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Multicore fiber space-division multiplexed reflectometer and interferometer for distributed vibration sensing

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Abstract: Multicore fiber space-division multiplexed reflectometer and interferometer hybrid sensor has been demonstrated to achieve truly uninterrupted distributed vibration sensing with broad vibration frequency response range and high spatial resolution. © 2018 The Author(s)

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1. Introduction

Despite the widely recognized feasibility of phase-sensitive optical time-domain reflectometer (Φ-OTDR) for distributed vibration sensing, the direct detection intensity-demodulation based Φ-OTDR sensor is however suffering from the nonlinear dependency of the backscattered optical intensity on vibration [1], i.e. the local optical intensity generally varies non-periodically on an applied periodical vibration. Therefore, quantitative vibration frequency measurement is actually difficult to be achieved. Although phase- instead of intensity-demodulation has been proposed to obtain the vibration frequency, it is at the expense of system complexity [2], and phase noise will be a severe problem that degrades the performance of system [1, 3]. What's more, the maximal detectable frequency of Φ-OTDR sensors is ultimately limited by the repetition rate of pump pulse, which becomes an intrinsic shortcoming of this technology.

In order to mitigate the limitations of direct detection intensity-demodulation based Φ-OTDR sensors, single mode fiber (SMF) based hybrid Φ-OTDR and Mach-Zehnder interferometer (MZI) sensing system has been proposed, which is able to locate the disturbance point and obtain the vibration frequency simultaneously. The adopted sensing configurations include continuous wave (CW) biased modulated pulses [4], time division multiplexed (TDM) probe light [5], and frequency division multiplexed (FDM) probe light [6]. However, there are some drawbacks in the SMF based hybrid systems. Either the offset CW light and pump pulse degrade each other's performance in terms of signal-to-noise ratio (SNR) for the first scheme, or the maximal detectable frequency is restricted by the temporally separated discontinuous measurements for the TDM scheme, or the reliability of the system gets bad due to the employment of environment sensitive (e. g. temperature change, vibration, etc.) reference fiber for the FDM scheme. In addition, a common drawback of the reported schemes is that the effective sensing length is actually half of the total fiber length due to the fold-back configuration.

In this work, we propose and have experimentally demonstrated a multicore fiber (MCF) based space-division multiplexed (SDM) reflectometer and interferometer hybrid system for distributed multi-point vibration sensing. Among which, the Φ-OTDR is used to locate the disturbance position, and the interferometer is dedicated to retrieving the vibration frequency. The SDM scheme allows for spatially separated implementation for the two sensors, thus the constraint of the hybrid system in SMF can be effectively eliminated. The proposed system enables truly uninterrupted distributed vibration sensing with broad vibration frequency response range and high spatial resolution. In the experiment, 2.42 km sensing range with 1 m spatial resolution and up to 12 KHz vibration sensing has been obtained. The proposed SDM hybrid sensing system provides some advantages over the one using SMF, including simpler data processing procedure, much higher SNR of the demodulated fast Fourier transform (FFT) power spectral density, no frequency dead zone, single-end access, etc.

2. Working principle and experimental setup

In the proposed MCF based SDM reflectometer and interferometer hybrid sensing system, the Φ-OTDR is used to locate the disturbance positions. It perceives the disturbance positions from the measured OTDR trace where the local optical intensity changes, due to the reason that external vibration modifies the local refractive index of the sensing fiber, so the phase difference of light will be varied, eventually the measured Rayleigh backscattered optical intensity will be altered at the perturbation point. However, in the conventional direct detection intensity-demodulation based Φ-OTDR sensor, the backscattered optical intensity variation actually has nonlinear dependency on vibration, so it is difficult to retrieve the vibration frequency precisely.

While in the proposed SDM hybrid system, the measurement of vibration frequency can be carried out by the interferometer instead of the reflectometer. The interferometer is constructed by two parallel spatial cores of the MCF, and its output is delivered to the near-end through another core. Owing to the angular position dependence on bending for a specific curvature radius, the cores of MCF undergo different local tangential strain when fiber is curved [7-8]. Vibration applied on the sensing fiber will alter the curvature of the sensing fiber; as a result the cores will subject to different strain and consequently different phase change between the two arms, eventually leads to the change of output optical intensity of the interferometer. Then the vibration frequency can be obtained by processing the sampled interference spectrum with FFT.

