Long-distance random fiber laser sensing system with ultra-fast signal demodulation

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Abstract: Based on shape characteristics of the Raman gain spectrum, we extend the Random fiber laser remote sensing scenarios from quasi-static to dynamic, achieving 10 kHz signal demodulation over 100 km fiber.

1. Introduction

Random fiber laser (RFL) has the characteristics of simple structure, wavelength agility and high efficiency [1–3]. It has shown its importance in many fields such as optical fiber sensing, optical fiber communication, optical imaging, etc [4]. Among them, the Rayleigh scattering-based RFL without sensing FBG has the advantages of being insensitive to temperature/strain and can realize ultra-long cavity, so that the environmental information applied on fiber Bragg grating (FBG) can be stably transmitted from the remote end back to the receiving port [5].

There are three main types of remote FBG sensing systems based on RFL: The first is based on a backward-pumped RFL, and the sensing FBG is used as a part of the RFL cavity. In 2012, based on this scheme and using sencond-order RFL, our group achieved a 100 km sensing distance with optical signal-to-noise ratio up to 35 dB [5]; The second type is based on a forward-pumped RFL, which can transmit more optical power to the remote FBG, achieving a 200 km sensing distance in Ref. [6]; In addition, it can also be based on a pulse modulated RFL for sensing [7], and the sensing principle is similar to the optical time domain reflectometry. The above-mentioned sensing scheme has significantly improved the FBG sensing distance. However, due to the low speed of the optical spectrum demodulation or the limitation of the sensing principle, the current remote RFL sensing is mostly used for measurements of quasi-static parameters for the sensing bandwidth does not break the limit determined by the optical round-trip time [8]. At present, the ultra-fast RFL sensing is mainly focused on short-distance scenes [9].

In this work, ultra-fast remote disturbance demodulation based on RFL is realized, by using the shape characteristics of the Raman gain spectrum. Based on a time-dependent power-balance model, we found that the RFL output power is sensitive to the Raman gain, which will change corresponding to the center wavelength of the FBG. By choosing the linear interval of the Raman gain spectrum, a 100 km remote dynamic sensing is realized with linear response to the strain, and achieved 10 kHz signal demodulation, which is 10 times higher than that determined by the lightwave round-trip time in the pulse-probing cases.

2. Principle

The time-dependent power-balance model can accurately describe the evolution of the RFL output power [10,11]. Therefore, it is suitable for studying the time-domain properties in RFL dynamic sensing case, which can be expressed as:

$$\frac{dP_0^{\pm}}{dz} \pm \frac{1}{v_g}\frac{P_0^{\pm}}{dt} = \mp\alpha_0 P_0^{\pm} \mp g_1 \frac{f_0}{f_1} P_0^{\pm}\left(P_1^{+}+P_1^{-}+\Gamma_1\right) \pm \varepsilon_0 P_0^{\mp}, \tag{1}$$

$$\frac{dP_1^{\pm}}{dz} \pm \frac{1}{v_g}\frac{P_1^{\pm}}{dt} = \mp\alpha_1 P_1^{\pm} \pm g_1\left(P_1^{\pm}+0.5\Gamma_1\right)\left(P_0^{+}+P_0^{-}\right) \mp g_2 \frac{f_1}{f_2} P_1^{\pm}\left(P_2^{+}+P_2^{-}+\Gamma_2\right) \pm \varepsilon_1 P_1^{\mp}, \tag{2}$$

$$\frac{dP_2^{\pm}}{dz} \pm \frac{1}{v_g}\frac{P_2^{\pm}}{dt} = \mp\alpha_1 P_1^{\pm} \pm g_2\left(P_2^{\pm}+0.5\Gamma_1\right)\left(P_1^{+}+P_1^{-}\right) \pm \varepsilon_2 P_2^{\mp}, \tag{3}$$

$$\Gamma_i = 4hf_i\Delta f_i\left\{1+\frac{1}{\exp[h(f_{i-1}-f_i)/K_BT]-1}\right\}, \tag{4}$$

where P is the optical power; lower indexes '0', '1' and '2' correspond to the 1365 nm pump, 1461 nm 1st-order stokes and 1550 nm 2nd-order stokes lasing, respectively; f is the wave frequency; v_g is the group velocity ($v_g = 2\times10^8 m/s$); α, g, ε and Γ are the fiber linear loss, Raman gain, Rayleigh backscattering coefficient, and the population of the ASE photon, respectively. The values of them can be found in Ref. [12]; Particularly, g_2 is estimated as $0.41 - 7.8 \times 10^{-15} \times 2\pi f_2\ W^{-1}km^{-1}$, which is determined by the center wavelength of the sensing FBG.

