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Spatial resolution improved OFDM-BOTDA utilizing frequency-division-multiplexed Brillouin phase/gain spectrum

Can ZHAO, Hao WU* & Ming TANG

Wuhan National Laboratory for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China

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Dear editor,

In the up-to-date dynamic measurement occasion, the traditional BOTDA (Brillouin optical time-domain analysis) measurement method of point-by-point frequency sweep fundamentally limits the measurement efficiency of the system, making it difficult to meet new application requirements, such as seismic activity detection, intrusion sensing, and dynamic measurement of civil structural health monitoring. To relieve the urgency of BOTDA for dynamic sensing, several sweeping free variants of traditional BOTDA schemes have been proposed, including slope-assisted BOTDA [1], optical frequency-agile technique [2], and multiple pump-probe pairs [3]. However, these methods suffer from either limited dynamic measurement range or high complexity and cost.

Recently, other kinds of BOTDA using optical orthogonal frequency division multiplexing (OFDM) probe have been reported [4], which can even realize Brillouin spectrum measurement with a single shot [5], making it promising for dynamic sensing. However, a major obstacle hindering its wider application is that the spatial resolution, which is determined by the duration of the OFDM symbol, is inversely related to the frequency offset of the adjacent subcarriers, which determines the Brillouin frequency shift (BFS) measurement accuracy. The contradiction between the spatial resolution and measurement accuracy is inherent, which means that the pursuit for higher spatial resolution will lead to worse frequency accuracy in a conventional BOTDA using an OFDM probe. Although a modified scheme using multiple pump pulses is proposed to improve the spatial resolution to be 12.5 m [6], the conflict has not been well relieved. In fact, the tradeoff between the spatial resolution and accuracy stems from the traditional BFS extraction method by curve fitting the measured Brillouin gain spectrum (BGS). It implies that this problem can be solved if an appropriate BFS extraction method is utilized. In previous reports, the Brillouin phase spectrum (BPS) is considered as a promising candidate for BFS location, due to its quasi linearity in the vicinity of BFS, which shows greater sensitivity to intensity variation near the Brillouin gain peak. Besides, the ratio of BPS to BGS (called K spectrum) is theoretically linear within the whole spectrum width, which has been used to implement dynamic sensing with wide range [7]. In this way, the BFS recovery is quite straightforward, similar to the slope-assisted technique. Moreover, the tradeoff between the spatial resolution and measurement accuracy can be well alleviated. As has been demonstrated, the BGS and BPS can be both easily reconstructed by BOTDA using OFDM probe [4, 8]. Thus, the spatial resolution is expected to be remarkably improved by using larger subcarrier frequency spacing, while a reasonable BFS accuracy can be maintained if the ratio of BPS to BGS is exploited for BFS extraction.

In this study, we propose a spatial resolution improved scheme by employing the ratio of BPS to BGS for BFS location in BOTDA using OFDM probe with direct detection. In our scheme, due to the frequency division multiplexing feature, a multiple K spectrum can be inherently constructed (detailed in Appendix A), which is demonstrated to improve the measurement accuracy. A proof-of-concept experiment is carried out using a 1.8 km long single mode fiber with a 50 ns pump pulse and 63 ns OFDM probe symbol which corresponds to a theoretical resolution of 6.3 m. The results show that the spatial resolution is significantly improved to be about 6.8 m, while the standard deviation of the BFS along the fiber is less than 1.5 MHz.

Experimental setup and results. The experimental setup of the multiple K spectrum BOTDA using OFDM probe is depicted in Figure C1, which is similar to our previous work [4]. In [4, 5], the nominal frequency spacing is about 4 MHz or 2 MHz, corresponding to 25 m and 50 m spatial resolution. In our setup, the nominal subcarrier spacing is

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[*] Corresponding author (email: wuhaoboom@qq.com)

about 15.6 MHz, which corresponds to a spatial resolution of about 6 m. To implement a BOTDA based on K spectrum, the slope should be calibrated. In the experiment, the number of subcarriers is increased to 128 and a constant amplitude zero autocorrelation (CAZAC) sequence is used to generate OFDM signals with a lower peak-to-average power ratio (PAPR). As shown in Figure D1(a), a representative result of the measured K spectrum is presented. It can be seen that the measured results show good linearity with a linear range of about 80 MHz, which is much larger than that of the BGS and BPS. Through linear fitting, the absolute slope of the linear region is about 0.075, which is quite close to the theoretical value of 0.053 ($2/\Delta v_B$). By processing all the OFDM signals, the K spectrum along the fiber is achieved. As shown in Figure D1(b), the profile of the measured K spectrum indicates a good uniformity of linearity and the slope keeps nearly constant along the fiber. The spikes out of the linear range can be attributed to the noise.

