Addressable Brillouin Random Fiber Lasing Resonance with High Optical Signal-to-Noise Ratio for Distributed Vibration Sensing

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***Abstract*—Addressable Brillouin random fiber lasing oscillation with 50 dB high optical signal-to-noise ratio was proposed and demonstrated for distributed vibration signal localization along 2.5 km.**

Keywords—Random fiber laser; Rayleigh scattering; stimulated Brillouin scattering; fiber sensing

I. INTRODUCTION

Random fiber lasers (RFLs) differ from traditional mirror-based cavity-structured lasers by utilizing weak Rayleigh scattering (RS) originating from the inhomogeneity along long-span silica fibers as the feedback [1]. Random lasing resonance with various fiber gain mechanisms can be formed, such as Raman scattering [2], Brillouin scattering [3], and rare-earth-doped fiber amplification [4], which has gained widespread attention because of its enormous potential in optical sensing and communication [1]. Traditionally, the laser resonant cavity can be flexibly utilized as a distributed laser sensor for sensitivity enhancement as well as configuration simplification, for instance, by employing the Raman gain mechanism [5]. More recently, a distributed fiber sensing system based on RS-based RFL has been demonstrated, in which the phase noise of the laser can be highly suppressed while the linewidth automatically turns to be narrow, benefiting a phase-sensitive optical time-domain reflectometer (φ-OTDR) without the need of extra high-coherence laser source injection [6]. Nevertheless, random fiber lasing resonance suffers from rather low optical signal-to-noise ratio (OSNR) of 23 dB due to amplified spontaneous emission in broadband Erbium-doped fiber amplification, leading to limited sensing distance along 63 m optical fibers, which is not favorable for practical long-distance sensing systems.

In this work, we proposed and experimentally demonstrated addressable Brillouin random fiber lasing resonance (ABRLR) with 50 dB OSNR for vibration sensing. Stimulated Brillouin scattering (SBS) along a 2 km single-mode fiber (SMF) provides accumulated sufficient narrowband gain. A semiconductor optical amplifier (SOA) inside a fiber loop mirror is used for pulse modulation to directly address the sensing location, where the RS is coherently superimposed within the optical pulse width range for providing RS-based random feedback carrying the vibration information. Consequently, the random lasing output with defined pulse repetition can be demodulated for vibration location. Experimental results show that the proposed ABRLR

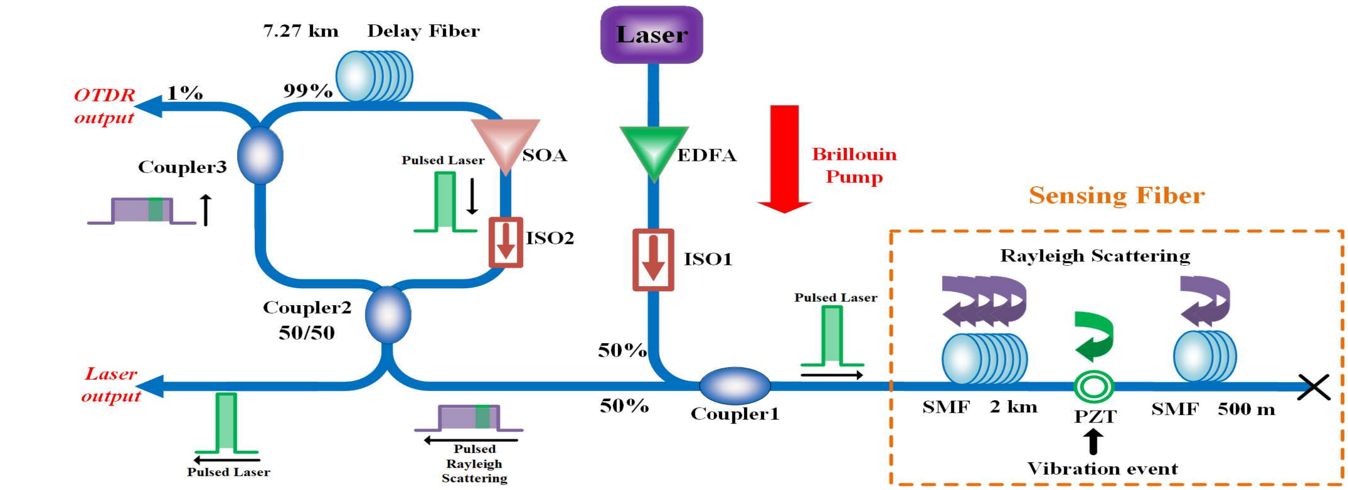

Fig. 1. The experimental setup of the proposed ABRLR

with high OSNR can locate the vibration signal with 33.4 m spatial resolution with a well-extended long distance of over 2 km.

