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Enabling simultaneous DAS and DTS measurement through multicore fiber based space-division multiplexing

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Abstract: Through space-division multiplexing using multicore fiber, simultaneous measurements of DAS and DTS have been achieved based on Φ-OTDR and ROTDR, respectively. Wavelet transform denoising has been employed to improve the temperature uncertainty to 0.5 ºC.

OCIS codes: (060.2370) Fiber optics sensors; (290.5860) Scattering, Raman; (290.5870) Scattering, Rayleigh; (290.5830) Scattering, Brillouin.

1. Introduction

With increasing demand of pipeline integrity management over very long range in remote areas, real-time detection and alarm on excavation, theft, leakage and other potential threats are becoming more and more important in oil and gas industry. Distributed optical fiber sensing turns out to be the utmost promising solution in this kind of applications; owning to its outstanding performance with tens of kilometers sensing range and meter-scale spatial resolution [1].

In order to achieve distributed intrusion detection and temperature monitoring of pipelines, distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) technologies have been employed [1], typically based on Phase-sensitive optical time-domain reflectometry (Φ-OTDR) and Raman optical time-domain reflectometry (ROTDR), respectively. Simultaneous interrogation of Φ-OTDR and ROTDR is necessary so as to ensure continuously real-time monitoring along the pipelines. However, it is difficult to implement the measurement using spontaneous Raman scattering (SpRS) signal and Rayleigh scattering signal simultaneously, due to nonlinear effects (including modulation instability (MI) and stimulated Brillouin scattering (SBS), etc.) in the sensing fiber when high pump power is injected [2]. In fact, the SpRS is very weak in optical fibers [3]; the incident pump power is generally very high (several Watts) in ROTDR sensors in order to increase the SpRS intensity [4]. However, the thresholds of SBS and MI are much lower than the required power level for ROTDR [2], which restricts the maximum usable input power. So in a single mode fiber (SMF) based hybrid sensing system, the required pump power levels for ROTDR and Φ-OTDR is incompatible, which has dramatically hindered the simultaneous implementation of DTS and DAS in SMFs.

In order to achieve simultaneous interrogations of DAS and DTS, space-division multiplexed hybrid Φ-OTDR and ROTDR sensor by using multicore fiber (MCF) has been proposed and experimentally demonstrated in this paper. The measurement of SpRS signal and Rayleigh scattering signal are carried out separately in distinct cores of the MCF, thus addressing the problem of incompatible input pump levels required in the hybrid system in SMFs, while only one set of pulse generation devices is required. Additionally, wavelet transform denoising (WTD) method has been employed to reduce the noise of ROTDR traces; eventually the worst temperature uncertainty is improved from 4.1 ºC to 0.5 ºC in 5.76 km sensing range with 3 m spatial resolution. With the ability of simultaneously distributed intrusion detection and temperature monitoring, the proposed hybrid sensor shows great potential for long-term real-time pipelines sensing in oil and gas industry.

2. Experimental setup

A MCF containing seven cores has been used in our experiment, as shown in Fig. 1(a). The MCF has 150 μm cladding diameter and 42 μm core-core pitch with the six outer cores arranged hexagonally [4]. Fig. 1 (b) shows the experimental setup. The coherent laser diode has less than 1 kHz linewidth. The CW output light from the laser is modulated by a semiconductor optical amplifier (SOA), which is driven by an electrical pulse generator with 30 ns rectangular wave shape. The pulse is then amplified by an erbium-doped fiber amplifier (EDFA), and followed by an optical band-pass filter to filter out the amplified spontaneous emission (ASE) noise. The boosted pulse is then divided into two paths. The upper one is used as the pump pulse for Φ-OTDR, which is then injected into one of the outer cores. Specifically, a tunable attenuator has been inserted in order to manage the input power. Then the Rayleigh backscattered light is acquired by a 125 MHz photodetector. The other path is used for ROTDR with the

30.8 dBm pump pulse being launched into the central core. At its receiver side, the Raman Stokes and anti-Stokes components are separated by a Raman filter and eventually detected by two 125 MHz avalanche photodiode, respectively. All the detectors are connected to an oscilloscope for data acquisition. The home-made MCF fan-in coupler has less than 1 dB insertion loss for every core. The 5.76 km fiber under test is assigned into several segments for the convenience of applying disturbance at different locations, among which fiber segment A and B are both wound into several loops with ~12 cm diameter, respectively.

