Optical Fiber Technology 54 (2020) 102119

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Relative intensity noise comparison of fiber laser and amplified spontaneous emission sources

Xin Cheng[a,b], Weiwei Pan[a,b], Xin Zeng[a,b], Jinyan Dong[a,b], Shuzhen Cui[a], Yan Feng[a,b,*]

[a] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, and Shanghai Key Laboratory of Solid-State Laser and Application, Shanghai 201800, China

[b] Center of Materials Science and Optoelectronics Engineering, University of the Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Keywords:
Raman fiber lasers
Relative intensity noise
Amplified spontaneous emission
Fiber laser oscillator

ABSTRACT

The performance of Raman fiber laser and amplifier largely depends on the temporal stability of the pump sources. Here the relative intensity noise of three different sources are experimentally investigated and compared, which are fiber laser oscillator, master oscillator power amplifier, and amplified spontaneous emission. The amplified spontaneous emission source exhibits the lowest intensity noise. The fiber laser oscillator and amplifier have inevitable relaxation oscillation and longitudinal mode beating, which results in higher intensity noise and frequency dependent features. The results firmly explain the recent demonstrations in the performance improvement with amplified spontaneous emission as pump sources and the beneficiation of backward pumping for single frequency fiber amplifier.

1. Introduction

Noise is a central topic in laser physics and engineering since its invention [1–4]. The laser noise property is of great importance for laser applications in precision measurement, optical communication, sensing and so on. It determines the final performance of those systems. In recent years, the importance of pump laser intensity fluctuation on the performance of Raman fiber lasers (RFLs) has received more and more attention. It is shown that the intensity fluctuation of the pump laser would be transferred to the Raman signal laser directly, which influences the stability of mode-locked Raman fiber lasers [5], the spectral purity of high order cascaded Raman random fiber lasers [6,7], and the output linewidth of Raman fiber amplifiers (RFAs) [8]. Therefore, finding suitable pump sources of low intensity fluctuation, i.e. low intensity noise, and detailed understanding of the pump laser influence become crucial tasks for future RFL development.

In term of intensity noise, single-mode single-frequency fiber lasers and amplifiers may naturally have the lowest intensity noise among different fiber sources [9]. But the power scaling capacity is limited by stimulated Brillouin scatting effect in optical fiber [10]. They are not suitable as high-power pump sources. In common RFLs, standard fiber laser oscillators formed with a pair of fiber Bragg gratings (FBGs) are used as pump sources. But the beating between longitudinal modes results in temporally fluctuating output, which manifests in radio frequency spectrum of the output as beat notes. High performance diodes are widely used as pump source for Raman amplifier in telecoms. But they are not powerful enough for the studied lasers.

Fiber-based amplified spontaneous emission (ASE) sources have lower coherence and lower noise, because they have broad spectrum and no longitudinal mode structure [11]. They have been applied for optical fiber sensor, fiber optic gyroscope and optical coherence tomography [12,13]. Recently, they have also been considered as promising pump source for RFLs because of lower temporal fluctuation [5,7,14]. However, in these works, temporal stability of the pump sources based on laser oscillator and fiber ASE are compared just roughly in terms of peak to peak fluctuation and standard deviation of the intensity. A better characterization of the temporal property of common pump sources will facilitate a better understanding of their influence on RFL performance.

In this contribution, we experimentally investigate the intensity noise of fiber laser and an ASE source for comparison. The relative intensity noise (RIN) spectrum of a 1095 nm fiber laser is measured at different power and different configurations. The integrated rms RIN value decreases with respect to output power. The RIN spectra of an oscillator and a master oscillator power amplifier (MOPA) at the same output power are compared. The RIN of an ASE source at 1064 nm is also characterized in detail, which shows lower RIN in general because of the mode-free nature. The implication of the experimental observation on RFL pumping is discussed. The quantitative and frequency-resolved measurements of intensity noise improve the understanding on

* Corresponding author.
E-mail address: feng@siom.ac.cn (Y. Feng).

https://doi.org/10.1016/j.yofte.2019.102119
Received 28 November 2019; Received in revised form 18 December 2019; Accepted 19 December 2019
Available online 06 January 2020

