A distributed optical fiber sensing system for synchronous vibration and loss measurement*

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We propose a fully distributed fusion system combining phase-sensitive optical time-domain reflectometry (Φ-OTDR) and OTDR for synchronous vibration and loss measurement by setting an ingenious frequency sweep rate (*FSR*) of the optical source. The relationships between *FSR*, probe pulse width and repeat period are given to balance the amplitude fluctuation of OTDR traces, the dead zone probability and the measurable frequency range of vibration events. In the experiment, we achieve synchronous vibration and loss measurement with *FSR* of 40 MHz/s, the proble pulse width of 100 ns and repeat rate of 0.4 ms. The fluctuation of OTDR trace is less than 0.45 dB when the signal-to-noise ratio (*SNR*) is over 12 dB for a captured vibration event located at 9.1 km. The proposed method can be used for not only detection but also early warning of damage events in optical communication networks.

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The conventional optical time-domain reflectometry (OTDR) has been widely used in the optical communication network failure diagnosis for its advantages of long monitoring distance, accurate location and high safety[1,2]. Although OTDR can detect loss events of an optical fiber, such as broken point, curve and attenuation, it's unable to make early warning of the potential threat and avoid the breaking of communication before it actually happens[3,4]. These potential threat events, such as broken points caused by engineering construction, usually disturb the fiber through vibration field even if the threat event is still far away from the fiber. This means that it is possible to make an early warning if the disturbance on the fiber can be identified. The phase-sensitive OTDR (Φ-OTDR) has been applied in many fields in recent years for its ability in distributed vibration sensing along the sensing fiber with fast response and high sensitivity[5-7]. However, narrow linewidth laser source with stable frequency must be utilized to generate high interference visualization for the Φ-OTDR system, which will introduce strong fading noise to the measurement result of Rayleigh backward scattering (RBS) power and make some regions of Φ-OTDR traces always in destructive interference area, leading to the occurring of dead zones[8,9]. To achieve traditional optical communication network monitoring and threat precaution at the same time, we present a fusion system based on ingenious frequency sweep of the laser source. By setting an appropriate frequency sweep rate (*FSR*), synchronous measurement on vibration and loss events is achieved, and dead zones in Φ-OTDR can also be suppressed at the same time.

In Φ-OTDR system, the Rayleigh backward scattering light returned from the sensing fiber exhibits a jagged appearance due to coherent interaction of a large number of random scattered waves within the probe pulse[8]. When a coherent pulse with duration of W and frequency of f is injected into the sensing fiber, the average power of RBS $P_1(t)$ and the power of the coherent part $P_2(t)$ will form the final result, which can be described respectively as[10]

$$P_1(t)=\sum_{i=0}^{I}a_i^2\exp\left(-2\alpha\frac{c\tau_i}{n_f}\right)rect\left(\frac{t-\tau_i}{W}\right), \quad (1)$$

$$P_2(t)=2\sum_{i=1}^{I}\sum_{j=i+1}^{I}a_ia_j cos\Phi_{ij}\exp\left[-\alpha\frac{c(\tau_i+\tau_j)}{n_f}\right]\times rect\left(\frac{t-\tau_i}{W}\right)rect\left(\frac{t-\tau_j}{W}\right), \quad (2)$$

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where a_i and τ_i are the amplitude and delay of the ith scattered wave, respectively. $\tau_i=2n_f z_i/c$, and z_i is the distance between the scattering centre and the input end. α is the attenuation of optical fiber, c is the velocity of light in vacuum, n_f is the refractive index, and I is the total number of scatters. $rect[x]=1$ when $0\le x\le 1$, otherwise $rect[x]=0$. $\Phi_{ij}=\Phi_j-\Phi_i=4\pi f n_f(z_j-z_i)/c$ denotes the phase difference between the ith and jth scatters.

