Replica Symmetry Breaking in Multi-wavelength Brillouin Random Fiber Laser

Zepeng Zhong
Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science
Shanghai University
Shanghai, China
zepengzhong@shu.edu.cn

Jilin Zhang
Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science
Shanghai University
Shanghai, China
1285882712@qq.com

Xu Guo
Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science
Shanghai University
Shanghai, China
2774563013@qq.com

Fufei Pang
Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science
Shanghai University
Shanghai, China
ffpang@shu.edu.cn

Mengshi Zhu
Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science
Shanghai University
Shanghai, China
zhmsh@shu.edu.cn

Liang Zhang*
Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science
Shanghai University
Shanghai, China
liangzhang@shu.edu.cn

***Abstract*—This paper reported an experimental evidence of replica symmetry breaking (RSB) in multi-wavelength Brillouin random fiber lasers (MWBRFLs) with disorders from both randomly distributed feedback and interplays among different orders Stokes waves.**

Keywords—replica symmetry breaking, random fiber laser, Brillouin scattering

I. Introduction

Random fiber lasers (RFLs) exhibit unique optical properties, compared with conventional cavity-based fiber lasers, such as longitudinal mode elimination and phased noise suppression [1][2]. In particular, randomly distributed feedback from refractive index inhomogeneity-induced Rayleigh scattering basically imposes disorders on random laser radiation with extraordinary stochastics, highlighting a promising photonic platform for exploring fundamentals of complex systems as well as nonlinear phenomena [3][4], including spin-glass behavior [5], turbulence [6], extreme event [7], *etc*. In magnetic systems, the phase transition happeing bwtween paramagnetic and spin glass state was called replica symmetry breaking. In 2016, the photonic spin-glass behavior of erbium-doped, which displayed the RSB above the threshold was discussed in a one-dimensional continuous-wave erbium-doped random fiber laser [8]. A high efficiency Brillouin random fiber laser constructed by a random fiber grating was experimentally realized, which provided a photonic platform to study RSB [9]. Up to date, RSB observation has been only reported in single-wavelength-operation random fiber lasers with disorders induced from randomly distributed feedback. In 2019, the RSB and radiating in a chaotic manner and exhibiting random laser behavior in multi-wavelength Brillouin fiber laser was theoretically discovered [10]. These findings imply that MWBRL can provide a platform to investigate RSB.

In this work, we firstly experimentally observed the RSB in a MWBRFL with disorders originating from both random feedback and multiple Stokes laser interplays. The evolution of RSB-related statistics was revealed, when the high-order Stokes light was generated from the 1st order to the 4th one. By statistical analysis of the corresponding PSD of the laser temporal output, the different $P(q)$ denoted the distribution of the order parameter q was obtained, which evidentially exhibits that the existence of highest-order Stokes light and interplays among different Stokes light influence the formation of the RSB.