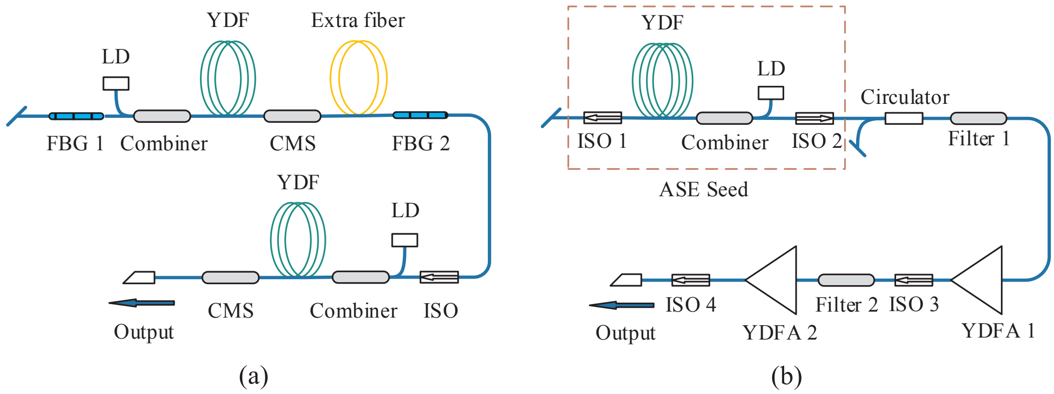

Fig. 1. Experimental configuration of the fiber laser oscillator and amplifier (a) and the fiber ASE source (b).

the pump laser influence on Raman fiber devices.

2. Experiment setup

The 1095 nm fiber laser consists of an Yb-doped fiber oscillator and a fiber amplifier, as shown in Fig. 1 (a). The fiber oscillator mainly consists of a fiber-pigtailed multimode diode laser at 976 nm, a (2 + 1) × 1 pump signal combiner, an Yb-doped gain fiber of 6 m length, a piece of PM 980 fiber (Extra fiber) used to lengthen the cavity, and a pair of homemade fiber FBGs. A cladding mode stripper (CMS) is inserted between the gain fiber and extra fiber to remove the residual pump laser. The gain fiber (PLMA-YDF-10/125, Nufern Inc.), whose nominal cladding absorption is 4.8 dB/m at 976 nm, has a core and cladding diameter of 10 μm and 125 μm, respectively. The FBGs are written in passive fibers (PM980, Nufern Inc.). FBG 1, which is spliced with one end of the combiner, has a peak reflectivity of 99% at 1095 nm. The full-width at half-maximum (FWHM) is 1.51 nm. FBG 2 with a peak reflectivity of 17% at 1095 nm, is used as the output coupler and its FWHM is 0.255 nm. The output from the oscillator is optically isolated and injected into the Yb fiber amplifier with similar configuration for power amplification. The output end of the fiber amplifier is cleaved at an angle of 8° to suppress the parasitic oscillation.

The schematic of the ASE source is illustrated in Fig. 1 (b). The ASE seed is built with an all open cavity. Two isolators (ISO 1, ISO 2) are spliced at both ends to avoid parasitic lasing. All polarization-maintaining (PM) active and passive fibers with a core diameter of 10 μm and numerical aperture of 0.080 are used. An optical circulator is inserted to provided additional isolation. After that, a filter (Filter 1) with 2 nm bandwidth centered at 1064.0 nm is used to narrow the linewidth. Then two home-made all-fiber linearly polarized YDFAs (YDFA 1, YDFA 2) are adopted to amplify the ASE seed with an isolator (ISO3) and a filter (Filter 2, 10 nm bandwidth) in between. The isolator and the filter are used to prevent the self-oscillation. Another isolator (ISO4) is spliced at the output to stop back reflected light.

The RIN properties of the light sources are measured with an InGaAs detector of 15 MHz bandwidth and a spectrum analyzer (Rohde& schwarz FSV4).

3. Experiment results and discussion

The 1095 nm fiber laser is investigated firstly. The output spectra directly from the oscillator at different powers are measured and shown in Fig. 2(a). The 3-dB linewidth with respect to output power is plotted on Fig. 2(b). The spectrum broadens from 0.07 nm at 1 W to 0.62 nm at 9 W nonlinearly. The linewidth at high power is much larger than that of the output FBG (0.255 nm). The broadening is a result of nonlinear processes inside the fiber laser oscillator, which indicates fluctuating laser emission.