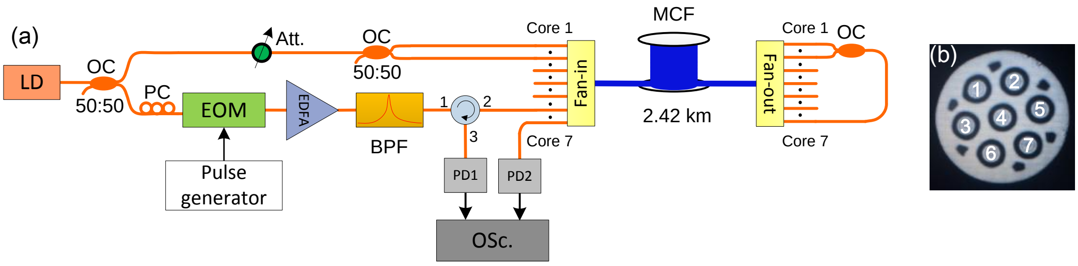

Fig. 1. (a) Experimental setup for the SDM hybrid reflectometer and interferometer sensor. LD: Laser diode; OC: optical coupler; PC: polarization controller; Att.: tunable attenuator; EOM: electro-optic modulator; EDFA: erbium-doped fiber amplifier; BPF: band-pass filter; PD: photodetector; OSc.: oscilloscope. (b) Cross section of the seven-core MCF used in the experiment.

The experimental setup used for the proposed sensing system is shown in Fig. 1(a). A coherent laser source with ~10 kHz linewidth has been used in the experiment, whose coherence length is about 6.4 km. The CW output of laser is divided into two branches through a 50:50 coupler. The upper branch is then further split into two paths for the two arms of the interferometer with a tunable attenuator being inserted to manage the input power flexibly. Light in the two paths are then launched into core 1 and core 2 (see Fig. 1(a)) respectively through a fan-in coupler. The fiber under test (FUT) for proof of concept is a seven core fiber (YOFC, China) with 2.42 km length, whose cross sectional view is shown in Fig. 1(b). At the far end, the output of the two cores from the fan-out coupler is combined again by a coupler, thus a Mach-Zehnder interferometer is constructed, which consists of two long arms. The output of the coupler is then connected to core 7, so the interference signal is transmitted back to the near end, and it is eventually detected by a 125 MHz photodetector. In this way, a configuration with single-end access is enabled, and sufficient optical power is available to ensure high SNR for the interference spectrum. On the other hand, the other branch is used to perform Φ-OTDR. An electro-optic modulator (EOM) driven by an electrical pulse generator with 10 ns duration is used to generate the pump pulse. 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 launched into core 6 through a circulator and the fan-in coupler. At the receiver side of the reflectometer, the backscattered Rayleigh signal is detected by a 200 MHz photodetector. The two detectors are connected to an oscilloscope for data acquisition.