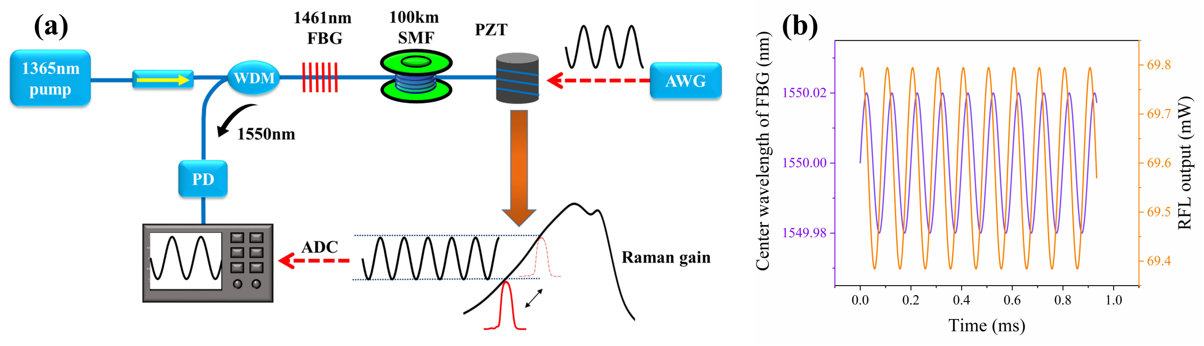

Fig. 1. Experimental setup for dynamic sensing.

The remote dynamic sensing is achieved based on a backward-pumped RFL [5], as shown in Fig. 1(a). In this case, the sensing FBG participates in the formation of the RFL, so the disturbance of FBG has a great impact on the RFL output, that is to say, the backward-pumped RFL is more sensitice to the FBG dynamic distrubance compared with forward-pumped [6] or pulse modulated [7] case.

When strain is applied on the FBG, the Raman gain will change according to the center wavelength of the FBG, which will further cause RFL output fluctuations. In order to obtain a linear response to the FBG disturbance, the linear interval of the Raman gain spectrum is selected. Applied 10 kHz sinusoidal disturbance with amplitude of $12.5\mu\varepsilon$ on FBG, the output power of RFL will fluctuate with corresponding frequency in Fig. 1(b). The simulation results show that the proposed scheme can realize the mapping of frequency domain information to the time domain, which is beneficial to the fast FBG demodulation.

3. Experimental demonstration

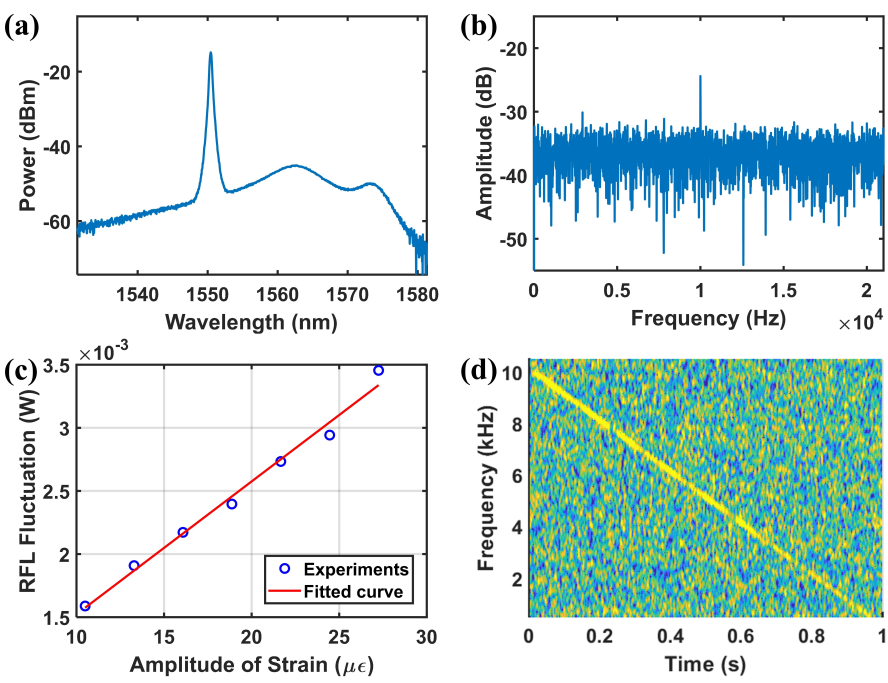

Fig. 2. (a) The output RFL spectrum at the WDM 1550 nm port. (b) The demodulated 10 kHz disturbance. (c) The amplitude of RFL fluctuation v.s. the amplitude of the strain applied to the FBG. (d) The short-time Fourier transform (STFT) result of the RFL output after applied linear chirp signal on FBG.