It is obvious that $P_1(t)$ denotes the loss along the fiber, and $P_2(t)$ denotes the coherent effect within the pulse. When external perturbation is applied on the sensing fiber, the jagged pattern of the RBS trace at the corresponding position will also be changed. Thus, the interference component $P_2(t)$ changes, while $P_1(t)$ keeps stable. However, due to the randomly distributed reflectivity and position of scattering point within the optical fiber, the interference result can only be described statistically[11], and amplitude destructive interferences can happen at some specific positions. Hence, the coherent fading noise of OTDR traces cannot be suppressed by accumulation because the adjacent Φ-OTDR traces are not independent. And the dead zones happen since the signal amplitude at these specific positions reaches near zero which will lead to big errors in retrieving phase factor from the amplitude. In order to suppress the coherent fading noise and the dead zones, we actively tune the light source with an ingenious *FSR* and make the amplitude of destructive interference area change. This is because the amplitudes of the Φ-OTDR traces are Rayleigh distributed while the laser frequency changes continuously[8]. However, light source tuning may also degrade the ability of broad band vibration event identification for the Φ-OTDR sensing system. Therefore, the balance has to be made among the amplitude fluctuation of OTDR traces, the dead zone probability and the measurable frequency range of vibration events.

When the frequency interval between two adjacent traces is Δf, the similarity of Φ-OTDR traces in different frequencies can be described by the cross-correlation (CC) value as[12]

$$C[\Delta f,W]=\frac{\sin^2(\pi\Delta fW)}{(\pi\Delta fW)^2}. \tag{3}$$

On one hand, the Φ-OTDR traces can be seen to be independent when $\Delta f>10$ MHz, at which time CC value is lower than 0.01%. Thus *FSR* should be large if well suppression on the fading noise and dead zone is desired. One the other hand, to ensure the precision of Φ-OTDR, the CC value between two adjacent Φ-OTDR traces should be high enough[13]. Taking 99.99% for example, Δf would be limited to $\Delta f<0.001\,7/W$ according to Eq.(3). This means that there is also an upper limit for *FSR*. Let the pulse period to be T, *FSR* can be described as

$$FSR<\frac{0.001\,7}{W\times T}. \tag{4}$$

In our demonstration, W=100 ns and T=0.4 ms. Therefore, the maximum acceptable *FSR* is 42.5 MHz/s according to Eq.(4). To suppress coherent fading noise and dead zone, we set *FSR* to be 40 MHz/s in the experiment to obtain enough independent Φ-OTDR traces. If N independent traces are obtained, coherent fading noise will be suppressed by a factor of $1/(N)^{0.5}$ simply after accumulation. Let the probability of dead zones happening at certain position to be P, and then the probability P_{FS} for the same position always in the dead zone can be described as

$$P_{FS}=P^N. \tag{5}$$

That means if enough independent traces are obtained, the probability P_{FS} of dead zones always happening at certain position will be very close to zero, and the dead zone of Φ-OTDR can be considered to be eliminated.

Contrary experiments are made to prove the validity of our method. The structure of the demonstration system is shown in Fig.1. A tunable laser source (TLS) with 1 kHz line-width is used as the light source, and its optical frequency is tuned by the personal computer (PC). The output light from TLS is stabilized to 15 dBm by erbium doped fiber amplifier 1 (EDFA1) to suppress the power fluctuation induced by the change of wavelength. Then the output of EDFA1 is shaped to optical probe pulse with the high extinction ratio modulator which consists of electro-optic modulator (EOM), optical switch (OS), photo diode (PD) and stabiliser[14]. The period T is 400 μs and the width is 100 ns (10 m spatial resolution) for the probe pulse. The probe pulse is further amplified by EDFA2 to 22 dBm, and the amplified spontaneous emission (ASE) noise is eliminated by the fiber Bragg grating (FBG) filter. Then the probe pulse is launched into a 34-km-long sensing fiber through an optical circulation (CIR). The vibration event is induced by a cylindrical piezoelectric ceramic (PZT) located at 9.1 km. The length of the fiber wrapped on PZT is about 10 m. The RBS is received by an avalanche photo diode (APD) receiver. A 5 MHz low pass filter (LPF) is used to remove the broadband noise of APD output. The output of LPF is gained by the amplifier (AMP) and converted into digital signal by a data acquisition card (DAQ) with a sampling rate of 50 MSa/s (corresponding to 2 m sampling interval) for further processing with PC. The pulse generator is used to trigger the high extinction ratio modulator and DAQ synchronously.