In the experiment, the RIN spectra of the fiber laser oscillator at different output power from 100 Hz to 10 MHz Fourier frequencies are measured and shown in Fig. 3(a) and (b). At frequencies lower than 100 Hz, any power fluctuation can be easily stabilized by active control. So low frequency noise is of no importance in practice. The up bound of 10 MHz is limited by the electronics bandwidth in the experiments. Nevertheless, noise at higher frequencies have limited effect anyway for high performance Raman fiber lasers or amplifiers, since most of them work in backward pumping scheme. In backward pump scheme, the walk-off between the pump and signal light results in a low-pass filtering effect in pump noise transfer [15]. The bandwidth is inversely proportional to the propagation time along the gain fiber. 10 MHz corresponds to a gain fiber length of 10 m, which is much shorter than that in reported Raman fiber devices. Therefore, a RIN measurement up to 10 MHz is enough for studying backward pumped Raman fiber devices.

From 100 Hz to 3 kHz Fourier frequencies, the RIN decreases with increasing output power, which is caused by gain saturation in the gain medium [9]. The broad peak at several hundred kHz is due to relaxation oscillation [16], which shifts from about 100 kHz to 700 kHz with the output power increasing from 1 W to 10 W. The sharp peaks at about 4.77 MHz and 9.54 MHz are the beat notes between the longitudinal modes of the laser oscillator, which relate to the length of the oscillator cavity of 21.5 m. As the output power increases, the beat peaks become flatter and decrease in height. However, in the valleys (2.40 MHz and 7.12 MHz) between the beat peaks of the RIN spectra, an opposite characteristic is exhibited, in which the RIN raises with the increase of the output power. Nevertheless, the overall RIN decreases with output power. The integrated rms RIN value drops from 0.75% to 0.56% when the output power increases from 1 W to 10 W.

In practice, there are two ways to obtain the same laser output power, directly from a laser oscillator or a MOPA. In even higher power application, MOPA is a necessary approach to achieve the power level. Here we compare the RIN characteristics at 10 W output power obtained by these two methods. In Fig. 4, the blue and black lines illustrate the RIN spectra directly from the oscillator at 2 and 10 W, respectively. Also shown in Fig. 4, the red line depicts the RIN spectrum at 10 W by amplification of the oscillator with 2 W output. In low frequency (< 4 kHz) range, extra noise is introduced during the amplification process, possibly due to a noisy pump diode source. A RIN spectrum of a pump diode laser at low frequency is shown in Fig. 5. From 4 to 100 kHz, the RIN is suppressed during the amplification. But the relaxation oscillation peak and beat notes are the same as in the RIN spectrum of the 2 W master oscillator. As seen in Fig. 4, the RIN spectra for the two different configurations at the same output are totally different. The integrated rms RIN value of MOPA source at 10 W is 0.71%, close to the rms RIN of oscillator at 2 W.

The output characteristics of the fiber ASE source is investigated as well. The output spectra at different powers are shown in Fig. 6.

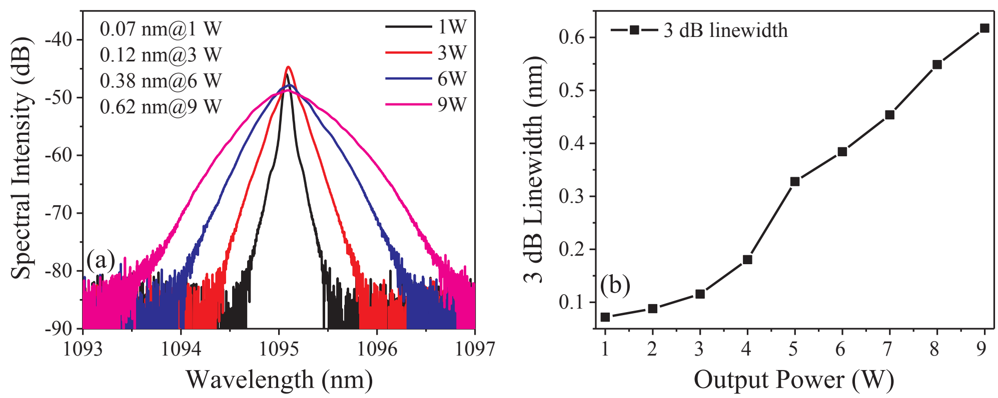

Fig. 2. Output spectra (a) and 3-dB linewidth (b) of the fiber laser oscillator at different powers.

