Enhancing the Spatial Resolution of Chirped-Pulse Phase-Sensitive Optical Time-Domain Reflectometry Using Digital Sub-Band Signal Processing

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A method based on digital filtering and an additional optical carrier is here proposed to enhance the spatial resolution of chirped pulse ϕ-OTDR distributed sensors. Results demonstrate a 10-fold resolution improvement with minimum SNR impact.

Keywords: Phase-sensitive optical time-domain reflectometry; digital signal processing.

1. Introduction

Phase-sensitive optical time-domain reflectometry (ϕ-OTDR) [1] is one of the most common methods for Rayleigh-based distributed acoustic sensing (DAS) [2]. Among several methods, *chirped-pulse ϕ-OTDR* systems [3] make use of a linearly chirped optical pulse and standard direct detection, thus providing a highly linear response to perturbations, a high measurand resolution, and an increased robustness to coherent fading. Although the great recent progresses in the method [3], its spatial resolution remains limited by the pulse width (e.g. 5-10 m) due to the need of long pulses for wide frequency sweep.

In this paper, a method based on sub-bands digital processing is proposed to enhance the spatial resolution of the chirped-pulse ϕ-OTDR. The method requires adding an optical carrier to the chirped pulse, which could remain long enough to provide good signal-to-noise ratio (SNR) to the measurements. Experimental results demonstrate a 10-fold spatial resolution improvement, with only a modest reduction (<3 dB) of SNR.

2. Experimental Demonstration

To validate the proposed method, a conventional chirped-pulse ϕ-OTDR setup has been used, with chirped pulses of 200 ns and a total chirp of 4 GHz. Compared to the standard method, here an optical carrier shifted by 9 GHz is added to the pulse, whilst the photodetector bandwidth is enlarged up to 12 GHz. A 100 m standard single-mode fibre is used for sensing, being bounded to a metallic wire accessible in 2 points and allowing us to heat the sensing fibre through Joule effect.

Fig. 1a shows the Rayleigh backscattered spectrum measured from the fibre near end. The $I_{bb}(f)$ component is a baseband, triangularly shaped term corresponding mostly to the spectrum of the standard chirped-pulse ϕ-OTDR signal. The component $I_{pb}(f)$ is however passband and it essentially represents the fibre field response to the chirped pulse. The method here proposed is based on sub-band filtering of the chirped pulse field response $I_{pb}(f)$, as shown in Fig. 1b. Although its reduced power, each filtered sub-band represents only a short temporal part of the pulse, resulting in an enhanced spatial resolution. To compensate the resulting SNR reduction, temporal traces obtained from several sub-bands are averaged, leading to an improved spatial resolution with a minor penalty on the SNR.

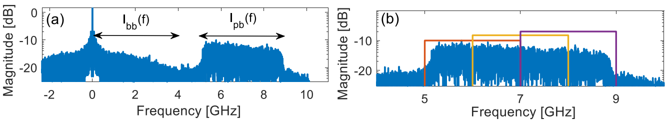

Fig. 1 (a) Spectrum of Rayleigh backscattered light. (b) Spectrum of the chirped pulse response and sub-bands filtering concept.

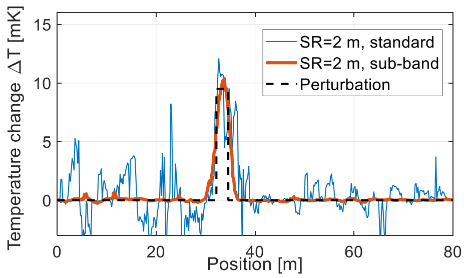

Fig. 2 Measurement of a 2.5 m hot-spot using 20 ns standard chirped pulses (blue) and 200 ns chirped pulses with sub-bands filtering (red).

To validate the method, a 2.5 m-long hot-spot of 10mK is induced at the position of 37 m. Using a pulse of 200 ns (i.e. representing a nominal resolution of 20 m) and 64 overlapping sub-bands of 0.4 GHz, the spatial resolution is improved to 2 m (inducing only a 1.77-fold penalty on the SNR). The red curve in Fig. 2 shows the temperature profile obtained with sub-band filtering method, proving a 10-fold improvement in the spatial resolution. Compared to a standard chirped-pulse measurement of 2 m resolution, sub-band filtering provides a much higher SNR (blue line), thus validating the proposed technique.

References

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