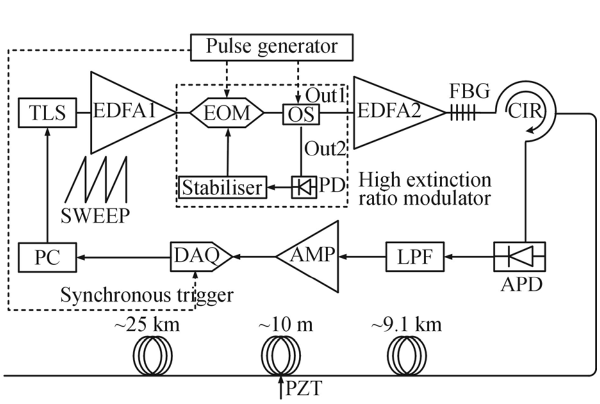


Fig.1 Schematic diagram of experimental setup

In our experiments, 2^{13} Φ-OTDR traces are obtained in 35 s with a frequency sweep range of 1.4 GHz. At least 4 independent Φ-OTDR traces can be obtained within 1 000 adjacent traces, which is good enough to suppress the fading noise efficiently. And the dead zone can also be greatly cancelled without sacrificing the broad band vibration event identification ability of the sensing system.

Fig.2 shows the experimental results of the 100 adjacent Φ-OTDR traces. The differential signal (down lines) can be gotten by subtracting two adjacent traces (up lines). When a 150 Hz sinusoidal stretching is applied to the sensing fiber at 9.1 km, we can not identify the event from differential signal of conventional Φ-OTDR without frequency sweep as shown in Fig.2(a), which is exactly the influence of dead zone. After applying *FSR* of 40 MHz/s, an obvious event peak at 9.1 km can be observed as shown in Fig.2(b).

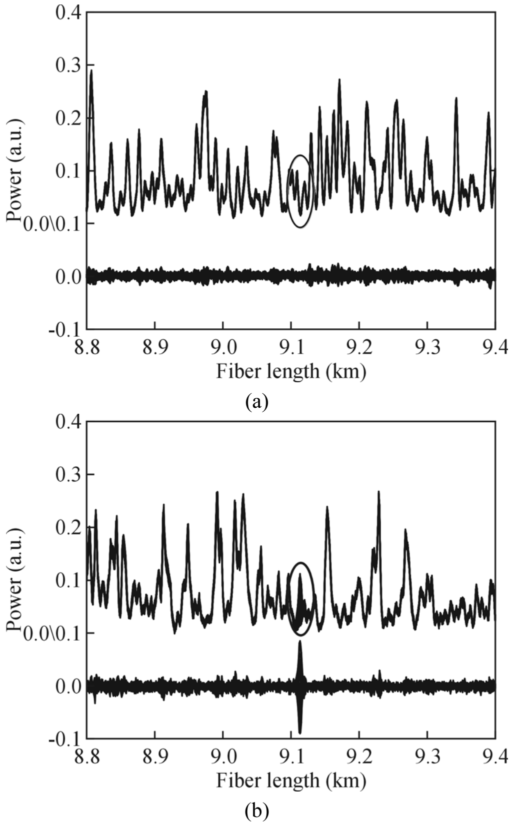


Fig.2 100 Φ-OTDR traces (up) and their superimposed differential signals (down) (a) without and (b) with frequency sweep

The amplitude variation versus time of the vibration location with *FSR* of 40 MHz/s is shown in Fig.3(a). It is obvious that amplitude destructive interferences happen from 510 ms to 630 ms at which time the mean amplitude of the RBS is only 0.03 V. While at other time, the amplitude is strong enough to identify the disturbance events. Fig.3(b) shows the power spectrum of corresponding vibration event. 150 Hz frequency can be clearly observed, and the signal-to-noise ratio (*SNR*) in power spectrum is 12 dB.