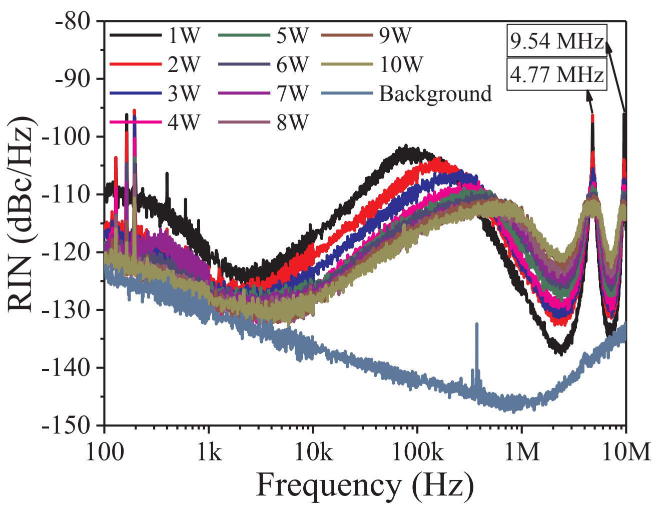

Fig. 3. RIN of the fiber laser oscillator at different power.

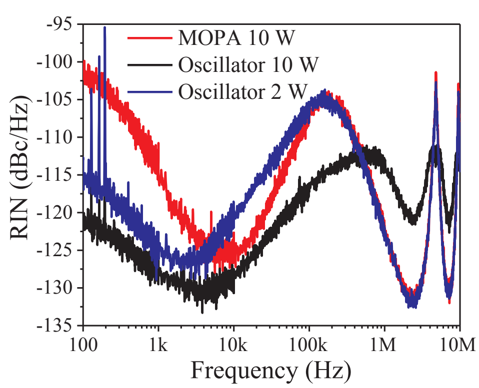

Fig. 4. RIN spectrum comparison between the fiber oscillator and amplifier.

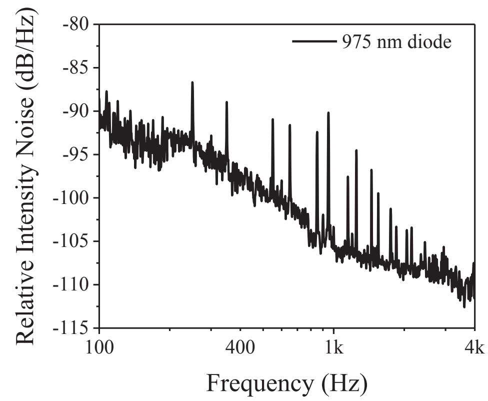

Fig. 5. RIN of a 975 nm diode laser.

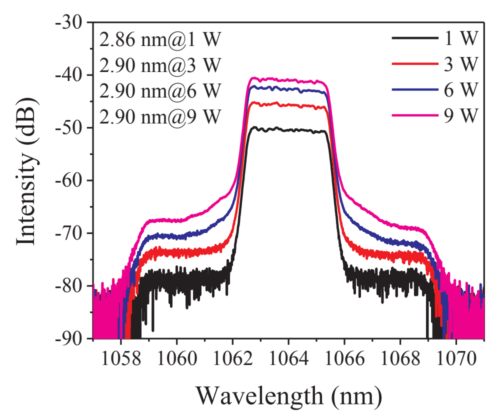

Fig. 6. Output spectra of the fiber ASE source.

Different from the fiber laser oscillator, the 3-dB linewidth of the fiber ASE source retains in the range of experimental errors at different output powers from 1 W to 9 W. The observation indicates a quiet output from the ASE source, since no nonlinearity induced linewidth broadening takes place.