II. Experimental Setup and Results

A. Experimental Setup

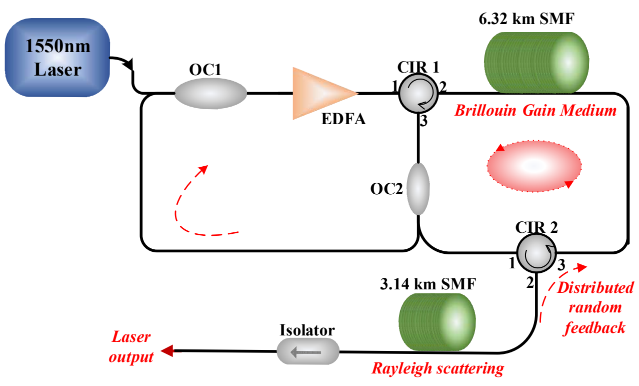

Fig. 1. Setup of the MWBRFL

The experimental setup is depicted in Fig. 1. The configuration of the MWBRFL consists of a main fiber ring cavity and a sub-fiber loop, a similar configuration can refer to Ref.[11]. In the main fiber ring cavity, the 6.32-km single-mode fiber (SMF), acting as the Brillouin gain medium, is connected to the cavity by two circulators (CIRs #1 and #2) and a 50/50 optical coupler (OC 2). Another 3.14-km SMF, providing the distributed random feedback for the Stokes lasing generation within the main fiber cavity, is incorporated through the CIR 2. Placing an isolator at the end of the 3.14-km SMF before the laser output is to block any Fresnel reflection upon the fiber end surface. The lasing Stokes lines are split by the OC 2 in the main fiber ring cavity and then recombined with the input 1550-nm laser by another 50/50 optical coupler (OC 1) in the sub-fiber loop. In order to enhance the optical power injected into the main fiber cavity, an Erbium-doped fiber amplifier (EDFA) is employed. A 50/50 optical coupler is used to divide the output laser into two channels, one of which is captured by a photoelectric detector (PD) and displayed by an oscilloscope and other inputs to an optical spectrum analyzer (OSA) to observe the highest-order Stokes light of the output laser.

B. Results

The OSA can monitor the subsequent generation of the high order of the Stokes light as increasing the EDFA power. Figure 1 shows the optical spectrum when EDFA power reaches 6.59 dBm, 9.04 dBm, 10.59 dBm, and 12.12 dBm, respectively. The highest order Stokes light of the four spectrums varies from the 1st to the 4th order. As shown in Fig. 2, time-domain waveforms have been accordingly recorded as the Stokes varies from the 1st to the 4th order.

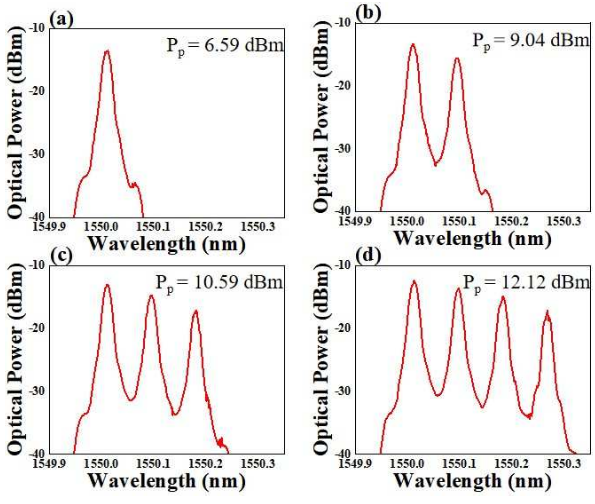

Fig. 2. The optical spectrum of the output laser with the different highest-order Stokes light. (a) 1st order, (b) 2nd order, (c) 3rd order, (d) 4th order

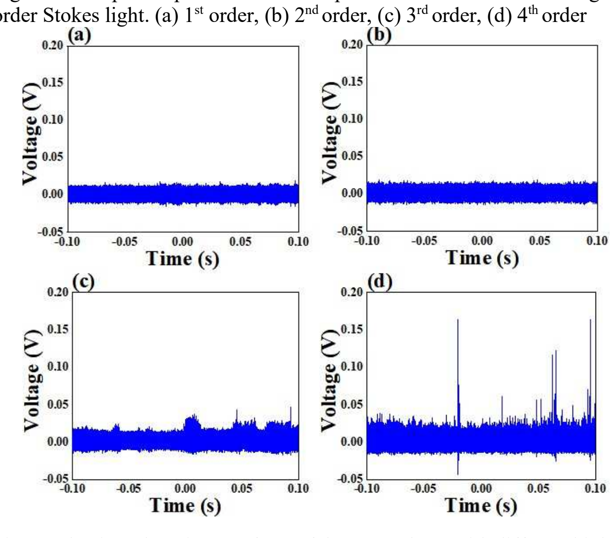

Fig. 3. The time-domain waveform of the output laser with different highest-order Stokes light. (a) 1st order, (b) 2nd order, (c) 3rd order, (d) 4th order