Based on the above results, multiple K spectrum experiments are carried out. In the experiment, the total number of the subcarriers is 32 and the even subcarriers are set zero. To avoid optical carrier crosstalk (detailed in Appendix B) and ensure enough frequency offset between the optical carrier and the sensing subcarriers, only the subcarriers with the index of 9, 11, 13, 15 are used for multiple K spectrum measurement. The BFS is extracted in two steps: first, calculate the ratio of the Brillouin phase to gain of each subcarrier (denoted as K value); second, take the index of the subcarrier whose K value is the closest to zero, then the BFS is calculated as follows:

$$\mathrm{BFS} = k \cdot K_{\mathrm{near0}} + k_{\mathrm{near0}} \cdot \Delta f + \Delta v_0, \tag{1}$$

where k is the slope of the K spectrum, K_{near0} is the K value closest to zero, k_{near0} is the subcarrier index corresponding to K_{near0}, Δf is the nominal frequency spacing of adjacent subcarriers, Δv_0 is the frequency spacing between the optical carrier and pump.

Using the obtained K values, the BFS distribution along the fiber is calculated according to (1). For comparison, the BFS distribution calculated using only the 13th subcarrier is also displayed in Figure D1(c). As shown in the figure, the measured BFS distribution consists of a longer leading part with a BFS of about 10.715 GHz and a tail of 10.745 GHz. The variance of the BFS distribution calculated using multiple K spectrum is about 1.5 MHz, while that of the BFS using the 13th subcarrier is as high as 3.3 MHz. Thus, the accuracy improvement from multiple K spectrum has been demonstrated. Most importantly, the spatial resolution of the system can be notably improved with increased frequency spacing of adjacent subcarriers. By inspection of the transition area near the fiber end, it is clear that the spatial resolution has been improved from tens of meters to 6.8 m, as shown in Figure D1(d).

It should be noted that the spatial resolution is still restricted by the optical pump pulse width, theoretically. Previously, the tradeoff between the BFS measurement accuracy and OFDM symbol duration seriously hinders the improvement of spatial resolution. This situation is effectively alleviated to some extent by multiple K spectrum techniques. In our experiment, the pulse width is set to 50 ns, considering a larger K spectrum linear range, which poses a fundamental limit for spatial resolution improvement. However, a narrower pulse width is actually feasible by exploiting pulse engineering, such as pre-pump pulse, dark pulse, which should be further studied in future work. But the BFS variance will increase as a narrow pump pulse width results in a reduced measurement SNR. Thus, we should optimize the symbol length and pump pulse width to obtain a spatial resolution with reasonable BFS variance. Besides, for a given OFDM symbol length and pulse width, the spatial resolution is determined and invariant with fiber length, but the BFS variance will increase with a longer fiber length due to reduced SNR. It is worth noting that the multiple K spectrum approach is demonstrated in our proposed direct detection scheme, but is also applicable to other systems including coherent OFDM and digital optical frequency comb. Last but not the least, the K spectrum owns distinct features such as simplicity in BFS extraction, independence from pump power variation [9], thus wider applications can be expected.

Conclusion. We have proposed and experimentally demonstrated a spatial resolution improved BOTDA using OFDM probe with a multiple K spectrum technique. A proof-of-concept experiment is implemented using an about 2 km fiber with a spatial resolution of about 6.8 m and a BFS variance of about 1.5 MHz, implying the measurement accuracy is not greatly affected by the improvement of the spatial resolution. The spatial resolution can be further improved by increasing the subcarrier frequency spacing together with the assistance of pump pulse engineering.

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Supporting information Appendixes A–D. 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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