3. Results and discussion

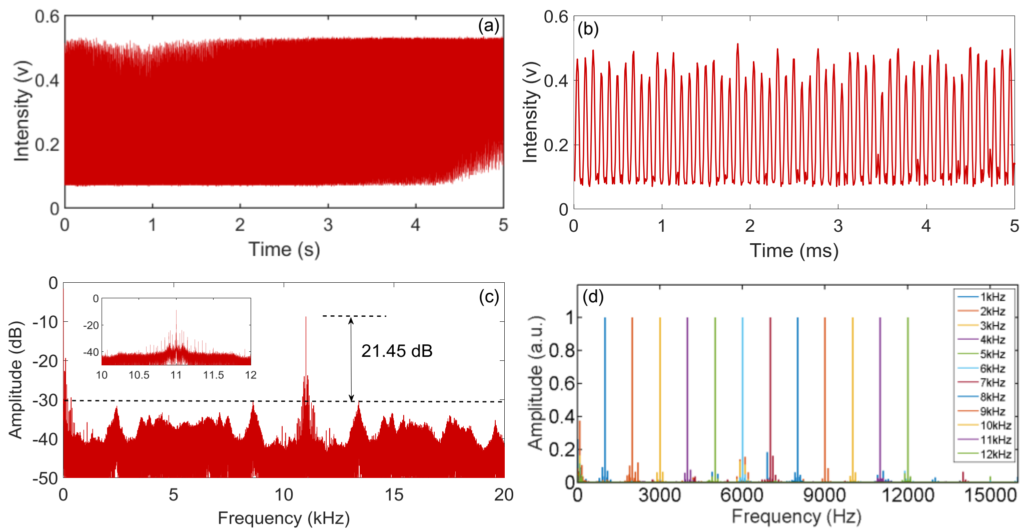

Fig. 2. (a) The measured interference spectrum of MZI when 11 kHz vibration is applied to 1.6 m fiber near the far end of the MCF, and (b) is the zoom-in view of the interference spectrum; (c) is the retrieved frequency spectrum after FFT; the inset shows the enlarged view around 11 kHz; (c) FFT spectra of the interference signal that is obtained by the interferometer when vibration is applied to the sensing fiber from 1 kHz to 12 kHz with 1 kHz interval.

In order to investigate the performance of vibration sensing based on the proposed SDM interferometer, 1.6 m fiber near the far end of the MCF has been wound to a cylindrical piezoelectric transducer (PZT) to generate periodical vibration. Fig. 2(a) shows a typical output interference spectrum of the interferometer that is measured when 11 kHz sinusoidal signal is applied to the PZT, whose zoom-in view is shown in Fig. 2(b), and the retrieved frequency spectrum after FFT is presented in Fig. 2(c), which matches very well with the applied value. The result indicates that sufficient optical power and high fringe contrast is achieved for the interferometer, thus it ensures high SNR for the FFT power spectral density, as confirmed by Fig. 2(c), where 21.45 dB SNR has been obtained. Repeated vibration measurements have been performed by applying different vibration frequency to the PZT from 1 kHz up to 12 kHz (limited by the cut-off frequency of the high voltage driver of PZT) with 1 kHz interval, and the measured intensity normalized frequencies (in linear scale) from FFT have been shown in Fig. 2(d). The result confirms the excellent reliability of the system for vibration sensing, and it also verifies a distinguished SNR of the FFT power spectra, which ensures sufficient SNR budget to achieve very high frequency vibration measurement beyond the one presented in this work.

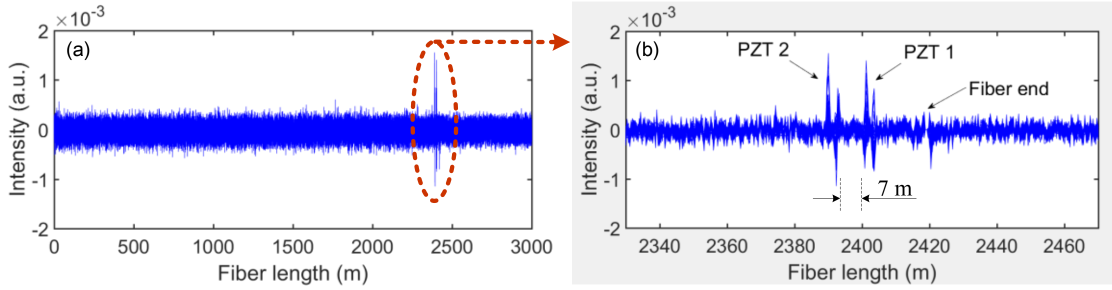

Fig. 3. (a) The superimposed 100 consecutive differential Φ-OTDR traces when vibration is applied to PZT 1 and PZT 2 simultaneously with 500 Hz and 300 Hz, respectively; (b) the enlarged view around the vibration points.

While in practical applications, it is more likely that multiple vibration events occur simultaneously, so experiment has also been carried out to investigate the feasibility of multi-event sensing based on the proposed hybrid sensor. In order to generate two vibration events simultaneously, another 1.9 m fiber has been wound to another PZT, and the distance between the two fiber sections is about 7 m. Two simultaneous vibrations with frequencies of 500 Hz and 300 Hz are then applied to PZT 1 and PZT 2, respectively. For the reflectometer, continuous acquisition of the time-domain traces is performed, and then the differential trace is obtained by employing the subtracting processing procedure, as shown in Fig. 3(a), and a partial view around the vibration points has been presented in Fig. 3(b), where two locations with obvious intensity fluctuation can be observed.