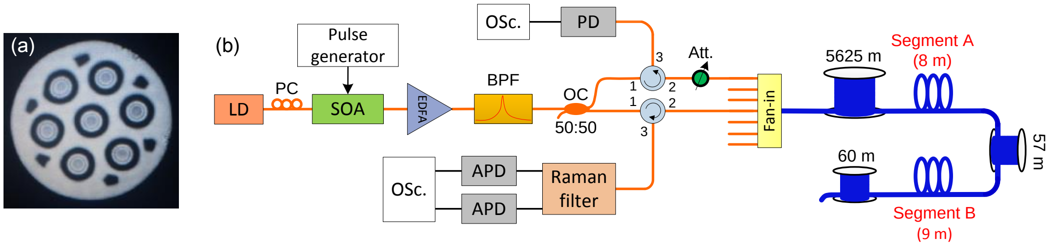

Fig. 1. (a) MCF cross sectional view; (b) Experimental setup; LD: Laser diode; PC: polarization controller; SOA: semiconductor optical amplifier; EDFA: erbium-doped fiber amplifier; BPF: band-pass filter; OC: optical coupler; Att.: tunable attenuator; APD: avalanche photodiode; PD: photodetector; OSc.: oscilloscope.

3. Results and discussion

In the proposed hybrid system, Φ-OTDR and ROTDR share identical pulse generation components, but have different pump powers, which allows for simultaneous measurement of Raman and Rayleigh scattering signals in separate cores of the MCF.

Fig. 2(a) shows the typical Φ-OTDR trace acquired in our experiment. In order to get high signal-to-noise ratio (SNR), 512 averages have been performed. The intensity fluctuation results from coherent Rayleigh interference of the backscattered light within the pulse duration. The intensity contains the local refractive index information of the fiber. Any perturbation applied on the fiber leads to the change of local refractive index, and eventually modifies the backscattered optical intensity. So intrusion can be retrieved by monitoring the intensity variation of Φ-OTDR trace, which is achieved by subtraction between a Φ-OTDR trace and an undisturbed reference trace [5].

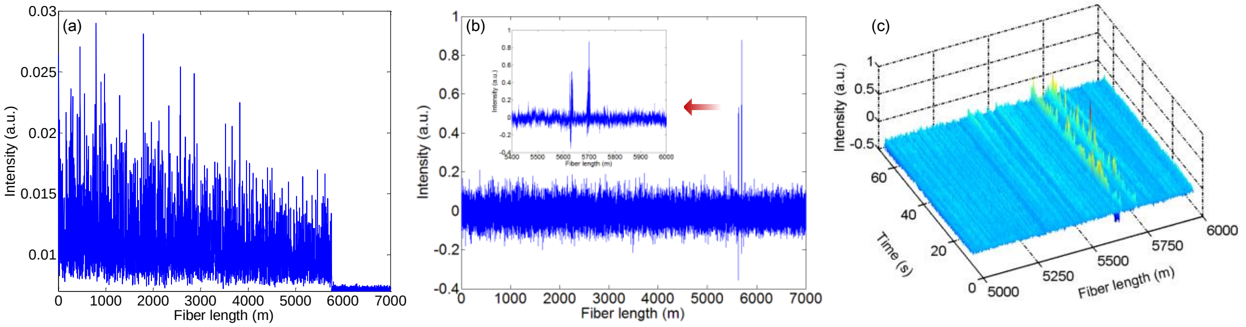

Fig. 2. (a) Typical Φ-OTDR trace; (b) The superimposed 885 consecutive differential Φ-OTDR traces when disturbances are applied at fiber segment A and B; (c) Evolution of differential Φ-OTDR trace as a function of time and fiber length.

Φ-OTDR has the advantage of high sensitivity, capability of multipoint detection, etc. In order to evaluate the performance of Φ-OTDR in the hybrid system, intrusion events were emulated by aperiodically tapping manually on fiber segment A and B; at the same time, the Φ-OTDR traces were consecutively recorded with 100 MS/s sampling rate. Then the raw traces were used to subtract the reference trace, thus the differential response can be obtained. Fig. 2(b) shows the superimposed 885 consecutive differential Φ-OTDR traces when disturbances are applied at fiber segment A and B. The inset presents the magnified view of differential trace around the disturbance places, where intrusion can be clearly identified. The two intensity change regions are locations of fiber section A and B, respectively. It also indicates that no optical intensity change occurs at other undisturbed positions, verifying excellent performance of multi-event detection and positioning. For better observation, the evolution of differential Φ-OTDR trace as a function of time and fiber length has been presented in Fig. 2(c).

