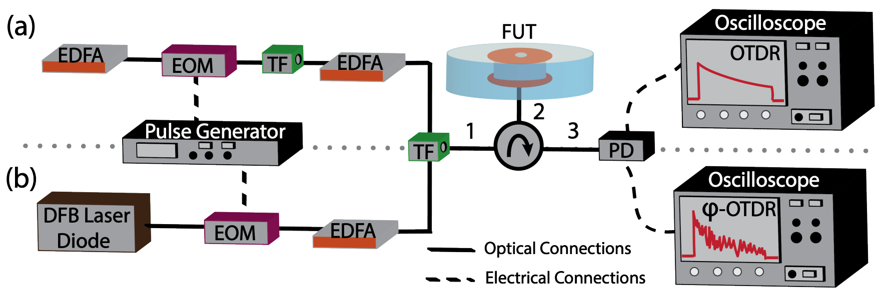

Fig. 1. Experimental Setup for (a) OTDR; (b) Direct-detection frequency-scanned φ-OTDR.

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3. Results and Discussion

Utilising the experimental setup shown on Fig. 1 (a), the back-scatter coefficient α_{BS} of the FUT namely, a standard SMF is measured to be -72.3 dB/m. Knowing the peak power and the width of the pulse, this value of α_{BS} is then used to calculate the Rayleigh back-scattered power, P_{BS} of the φ-OTDR system from the following standard equation [2]:

$$P_{BS} = P_{in}\,\alpha_{BS}\,R_{sp}\,exp(-2\alpha z) \tag{1}$$

where P_{in} is the input power to the fibre, R_{sp} is the spatial resolution, α is the total attenuation coefficient of the fibre, and z is each position along the fibre. This approach has the advantage to deliver an accurate value of the mean power, when compared to a statistical estimation. The noise of the system is obtained by calculating the standard deviation of various consecutive time-domain φ-OTDR traces (obtained using Fig.1 (b)) at each fibre position. Correspondingly, the optical SNR of the φ-OTDR system is simply calculated by taking a ratio between the mean power and this noise.

The FS of the back-scattered light, caused by the localised external perturbations acting along the fibre, in the φ-OTDR system is currently estimated by cross-correlation with a similar reference measurement in known conditions. A number of experimental parameters, such as the SNR and pulse width, can improve the accuracy/uncertainty in the estimation of the FS. Due to the mathematical similarity of the φ-OTDR with Radar and Sonar systems, a similar approach for estimating the uncertainty in time-delay [3] is utilised for estimating the FS uncertainty of a φ-OTDR system as follows:

$$\sigma = \frac{1}{\beta\,SNR}; \qquad \beta = \left((2\pi)^2 \frac{\int f^2 |U|^2 df}{\int |U|^2 df}\right)^{1/2} \tag{2}$$

where β is the normalised standard deviation of the power spectral density ($|U|^2$) of the signal, used for the cross-correlation, which is straightforwardly calculated from the pulse waveform and SNR is the ratio between the optical power of the signal and the noise. For a given interrogating pulse the value of β is constant and its inverse $1/\beta$ is a scaling factor for the width of the auto-correlation peaks. Equation (2) logically shows that the frequency shift uncertainty is inversely related to the SNR and to the pulse width, which is experimentally validated as can be seen on Fig. 2 (a) and Fig. 2 (b) . Thus, it is demonstrated, for the first time to the best of our knowledge, that the measurement accuracy of the φ-OTDR system improves by the SNR and pulse width. This accuracy of the measurement can be quantified beforehand from the experimental conditions.

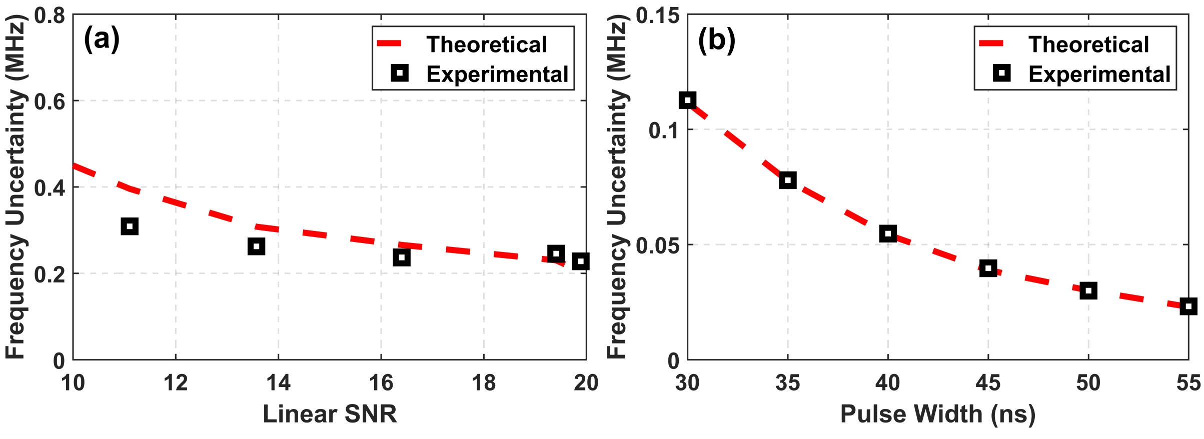

Fig. 2. Frequency uncertainty as a function of: (a) SNR; and (b) pulse width.

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