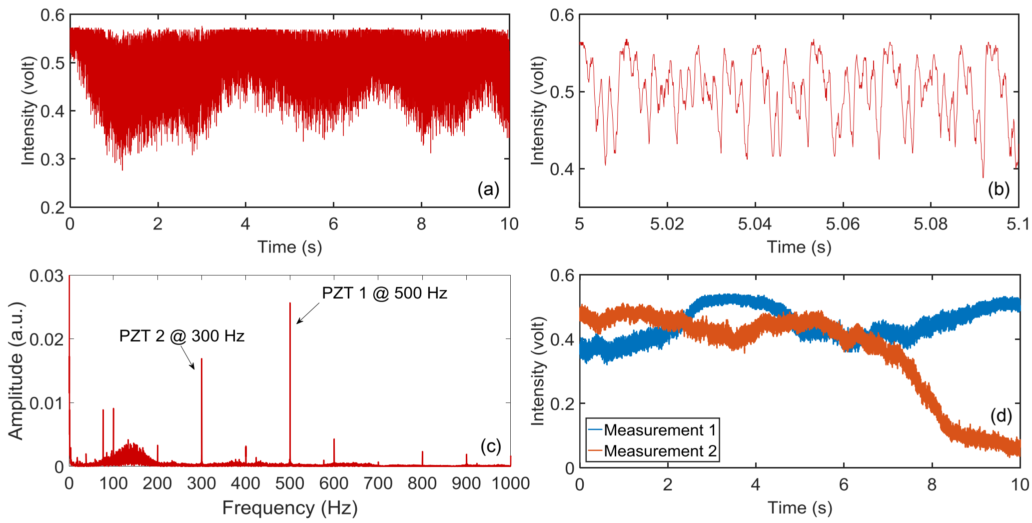

Fig. 4. (a) The measured time-domain interference spectrum of MZI in 10 seconds when vibration is applied to PZT 1 and PZT 2 with 500 Hz and 300 Hz, respectively; (b) zoom-in view of the interference spectrum; (c) the retrieved frequency spectrum after FFT.

Meanwhile, the detection of the interferometer has also been carried out in parallel with the reflectometer. Fig. 4(a) shows the measured interference spectrum of the MZI in 10 seconds when simultaneous vibrations are applied to PZT 1 and PZT 2 with 500 Hz and 300 Hz, respectively. Fig. 4(b) presents a partial view of Fig. 4(a) for better observation. FFT is then performed by using the sampled interference spectrum, and the retrieved frequency spectrum after FFT is presented in Fig. 4(c). Two dominant peaks can be observed at 500 Hz and 300 Hz respectively, which is consistent with the applied values, as marked in the figure. So the feasibility of measurement of multiple vibration frequencies by using the proposed interferometer is verified. Consequently, the experiment demonstrates the capability of detection of multiple simultaneous vibration events with both the locations and frequencies based on the proposed hybrid system. While it should be pointed out that adopting the current acquisition and processing technique, it is unable to determine the frequency of each location. But this problem can be solved by using the frequency mapping method based on the under-sampling technique [6], which compares the measured frequency of interferometer with that of the reflectometer, and each frequency can then be targeted to a specific measured vibration location due to the certain mathematical relation between the undersampled frequency and the actual value.

In order to evaluate the impact of phase noise on the performance of the interferometer, the output spectra of the interferometer without vibration applied on the sensing fiber have been record, as shown in Fig. 4(d). It reveals that the output is not constant but shows intensity fluctuation, which is actually caused by the phase noise that comes from the wavelength drift of the laser and/or the indoor air flow induced shaking on the short free fiber section, etc. However, as can be seen that the phase noise has the feature of low frequency and weak power spectrum density, as can also be seen from Fig. 2 and Fig. 4, so it won't lead to severe detrimental impact on the measurement at all. Apparently, it might lead to slow envelop change of the time-domain interference spectrum of the interferometer, as shown in Fig. 2(a) and Fig. 4(a).

