Study and mitigation of crosstalk and fading effects in fibre Bragg grating-assisted direct-detection phase optical time-domain reflectometry

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Abstract
Over the past decade, phase optical time-domain reflectometry φ-OTDR has garnered considerable attention due to its extensive potential in sensing applications. This technique involves transmitting an optical pulse generated by a narrow linewidth laser (NLL) through an optical fibre and measuring the Rayleigh-backscattered signal as a function of time. Using an NLL enables the detected power to become sensitive to the phase difference between the signals backscattered by the scattering centres within the resolution length (half the pulse width). Consequently, any external perturbation that locally modifies the refractive index or/and elongates the fibre will result in a change in the recorded backscattered power at the perturbation location. In particular, phase-ODTR systems have been applied for vibration localisation, intrusion sensing, detection of seismic waves and railway monitoring. A primary challenge in applying φ-OTDR to standard optical fibres is the low signal-to-noise ratio (SNR) due to the weak power level of Rayleigh backscattering. To improve the signal reception, one of the quasi-distributed enhancement approaches includes integrating arrays of identical weak fibre Bragg gratings (FBGs) in the sensing fibre. The fundamental concept of the so-called FBG-assisted phase-OTDR involves analysing the interference signal created by the waves reflected by two consecutive FBGs. This interference signal can be detected on the φ-OTDR trace if the distance between two successive FBGs is smaller than the resolution length. Any disturbance occurring between two successive FBGs will lead to a change in the phase difference between the two reflected waves, thus modifying the power recorded at the interference signal position on the φ-OTDR trace. However, interrogating a series of identical FBGs increases the SNR but also introduces some undesirable effects, such as spectral shadowing crosstalk and polarisation fading effects.

This thesis has successfully achieved the study and mitigation of spectral shadowing crosstalk and polarisation fading effects in FBG-assisted direct-detection φ-OTDR. For both cases, numerical and experimental investigations have allowed the validation of the proposed methods. Furthermore, the thesis has successfully demonstrated the monitoring of a fibre-to-the-home passive optical network (FTTH-PON) with an FBG-assisted φ-OTDR. The relevant results obtained during this thesis are presented as follows.

- A simulation tool enabling the simulation of an FBG-assisted direct-detection φ-OTDR has been developed. As the conventional double-pulse interrogation technique cannot be used to compensate for spectral shadowing when interrogating a cascade of equally-spaced FBGs, reduced delay and triple-pulse techniques have been

proposed to recover the signal reflected by each FBG, which is required to compensate spectral shadowing. In the case of the reduced delay technique, the compensation method was theoretically explained and tested on a cascade of four identical FBGs equally-spaced by 10 m. In the case of the triple-pulse technique, the compensation method was theoretically explained and experimentally validated on a cascade of seven identical FBGs equally-spaced by 4 m.

- A simulation tool was developed to analyse the polarisation effects in FBG-assisted phase-OTDRs for both unspun and spun fibres. A piezo transducer was considered to induce a vibration between two successive FBGs. The numerical results showed that for the unspun fibre case, the polarisation fading sensitivity PFS strongly depends on the ratio between the distance separating two consecutive FBGs and the beat length. The simulation work also quantified the mitigation effect of the polarisation fading effect when using spun fibres. PFS values as small as 0.2 dB can be reached when using a typical hi-bi spun fibre. The numerical analysis was followed by an experimental study. An experimental setup was developed to measure the PFS for several fibre types. The obtained results qualitatively comply with the numerical data.

- The developed φ-OTDR was used to interrogate an FTTH network installed over a total distance of 25 km. This FTTH network includes a 1x4 splitter at the FAT (Fibre Access Terminal). The sensor interrogates each branch of the aerial section with a probe signal consisting of double-pulse interrogation signal. In the final metres of each branch, a pair of weakly reflective FBGs, spaced 10 m apart, reflects the interfering signal for vibration detection. The FFT allowed the vibration frequency recovery of each branch and enabled to locate a moving cable and its vibration frequency. To mitigate the polarisation fading effect, several states of polarisation (SOPs) were swept thanks to the polarisation synthesiser. Therefore for each branch, the SOP for which the interference of the reflected signal by the FBG pair is the most sensitive is detected. In the same φ-OTDR configuration, a distributed feedback (DFB) laser was successfully used to interrogate the last 10 m between an FBG pair located at 25 km for 1-10 Hz vibration frequency.