In Fig. 7, we show the measured RIN spectra of the ASE source at different output power and the background noise from 100 to 10 MHz Fourier frequencies. There are a large amount of discrete noises in the low frequency range (< 3 kHz), which may be caused by mechanical vibration and sound waves in the experimental environment. These spikes are absent in the measurements of the laser sources, because they are done in a different lab. The RIN at 100 Hz decreases from −95 to −120 dBc/Hz when the output power is scaled from 1 to 10 W. This reduction originates from both the pump noise reduction at higher current operation and the gain saturation in the gain medium [9]. Different from the fiber laser source, the RIN spectra are flat around −120 dBc/Hz without peaks, because the ASE source is free of longitudinal modes and relaxation oscillation. The rms RIN value of the ASE source integrated from 100 Hz to 10 MHz drops slightly from 0.19% at 1 W output power to 0.15% at 10 W. Therefore, indeed the ASE source has a few times lower temporal fluctuation than the fiber laser, which firmly explains the observation in literatures [5–7].

To compare the RIN properties of the fiber laser oscillator, MOPA and ASE, their RIN spectra at the same power of 10 W are plotted together in Fig. 8. As discussed in previous paragraphs, the rms RIN integrated from 100 Hz to 10 MHz are 0.56%, 0.71%, and 0.15%, respectively. The ASE source is surely quieter and therefore is beneficial

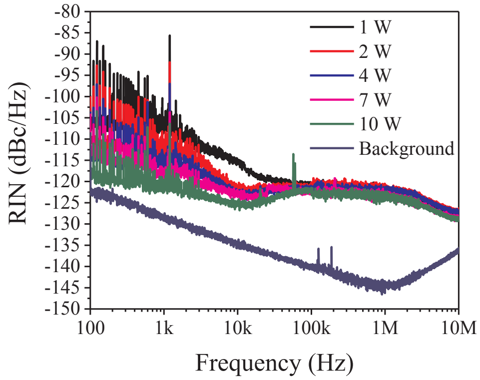

Fig. 7. RIN spectra of the ASE source at different powers.

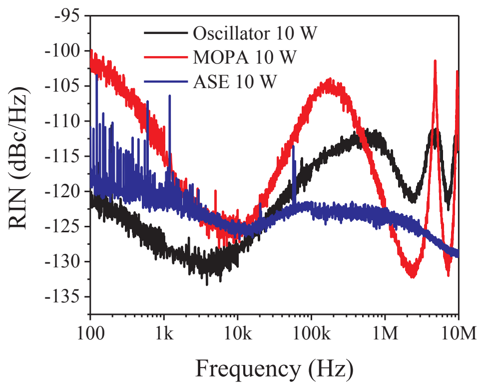

Fig. 8. RIN spectra of different sources at 10 W.

in pumping Raman fiber laser or amplifier. As shown in literatures, the use of ASE as pump source has improved the pulse stability of a mode-locked Raman fiber laser [5], and the spectral purity of a high order cascaded Raman random fiber laser [6,7].

However, ASE sources are more complex and expensive than standard fiber lasers, since it requires more amplification stages to achieve the same power level. As one can see from the RIN spectra in Fig. 8, the higher integrated RIN for the fiber oscillator and amplifier is mainly contributed by the longitudinal mode beating in MHz and higher frequency. When one pumps a Raman fiber amplifier in the backward configuration, the influence of these giant noise components can be suppressed with proper design, since a backward pumped Raman fiber amplifier behaves like a low pass filter [15]. For example, fiber lasers with shorter cavity length is preferred, since the beat noises move to higher frequency which can be more effectively filtered. In fact, backward pumping has been widely used in optical telecommunication to improve the noise figure and in single frequency fiber amplifiers to avoid the linewidth broadening.

Also seen in Fig. 8, although the overall noise is lower for ASE, there are frequency ranges where the fiber laser source has lower noise. Therefore, for applications where forward pumping is necessary, one should choose proper pump source by considering the range of frequency that is interested.