To obtain the $P(q)$, which is regarded as the distribution of the overlap between the replicas describing the glassy phases, the time window with 10 ms of the time-domain waveform is converted to the frequency-domain waveform by Fourier transform and further converted to the power spectral density (PSD). Meanwhile, the PSD in the time window $\boldsymbol{\tau}$ = 10 ms is equally divided into $\boldsymbol{N_s}$ =100 samples with $\boldsymbol{N}$ = 1500 data points in each sample. The correlation between any two samples of the PSD, which are two different replicas, such as $\boldsymbol{a}$, and $\boldsymbol{b}$, can be calculated as:

$$q_{ab} = \frac{\sum_{k=1}^{N} \Delta_a(k)\Delta_b(k)}{\sqrt{\sum_{k=1}^{N} \Delta_a(k)^2}\sqrt{\sum_{k=1}^{N} \Delta_b(k)^2}}, \quad (1)$$

where $\boldsymbol{N}$ is the number of the data point of each replica, $\boldsymbol{a}$, $\boldsymbol{b}$ =1, 2, . . . , $\boldsymbol{N_s}$ denote the different replicas, $\boldsymbol{N_s}$ =100 is the total number of replicas, $\Delta_a(k) = PSD_a(k) - \overline{PSD}(k)$ is the PSD fluctuation and the average PSD is

$$\overline{PSD}(k) = \sum_{a=1}^{N_s} PSD_a(k)/N_s \quad (2)$$

The temporal outputs with different highest-order Stokes lights can individually obtain a set of data about the value-$\boldsymbol{q}$, according to Eqs. (1) and (2). A set of data contains N_s *(N_s - 1) values of $\boldsymbol{q}$ for each output with different highest-order Stokes light. Figure 4 depicts the distribution $P(\boldsymbol{q})$ of different highest-order Stokes lights in the output laser. Fig. 4 illustrates the PDFs of the value-$\boldsymbol{q}$ as the highest order of Stokes light varies from 1st order to 4th one. In Fig. 4(a), most value-$\boldsymbol{q}$ muster around 1 and -1, which means the replicas are almost divided into two pure states and RSB emerges. When the highest-order Stokes light is the 2nd-order Stokes light, the value-$\boldsymbol{q}$ tends to extend to the whole range of values. The phenomenon is more obvious when 3rd-order Stokes light exists in the output laser. As the highest-order Stokes light in the output laser varies to the 4th order, the distribution of the value-$\boldsymbol{q}$ covers the whole range of values. These phenomena imply that the replicas are divided into more pure states when the highest-order Stokes light in the output laser varies from 1st order to 4th one and the existence of the high-order Stokes light and the interaction among the different order Stokes light have an effect on the phenomenon of the RSB, as shown in Figs. 4 (b)-(d).

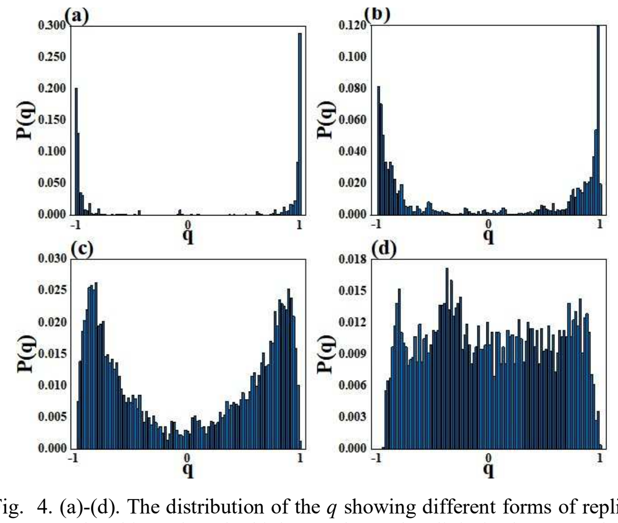

Fig. 4. (a)-(d). The distribution of the q showing different forms of replica symmetry breaking when the highest-order Stokes light in the output laser varies from 1st order to 4th order. (a) 1st order, (b) 2nd order, (c) 3rd order, (d) 4th order

The replica order parameter matrix $\boldsymbol{Q}$ can be used to reflect the number of the pure state. Every pure state corresponds to a value-$\boldsymbol{q}$. By means of the matrix $\boldsymbol{Q}$, the conclusion is that when the highest-order Stokes light in the output laser varies from 1st order to 4th one, the increase of pure state is more explicit. Figures 5(a)-5(d) show heatmap plots of the MWBRFL with values of the order parameter q representing correlations between PSD fluctuations at different time points T_i and T_j, when the highest-order Stokes light varies from 1st order to 4th one. The color code essentially depicts in green absence of correlations between PSD fluctuations, whereas yellow ($\boldsymbol{q}$=1) and blue ($\boldsymbol{q}$ =-1) indicate correlated and anti-correlated fluctuations, respectively. As shown in Fig. 5, when the highest order is only the 1st order, the pure state is several. However, the pure state is obviously more and more when the highest order varies from the 1st order to the 4th one.