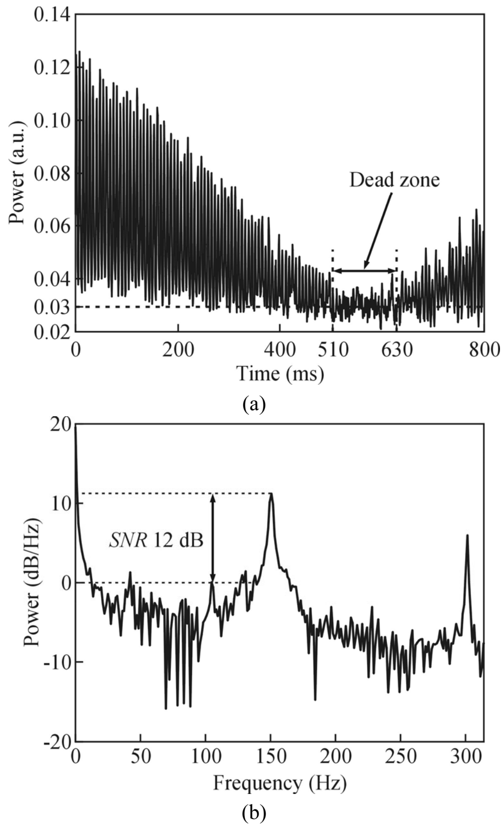
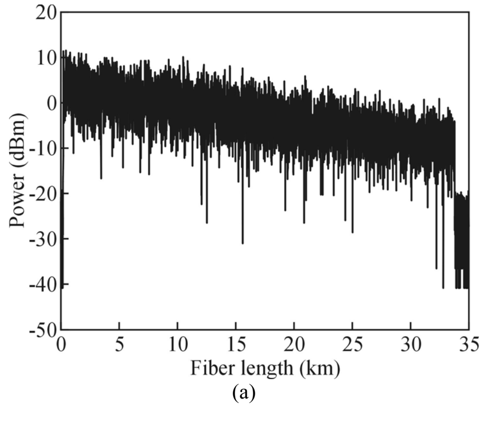


Fig.3 (a) Time domain signals at vibration location; (b) Frequency response of vibration event

Fig.4(a) and (b) show the OTDR traces with 2^{10} and 2^{13} Φ-OTDR traces without frequency sweep, respectively. The amplitude fluctuations of the OTDR traces are 2.965 1 dB and 2.842 2 dB, respectively. This result indicates that the amplitude fluctuations of the OTDR traces are strong, and accumulation has little benefit to the result since the obtained traces are of similar jagged appearance. After applying light source tuning, the amplitude fluctuations of the OTDR traces with 2^{10} Φ-OTDR traces is 0.820 1 dB as shown in Fig.4(c). For 2^{13} Φ-OTDR traces, the fluctuation of OTDR traces can be further decreased to be 0.432 6 dB as shown in Fig.4(d), which is good enough to distinguish attenuation events in most situation. The peak dynamic range of this system is around 28 dB, corresponding to a maximum sensing length of 70 km with the fiber loss coefficient is 0.2 dB/km.