4. Conclusion

The RIN characteristics of a standard fiber laser oscillator, a MOPA and a fiber ASE source are compared in detail. For the fiber oscillator, the integrated rms RIN drops from 0.75% to 0.56% when the output power increases from 1 W to 10 W. The integrated rms RIN of the MOPA source at 10 W is 0.71%, close to that of the oscillator at 2 W. Different from the fiber laser source, the RIN spectra of the ASE are flat without peaks, because it is free of longitudinal modes and relaxation oscillation. The ASE source has the lowest RIN of 0.15% at 10 W. The results firmly explain the recent experimental demonstrations in the use of ASE source as pump sources for performance improvement of Raman fiber lasers and amplifiers. The revealed noise distribution in the frequency domain for fiber oscillator and amplifier explains well why backward pumping is beneficial for single frequency fiber amplifier.

Funding

This work was supported by The National Key R&D Program of China (2018YFB0504600, 2018YFB0504602); The Science and Technology Commission of Shanghai Municipality (19441909800).

CRediT authorship contribution statement

Xin Cheng: Writing - original draft, Data curation. **Weiwei Pan:** Validation. **Xin Zeng:** Methodology. **Jinyan Dong:** Investigation. **Shuzhen Cui:** Resources. **Yan Feng:** Conceptualization, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A.L. Schawlow, C.H. Townes, Infrared and optical masers, Phys. Rev. 112 (6) (1958) 1940–1949.
[2] A.E. Siegman, "Lasers," University Science, 1986.
[3] T.C. Ralph, et al., Understanding and controlling laser intensity noise, Opt. Quant. Electron. 31 (5–7) (1999) 583–598.
[4] R. Paschotta, A. Schlatter, S.C. Zeller, H.R. Telle, U. Keller, Optical phase noise and carrier-envelope offset noise of mode-locked lasers, Appl. Phys. B-Lasers Opt. 82 (2) (2006) 265–273.
[5] W. Pan, L. Zhang, J. Zhou, X. Yang, Y. Feng, Raman dissipative soliton fiber laser pumped by an ASE source, Opt. Lett. 42 (24) (2017) 5162–5165.
[6] V. Balaswamy, S. Ramachandran, V.R. Supradeepa, High-power, cascaded random Raman fiber laser with near complete conversion over wide wavelength and power tuning, Opt. Express 27 (7) (2019) 9725–9732.
[7] Jinyan Dong, et al., High order cascaded Raman random fiber laser with high spectral purity, Opt. Express 26 (5) (2018) 5275–5280.
[8] Y. Miao, P.F. Ma, W. Liu, H.W. Zhang, P. Zhou, First demonstration of co-pumped single-frequency Raman fiber amplifier with spectral-broadening-free property enabled by ultra-low noise pumping, IEEE Access 6 (2018) 71988–71993.
[9] G. Guiraud, N. Traynor, G. Santarelli, High-power and low-intensity noise laser at 1064 nm, Opt. Lett. 41 (17) (2016) 4040–4043.
[10] R.G. Smith, Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and brillouin scattering, Appl. Opt. 11 (11) (1972) 2489.
[11] Martin Blazek, Sébastien Hartmann, Andreas Molitor, W. Elsaesser, Unifying intensity noise and second-order coherence properties of amplified spontaneous emission sources, Opt. Lett. 36 (17) (2011) 3455–3457.
[12] A.D. Kersey, et al., Fiber grating sensors, J. Lightwave Technol. 15 (8) (1997) 1442–1463.
[13] J.L. Wagener, M.J.F. Digonnet, H.J. Shaw, A high-stability fiber amplifier source for the fiber optic gyroscope, J. Lightwave Technol. 15 (9) (1997) 1689–1694.
[14] J. Xu, P. Zhou, J. Leng, J. Wu, H. Zhang, Powerful linearly-polarized high-order random fiber laser pumped by broadband amplified spontaneous emission source, Sci. Rep. 6 (2016) 35213.
[15] W. Liu, P.F. Ma, Y. Miao, H.S. Wu, P. Zhou, Z.F. Jiang, Intrinsic mechanism for spectral evolution in single-frequency raman fiber amplifier, IEEE J. Sel. Top. Quantum Electron. 24 (5) (2018) 8.
[16] L.N. Ma, Y.M. Hu, S.D. Xiong, Z. Meng, Z.L. Hu, Intensity noise and relaxation oscillation of a fiber-laser sensor array integrated in a single fiber, Opt. Lett. 35 (11) (2010) 1795–1797.