Compared with the hybrid system using SMF, in the proposed SDM system, sufficient optical power can be injected into the sensing fiber for the interferometer, thus much better SNR can be obtained and consequently ensures high measurement accuracy of frequency. Due to the separate implementation of the reflectometer and interferometer, the measured data of the two sensors are independent, which allows for simpler data processing procedure. More importantly, the proposed structure manages to get rid of the detrimental impact of CW light on Φ-OTDR in the hybrid system using SMF. The MCF provides redundant core for the output of the interferometer to be transmitted back to the near-end, therefore singe-end access is enabled. Note that the maximal detectable vibration frequency of the proposed system is essentially determined by the sampling frequency of the oscilloscope and the bandwidth of the photodetector, so apparently it could achieve very broad frequency response range, and there is no dead zone in the detectable range.

Eventually, it should be pointed out that it is difficult to achieve comparable performance by using SMFs bundle instead of the MCF in the proposed system deployment. This is because the MCF has integrated and all-solid cores arrangement. This firm integral fiber structure enables the system to eliminate the common environment noise (e.g. temperature variation), but output the differential response (e.g. vibration induced differential strain). While SMFs bundle can't be as compact and uniform as the MCF along very long range. In this case, it is difficult to ensure that the external environment variation transfers identically to the two arms of the interferometer, especially when the multiple SMFs are bundled loosely, which will cause strong noise. It might even lead to nonlinear relative phase change between the two arms because of the distinct transformation amounts of external disturbance (e.g. temperature and strain). These factors will eventually degrade the accuracy and reliability of the SMFs bundle based system.

In conclusion, we proposed and experimentally demonstrated a MCF based SDM reflectometer and interferometer hybrid system. It allows for independent interrogation of the two sensors, so the constraint of the hybrid system in SMF can be completely eliminated. The proposed SDM system is able to locate multiple vibration point and measure the vibration frequency simultaneously with high reliability, enabling truly uninterrupted distributed vibration sensing with broad vibration frequency response range and high spatial resolution. Therefore, it shows great potential for long-haul distributed vibration sensing applications.

4. References

[1]. X. Fan, G. Yang, S. Wang, Q. Liu, and Z. He, "Distributed Fiber-Optic Vibration Sensing Based on Phase Extraction From Optical Reflectometry," J. Lightwave Technol. 35, 3281-3288 (2017).

[2]. Z. Wang, L. Zhang, S. Wang, N. Xue, F. Peng, M. Fan, W. Sun, X. Qian, J. Rao, and Y. Rao, "Coherent Φ-OTDR based on I/Q demodulation and homodyne detection," Opt. Express 24(2), 853–858 (2016).

[3]. Z. Pan, K. Liang, Q. Ye, H. Cai, R. Qu, Z. Fang, "Phase-sensitive OTDR system based on digital coherent detection," Proc. SPIE 8311, 83110S1-S6 (2011).

[4]. T. Zhu, Q. He, X. H. Xiao, and X. Y. Bao, "Modulated pulses based distributed vibration sensing with high frequency response and spatial resolution," Opt. Express 21(3), 2953–2963 (2013).

[5]. Q. He, T. Zhu, X. Xiao, B. Zhang, D. Diao, and X. Bao, "All fiber distributed vibration sensing using modulated time-difference pulse," IEEE Photonics Technol. Lett. 25(20), 1955–1957 (2013).

[6]. H. He, L. Shao, B. Luo, Z. Li, X. Zou, Z. Zhang, W. Pan, and L. Yan, "Multiple vibrations measurement using phase-sensitive OTDR merged with Mach-Zehnder interferometer based on frequency division multiplexing," Opt. Express 24, 4842-4855 (2016).

[7]. G. M. H. Flockhart, W. N. MacPherson, J. S. Barton, J. D. C. Jones, L. Zhang, and I. Bennion, "Two-axis bend measurement with Bragg gratings in multicore optical fiber," Opt. Lett. 28, 387–389 (2003).

[8]. Z. Zhao, M. A. Soto, M. Tang, and L. Thévenaz, "Distributed shape sensing using Brillouin scattering in multi-core fibers," Opt. Express 24(22), 25211–25223 (2016).