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Time-slot multiplexing based bandwidth enhancement for fiber distributed acoustic sensing

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Dear editor,

The phase-sensitive optical time-domain reflectometry (φ-OTDR) has been demonstrated as the most common technique in fiber distributed acoustic sensing (DAS). However, traditional φ-OTDR based DAS suffered from the inherent trade-off between the maximum frequency response and the distance which can be characterized by distance bandwidth product (DBP), since the time interval of the probe pulses should be larger than the pulse round-trip flight time. In order to broaden the detection bandwidth of the DAS system, a lot of work so far has been developed. The most common technique is frequency division multiplexing (FDM), in which multiple measurements can be realized by injecting multiple frequency components into sensing fiber at the same period of the pulse emission and the DBP limitation can be broken [1–3]. However, the crosstalk among small spacing frequencies induced by harmonic components will deteriorate the acoustic sensing performance such as the SNR. In addition, the multi-frequency modulation and frequency sweeping greatly increase the complexity of the system. Besides, there are other methods such as non-uniform sampling [4], compressing sensing [5], and utilizing Vernier effect [6], but they can only detect special signals without universality. Recently, an interleaved chirped pulses scheme is proposed to multiply the bandwidth of the fiber DAS [7]. However, the complexity of the system is increased since frequency sweeping and pulse compression are introduced. Overall, there still exists further space to improve the high frequency detection performance of the long-sensing range fiber DAS.

In this study, a bandwidth enhancement technique for fiber DAS based on the backscattering enhanced fiber (BEF) and time-slot multiplexing method is proposed and demonstrated, which could effectively extend the maximum measurable frequency of the long-distance fiber DAS without increasing the complexity of the system. The experimental results prove that a 100 kHz acoustic wave is recovered precisely with a 300 kHz detection bandwidth over 1020 m sensing fiber, and the DBP can be extended to 6 times as large as that of traditional DAS systems without SNR deterioration.

Principle. First, the scattering characteristic of the single mode fiber (SMF) and BEF is simulated, and the results are illustrated in Figure A1. The Rayleigh backscattering signal (RBS) of the SMF in one pulse width was obtained which shows random fluctuating intensity peaks as illustrated in Figure A1(b). As shown in Figure A1(c), 3 signal traces along the fiber can be obtained by probing 3 pulses, which are shown as continuous random intensity traces. Consequently, in order to avoid the overlap between two adjacent traces, the pulse duration T should be larger than the transmission time of one single pulse ($2n_{\mathrm{eff}}L/c$, n_{eff} is the refractive index, L is fiber length, and c is light velocity), then the response bandwidth of the fiber DAS is limited. While for BEF, the reflectivity of one backscattering enhanced point (BEP) is much larger which was set to 10 dB higher than the Rayleigh scattering point (RSP) in the simulation, and the signal exhibits enhanced reflected peak as depicted in Figure A1(e). Hence, the backscattering intensity distribution of the whole BEF presents the form of a series of discrete peaks. A simulation result of 3 separated BEF intensity traces is presented in Figure A1(f), in which the fiber contains 11 BEPs corresponding to 11 discrete peaks with the equal interval of 10 m. Consequently, the time slots between the adjacent discrete peaks provide redundant time resources to reduce the necessary interval of adjacent probe pulses, and further the response bandwidth of fiber DAS could be raised.

Based on the special characteristics of discrete intensity peaks and time slots of the signal trace from BEF, the time-