II. Experimental Setup

The experimental setup of the ABRLR based on the half-open linear cavity is illustrated in Fig. 1. The half-open random cavity consists of a 2.5 km SMF and a fiber loop mirror, in which an isolator (ISO 2) to ensure unidirectional light, while a SOA is used as pulse modulation to generate a series of 300 ns optical pulses. By changing its repetition frequency of the pulses, the specific small section of the fiber along 2.5 km SMF can be to addressed and selected to offer random feedback for lasing output. To provide sufficient gain, a commercial laser with the linewidth of 20 kHz is boosted by an erbium-doped fiber amplifier (EDFA) as the Brillouin pump and injected into sensing fiber through the coupler 1. A piezoelectric (PZT) ring-shaped cylinder wrapped with 3 m optical fiber is inserted between the 2 km SMF and the 500 m SMF, and driven at 100 Hz to induce vibration event along the fiber. Since the tens of megahertz narrowband gain of photon-acoustic coupled Brillouin scattering along 2-km SMF exhibits significant phase noise suppression, high coherence, and high OSNR for random lasing resonance [7], the long-distance sensing range is expected. In this scenario, the repetition frequency can be set as 18.28 kHz so that the vibration location at the end of the 2 km SMF can be accurately addressed. The delay fiber in the loop ensures that the RS produced by adjacent optical pulses does not overlap for sensing demodulation.

III. Results And Discussion

The time-domain characteristics of the proposed ABRLR are measured using a 350 MHz bandwidth photodiode detector (PD) and a 4 GHz bandwidth oscilloscope (OSC). Fig. 2(a) displays the time pulse sequences, where the repetition frequency of the pulse sequences is directly modulated by the SOA (300 ns, 1.26 V @50 Ω) to match the round-trip time of RS at the vibrating end of the 2 km SMF in the random cavity of 54.7 μs. The pulse width of each optical pulse is 300 ns. The electrical spectrum is measured with a 350 MHz bandwidth PD and a 20 GHz bandwidth electrical spectrum analyzer (ESA). The spacing of the frequency comb presented in Fig. 2(b) corresponds to the free spectral range (FSR) of the laser and matches the pulse repetition interval shown in Fig. 2(a). In Fig. 3(a), the Rayleigh scattered Stokes wave is amplified by the SBS gain and the SOA to compensate for the round-trip loss for Brillouin random lasing oscillation as the pump power increases above 108 mW. The spectrum of the ABRLR is analyzed using an optical spectrum analyzer (OSA) with a resolution of 0.02 nm. As shown in Fig. 3(b), the wavelengths of the Brillouin pump and the generated Stokes light are concentrated at 1550.072 nm and 1550.16 nm, respectively, demonstrating a Brillouin wavelength upshift of 0.088 nm for the Stokes light compared to the pump light. In

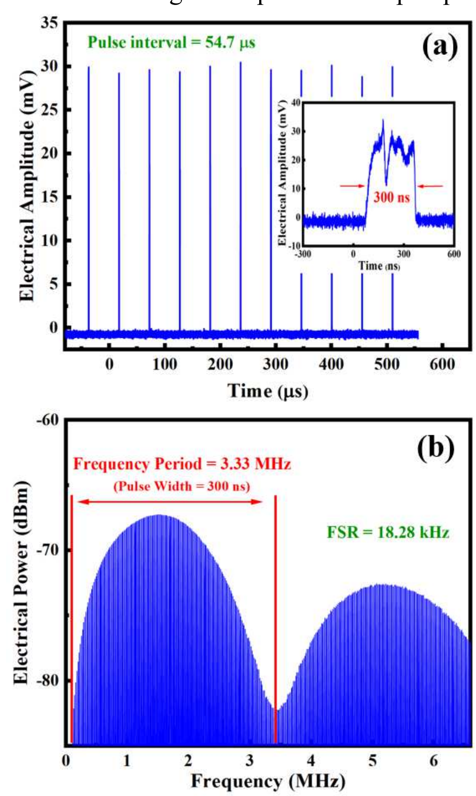

Fig. 2. (a) The time-domain characteristics of the proposed ABRLR. (b) The ESA spectrum of the propose ABRLR.

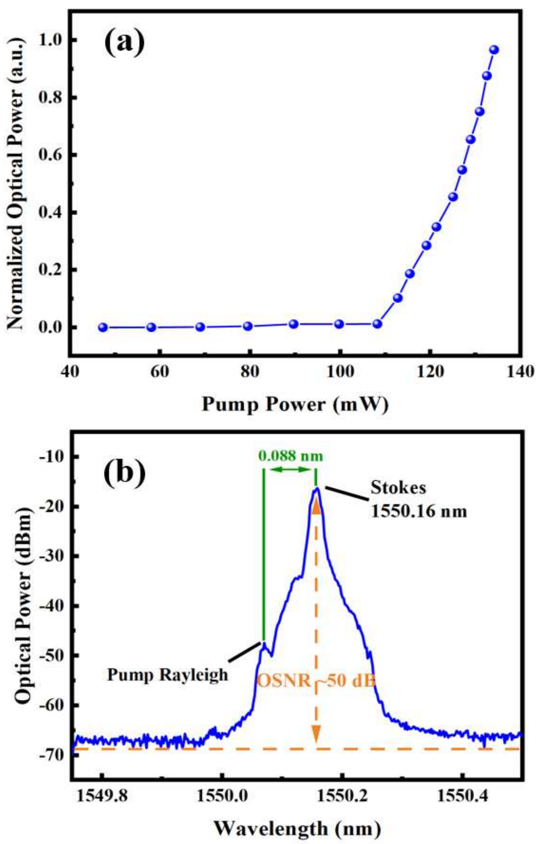

Fig. 3. (a) The output power of the proposed ABRLR. (b) The optical spectrum of the propose ABRLR.

addition, the ABRLR has a high OSNR of 50 dB well above the threshold. This way, Brillouin random fiber lasing oscillation is verified in the random cavity for generation of highly coherent random fiber lasing pulses [8].