On the other hand, the measurement of ROTDR was carried out simultaneously in the central core. DTS based on ROTDR resolves temperature by calculating the power ratio between Raman anti-Stokes and Stokes light [4]. Due to the weak SpRS intensity, the ROTDR traces were averaged by 52100 times. However, it is still found that the traces are quite noisy. To remove the noise and increase the accuracy, wavelet transform denoising (WTD) technique is employed. WTD decomposes the raw signal into a series of frequency bands, then the soft thresholding is set to remove the high frequency noise components, and the denoised signal can be retrieved through inverse wavelet transform [6]. Fig. 3(a) shows the measured raw trace together with the wavelet transform denoised trace. The magnified inset indicates that trace becomes much smother after denoising, giving rise to significant SNR enhancement. A hot-spot with 60 m length was put at the fiber end and was detected, as shown in the inset of Fig. 3(a), in order to evaluate the performance of DTS in the hybrid system.

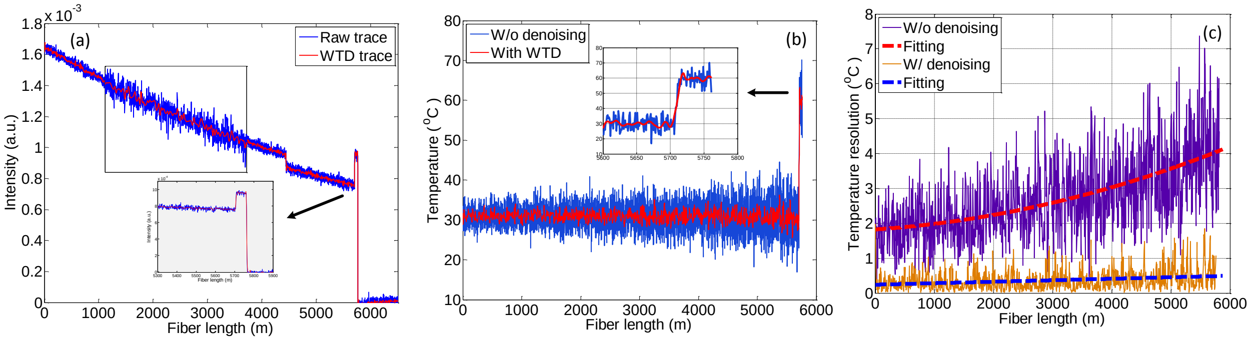

Fig. 3. (a) Raman Anti-Stokes traces; (b) Resolved temperature distribution without and with denoising along the sensing fiber; the inset shows the enlarged view around the hot-spot at the fiber end; (c) Comparison of temperature uncertainties obtained without and with denoising.

For comparison, both the raw trace and the denoised trace have been used to calculate the temperature profile respectively. The resolved temperature distribution along the sensing fiber is presented in Fig. 3(b). It is found that the obtained temperature profile with denoising has much less fluctuations than the one without denoising, which indicates that WTD can significantly reduce the measurement uncertainty. To verify this, the temperature uncertainties without and with denoising have been compared quantitatively by calculating their standard deviations with a window of 5m, as shown in Fig. 3(c). Quadratic fitting has been applied to the calculated temperature uncertainties; the worst temperature uncertainties are estimated to be 4.1 °C and 0.5 °C for the cases without and with denoising, respectively. So it confirms that WTD technique can be used to enhance the SNR of system notably and consequently improve the measurement uncertainty of ROTDR sensors.

In conclusion, we proposed and demonstrated a MCF space-division multiplexed sensing scheme, in which Φ-OTDR and ROTDR are implemented separately in distinct spatial cores of the MCF. The proposed system overcomes the power restriction of the hybrid system in SMFs, enabling simultaneously interrogation of DAS and DTS. Note that only one set of pulse generation devices is required, so the proposed system would be a cost-effective solution for real applications. In addition, wavelet transform denoising technique has been used to enhance the SNR of measurement and reduce the temperature uncertainty of ROTDR, showing excellent performance. The new hybrid DAS and DTS system using MCF based spatial-division multiplexing technology shows great potential in pipelines monitoring in oil and gas industry.

Acknowledgements

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