The experimental setup based on the above principle is consistent with the simulation, as shown in Fig. 1(a). Here, the FBG is tightly wrapped around the piezoelectric ceramic transducer (PZT) used to apply dynamic disturbance. The center wavelength of the FBG is focused on the 1550 nm at the rising edge of the Raman gain spectrum (Fig. 2(a)). When the center wavelength of FBG shift with the frequency of 10 kHz and amplitude of 0.02 nm (240 V peak-to-peak voltage on PZT), the output power at the WDM 1550 port presents corresponding fluctuations(Fig. 2(b)), and there is no frequency multiplier signal indicating that the system has a good linearity. In addition, we change the voltage on PZT from 120 V to 240 V. The relationship between the amplitude of strain and the amplitude of RFL fluctuation is illustrated in Fig. 2(c), showing the R-square close to $\sim$ 0.988. Figure 2(d) illustrates the demodulated result of a linear chirped strain signal from 500 Hz to 10 kHz, showing a high sensing bandwidth of our proposed sensing scheme.

4. Conclusion

A high-bandwidth dynamic sensing scheme based on long-distance backward-pumped random fiber laser is achieved by mapping the frequency domain information to the time domain. The simulation based on a time-dependent power-balance model and the corresponding experiments verify the feasibility of the proposed scheme, showing high bandwidth and good linearity to disturbances. This work paves the way for ultra-fast and ultra-long-distance interrogation for optical fiber sensors.

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References

1. S. K. Turitsyn, S. A. Babin, A. E. El-Taher, P. Harper, D. V. Churkin, S. I. Kablukov, J. D. Ania-Castañón, V. Karalekas, and E. V. Podivilov, "Random distributed feedback fibre laser," Nat. Photonics **4**, 231–235 (2010).
2. Y. Li, P. Lu, X. Bao, and Z. Ou, "Random spaced index modulation for a narrow linewidth tunable fiber laser with low intensity noise," Opt. Lett. **39**, 2294 (2014).
3. Zinan Wang, Han Wu, Mengqiu Fan, Li Zhang, Yunjiang Rao, Weili Zhang, and Xinhong Jia, "High Power Random Fiber Laser With Short Cavity Length: Theoretical and Experimental Investigations," IEEE J. Sel. Top. Quantum Electron. **21**, 10–15 (2015).
4. D. V. Churkin, S. Sugavanam, I. D. Vatnik, Z. Wang, E. V. Podivilov, S. A. Babin, Y. Rao, and S. K. Turitsyn, "Recent advances in fundamentals and applications of random fiber lasers," Adv. Opt. Photonics **7**, 516 (2015).
5. Z. N. Wang, Y. J. Rao, H. Wu, P. Y. Li, Y. Jiang, X. H. Jia, and W. L. Zhang, "Long-distance fiber-optic point-sensing systems based on random fiber lasers," Opt. Express **20**, 17695 (2012).
6. M. Fernandez-Vallejo, M. Bravo, and M. Lopez-Amo, "Ultra-long laser systems for remote fiber Bragg gratings arrays interrogation," IEEE Photonics Technol. Lett. **25**, 1362–1364 (2013).
7. D. Leandro, V. DeMiguel Soto, R. A. Perez-Herrera, M. Bravo Acha, and M. Lopez-Amo, "Random DFB fiber laser for remote (200 km) sensor monitoring using hybrid WDM/TDM," J. Light. Technol. **34**, 4430–4436 (2016).
8. J. Hu, Z. Chen, J. T. Teo, and C. Yu, "100-km long distance FBG vibration sensor based on matching filter demodulation," 21st Int. Conf. on Opt. Fiber Sensors **7753**, 77538N (2011).
9. Y. Xu, L. Zhang, S. Gao, P. Lu, S. Mihailov, and X. Bao, "Highly sensitive fiber random-grating-based random laser sensor for ultrasound detection," Opt. Lett. **42**, 1353 (2017).
10. J. Xu, J. Ye, J. Wu, W. Liu, H. Zhang, J. Leng, and P. Zhou, "Passively spatiotemporal gain-modulation-induced stable pulsing operation of a random fiber laser," Photonics Res. **5**, 598 (2017).
11. N. Tarasov, L. A. Melnikov, I. D. Vatnik, Y. A. Mazhirina, and D. V. Churkin, "Self-gain-modulation random distributed feedback Raman fiber laser with switchable repetition rate," Opt. Express **29**, 29857 (2021).
12. Z. Wang, H. Wu, M. Fan, Y. Rao, X. Jia, and W. Zhang, "Third-order random lasing via Raman gain and Rayleigh feedback within a half-open cavity," Opt. Express **21**, 20090 (2013).