Owing to the high coherence of the generated optical pulses, the ABRLR is very sensitive to the phase within the selected segment when the light pulses are addressed to the vibrating point at the end of the 2 km SMF. As a proof-of-concept, different repetition frequencies of the pulses are modulated by the SOA and vibration signals are collected at the OTDR output in the fiber loop. When the pulse repetition frequency is 18.28 kHz, the end of the 2 km optical fiber can be addressed. At this time, the corresponding vibration point can be located with a spatial resolution of 33.4 m, as shown in the blue track in Fig. 4. In comparison, the RS information is collected without vibration applied, as shown by the orange trace in Fig. 4. Signal peaks on the remaining fiber lengths are arising from the coherent superposition of single backscattered Rayleigh light. The 2 km SMF provides both Brillouin gain as a gain fiber and random feedback for the ABRLR, and can also be used as a sensing fiber. It should be noted that a higher spatial resolution could be further reduced by shorter pulse width modulation of SOAs. Unlike the weak backscattered signal in traditional φ-OTDR, the RS information at the vibrating point here is the lasing oscillation output after circulation in the random cavity, and does not require identification of the vibrating point through post-processing methods such as moving differential algorithm, highlighting a fast-response sensing system.

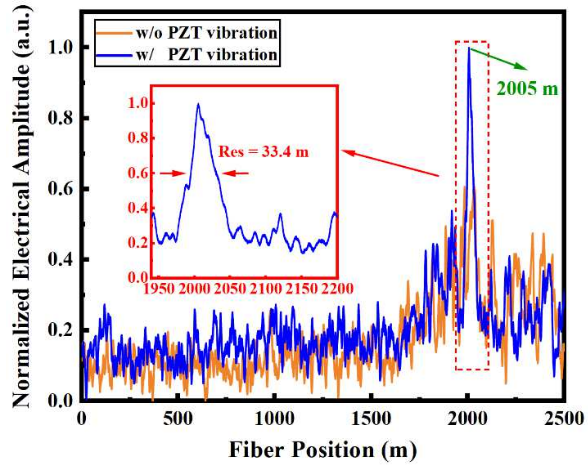

Fig. 4. Vibration information along the whole sensing fiber.

IV. Conclusion

In summary, the proposed ABRLR features extremely high OSNR, which preliminarily demonstrates its potential for distributed vibration signal localization with well-extended sensing distance of over 2 km. While there is still significant optimization required to fully realize the potential of this new approach, the method presented here offers a novel perspective for distributed vibration sensing.

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References

[1] D. V. Churkin, *et al.*, "Recent advances in fundamentals and applications of random fiber lasers," Advances in Optics and Photonics, vol. 7, no. 3, pp. 516-569, 2015.

[2] Z. Wang, *et al.*, "High power random fiber laser with short cavity length: theoretical and experimental investigations," IEEE Journal of Selected Topics in Quantum Electrons, vol. 21, no. 1, pp. 10-15, 2015.

[3] M. Pang, X. Bao, L. Chen, Z. Qin, Y. Lu, and P. Lu, "Frequency stabilized coherent Brillouin random fiber laser: theory and experiments," Optics Express, vol. 21, no. 22, pp. 27155-27168, 2013.

[4] M. I. Skvortsov, A. A. Wolf, A. V. Dostovalov, O. N. Egorova, S. L. Semjonov, and S. A. Babin, "Narrow-linewidth Er-doped fiber lasers with random distributed feedback provided by artificial Rayleigh scattering," Journal of Lightwave Technology, vol. 40, no. 6, pp. 1829-1835, 2022.

[5] Y. Han, T. V. A. Tran, S. Kim, and S. B. Lee, "Multiwavelength Raman-fiber-laser-based long-distance remote sensor for simultaneous measurement of strain and temperature," Optics Letters, vol. 30, no. 11, pp. 1282-1284, 2005.

[6] M. M. Correia, W. Margulis, A. S. L. Gomes, and J. P. v. d. Weid, "Distributed vibration sensor with a lasing phase-sensitive OTDR," Optics Express, vol. 30, no. 22, pp. 40243-40250, 2022.

[7] Y. Jiang, *et al.*, "Laser linewidth compression in cascading Brillouin random fiber lasers," IEEE Photonics Journal, vol. 14, no. 5, pp. 1-6, 2022.

[8] L. Zhang, et al., "Coherent Brillouin random fiber laser for application in phase-sensitive optical time domain reflectometry," in Conference on Lasers and Electro-Optics, pp. SW3L.3, 2018.