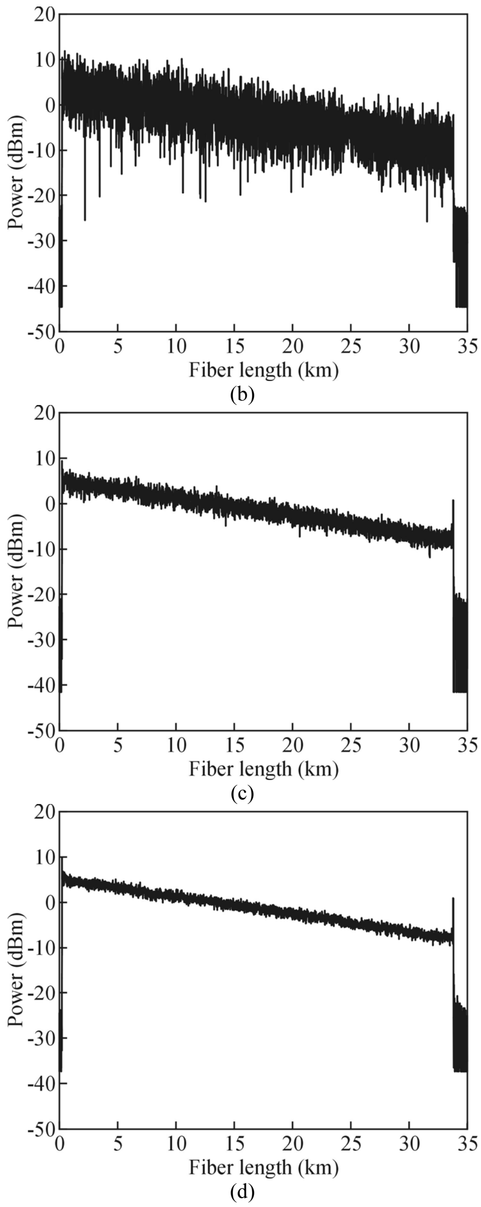


Fig.4 Accumulative results of 2^{10} and 2^{13} Φ-OTDR traces with and without frequency sweep

In conclusion, we present a fully distributed fusion system combining Φ-OTDR and OTDR for synchronous vibration and loss measurement by setting an ingenious *FSR* of the optical source. The relationships between *FSR*, probe pulse width and repeat period are given to balance the amplitude fluctuation of OTDR traces, the dead zone probability, and the measurable frequency range of vibration events. The proposed method can be used for not only detection but also early warning of the potential threat, and can avoid the breaking of communication before it actually happens.

References

[1] L. E. Y. Herrera, G. C. Amaral and J. P. von der Weid, Applied Optics **55**, 1177 (2016).

[2] Jia Liu, Jin-long Yu, Jing-zhong Guo, Chao Gao, Wenrui Wang and En-ze Yang, Optoelectronics Letters **7**, 458 (2011).

[3] G. C. Amaral, J. D. Garcia, L. E. Y. Herrera, G. P. Temporao, P. J. Urban and J. P. von der Weid, Journal of Lightwave Technology **33**, 5025 (2015).

[4] Chuan-qi Li, Da-chi Wang and Jin-lin Hu, Optoelectronics Letters **10**, 144 (2014).

[5] Ren M., Lu P., Chen L. and Bao X., IEEE Photonics Technology Letters **28**, 697 (2016).

[6] Qin Li, Chun-xi Zhang, Li-jing Li, Sheng Liang, Xiang Zhong and Chuan-sheng Li, Journal of Optoelectronics·Laser **25**, 631 (2014). (in Chinese)

[7] Zheng-pu Peng, Yun-jiang Rao, Fei Peng, Hui-juan Wu, Xin-hong Jia and Xiao-yu Li, Journal of Optoelectronics·Laser **25**, 724 (2014). (in Chinese)

[8] Wang Z., Pan Z., Fang Z., Ye Q., Lu B., Cai H. and Qu R., Optics Letters **40**, 5192 (2015).

[9] Jun Zhou, Zhengqing Pan, Qing Ye, Haiwen Cai, Ronghui Qu and Zujie Fang, Lightwave Technology **31**, 2947 (2013).

[10] Ling Zhou, Feng Wang, Xiangchuan Wang Yun, Pan, Zhenqi Sun, Ji Hua and Xuping Zhang, Photonics Technology Letters **27**, 1884 (2015).

[11] Wojcik Aleksander Karol, Signal Statistics Of Phase Dependent Optical Time Domain Reflectometry, Texas A&M University, 2007.

[12] Fan Zhu, Xuping Zhang, Lan Xia, Zheng Guo and Yixin Zhang, IEEE Photonics Technology Letters **27**, 2523 (2015).

[13] Shimizu K., Horiguchi T. and Koyamada Y., Lightwave Technology **10**, 982 (1992).

[14] Yixin Zhang, Xuelin Wu, Zhoufeng Ying and Xuping Zhang, Electronics Letters **50**, 1014 (2014).