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slot can be multiplexed to increase the highest response frequency. As illustrated in Figures B1(a) and (b), the SMF and BEF respectively show the characteristics of continuous distribution and discrete peaks. For the SMF, the repetition period of the probe pulses (T) should be larger than the one pulse transmission time along the fiber. While, for the BEF shown in Figures B2(c)–(g), the later trace can be inserted into the time slot of the last trace, which means that the later pulses can be injected without waiting for the last one to return. Consequently, multiple intensity traces can be multiplexed into one period, and thus the repetition time of the probe pulse can be shortened to $T/(n+1)$, in which n is the multiplexing coefficient, i.e., the multiplexing number whose value is a non-negative integer. Take $n=1$ for example, the repetition period is $T/2$, then the first half of the later trace is inserted into the second half of the last trace, which makes the sampling rate of the DAS system twice as high as the SMF. And so on, the sampling rate and the DBP can be improved to $(n+1)$ times without crosstalk and distortion. It should be noted that the enhancement of DBP is limited by the spatial interval of two adjacent BEPs and the duration of each BEP peak, and the maximum number of multiplexed traces can be calculated as Eq. (B1), as well as the DBP of the BEF based DAS system can be expressed as Eq. (B2). Consequently, through narrowing the injected pulse and increasing the interval of two BEPs, the DBP of the system can be greatly enhanced. Another important issue is the trace demultiplexing and demodulation which is exhibited in Figure C1. Firstly, the correlation mechanism is utilized to locate the starting point of a single trace and distinguish the different backscattered traces. Then, by demodulating the phase difference between two adjacent BEP peaks through the IQ demodulation method, the phase information along the whole fiber can be obtained. Finally, the demodulated results can be realized by recombining the phase values in the order of traces insertion.

Experimental setup and results. The experimental setup of the system is depicted in Figure D1. Firstly, a single pulse trace without overlap is measured in advance under the sampling rate of 1 kHz to act as the reference signal. As illustrated in Figure D2(a), the round-trip time is 10.2 µs, which means the highest scan rate is 98 kHz for traditional fiber DAS. We first carry out a double bandwidth enhancement experiment. As demonstrated in Figure D2(b), with a pulse repetition of 5 µs, the BEPs of superimposed trace become much denser because the latter trace is inserted into the time slot of the previous trace. Cross-correlation between the multiplexed trace and the reference trace is calculated to perform demultiplexing which is depicted in Figure D2(c). The demodulated time domain and power spectral density (PSD) results of a 50 kHz sinusoidal signal through the time-slot multiplexing scheme are shown in Figures D2(d) and (e), which presents a peak located at 50 kHz with an SNR of 46.7 dB. Hence, it has been proved that the time-slot method can recover the acoustic signal successfully and correctly. Further, the pulse repetition rate is increased to 3 times (313 kHz), 4 times (418 kHz), 5 times (520 kHz), and 6 times (600 kHz) of the traditional system respectively. As demonstrated in Figures D3(a)–(d), with more pulses inserted, the sampling points of sinusoidal wave become more and more, leading to a higher waveform fidelity. The PSD shown in Figures D3(e)–(h) demonstrated that the SNR of the recovered waveforms keep above 48 dB as the number of multiplexing pulses increases, indicating that there is no SNR degradation.

Here, the pulse width is 30 ns and the adjacent BEP's interval is 200 ns. Then, there is a 170 ns time-slot between the two peaks reflected from the adjacent BEPs, which can insert up to 5 additional BEP peaks corresponding to $n=5$. Therefore, the DBP of the DAS system based on time-slot multiplexing method can theoretically reach $6c/2n_{\mathrm{eff}}$ according to Eq. (B2), which is 6 times of the traditional fiber DAS with DBP value of $c/2n_{\mathrm{eff}}$. In the experiment, the pulse repetition rate of 600 kHz was set to detect the acoustic signal which can realize a 300 kHz frequency response. As an example, a 100 kHz sine wave is applied at the position of 1010 m, and the demodulated signals with high fidelity are illustrated in Figure D4. The PSD result shows a peak located at 100 kHz with a high SNR up to 48 dB. Besides, it is proved that the system can achieve 300 kHz Nyquist bandwidth according to the frequency domain result, which cannot be realized in the traditional DAS system.

Conclusion. This study proposes and demonstrates a novel scheme based on the discrete characteristic of BEF and time-slot multiplexing method to extend the response bandwidth of optical fiber DAS without introducing any extra complexity of the system. The experimental results prove that the sensing performance such as SNR has no degradation with the increase of multiplexing number beyond the DBP limitation. Moreover, an ultimate acoustic wave signal frequency of 100 kHz is recovered precisely with a 300 kHz detection bandwidth over 1020 m sensing fiber, indicating that the DBP is 6 times that of the traditional single pulse DAS system. This method can extend the upper measurable frequency of fiber DAS, which provides a meaningful technique for long-distance and high-frequency detection applications such as railway health monitoring, pipeline detection and power cable partial discharge monitoring.

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Supporting information Appendixes A–E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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