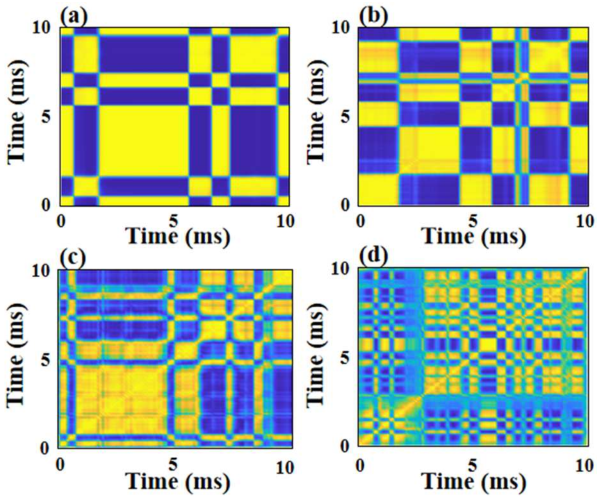

Fig. 5. The different replica order parameter matrix when the highest-order Stokes light in the output laser varies from 1st order to 4th order. (a) 1st order, (b) 2nd order, (c) 3rd order, (d) 4th order

III. Conclusions

The RSB in a WMBRFL with randomly distributed feedback was experimentally investigated, in which the interactions among different order Stokes light results in more pure states and disorders. When the highest order of the Stokes light varies from 1st order to 4th order, the distribution of the value-q transforms turns out to dynamically evolute from mustering around the 1 and -1 to almost covering the whole range of values.

Funding: National Natural Science Foundation of China (Grants 62275146, 61905138); Science and Technology Commission of Shanghai Municipality (Grant 20ZR1420800). State Key Laboratory of Advanced Optical Communication Systems and Networks (2022GZKF004); STCSM (SKLSFO2022-05); 111 Project (Grant D20031); Shanghai Professional Technology Platform (19DZ2294000).

References

[1] Turitsyn, S. K., Babin, S. A., El-Taher, A. E., Harper, P., Churkin, D. V., Kablukov, S. I., ... & Podivilov, E. V. (2010). Random distributed feedback fibre laser. Nature photonics, 4(4), 231-235.

[2] Zhu, T., Bao, X., & Chen, L. (2011). A single longitudinal-mode tunable fiber ring laser based on stimulated Rayleigh scattering in a nonuniform optical fiber. Journal of Lightwave Technology, 29(12), 1802-1807.

[3] Wiersma, D. S. (2008). The physics and applications of random lasers. Nature physics, 4(5), 359-367.

[4] Florescu, L., & John, S. (2004). Photon statistics and coherence in light emission from a random laser. Physical review letters, 93(1), 013602.

[5] Angelani, L., Conti, C., Ruocco, G., & Zamponi, F. (2006). Glassy behavior of light in random lasers. Physical Review B, 74(10), 104207.

[6] Gonzalez, I. R. R., Lima, B. C., Pincheira, P. I., Brum, A. A., Macêdo, A. M., Vasconcelos, G. L., ... & Kashyap, R. (2017). Turbulence hierarchy in a random fibre laser. *Nature Communications*, *8*(1), 15731.

[7] Lima, B. C., Pincheira, P. I., Raposo, E. P., Menezes, L. D. S., de Araújo, C. B., Gomes, A. S., & Kashyap, R. (2017). Extreme-value statistics of intensities in a cw-pumped random fiber laser. Physical Review A, 96(1), 013834.

[8] Lima, B. C., Gomes, A. S., Pincheira, P. I., Moura, A. L., Gagné, M., Raposo, E. P., ... & Kashyap, R. (2017). Observation of Lévy statistics in one-dimensional erbium-based random fiber laser. JOSA B, 34(2), 293-299.

[9] Zhou, Z., Chen, L., & Bao, X. (2021). High efficiency Brillouin random fiber laser with replica symmetry breaking enabled by random fiber grating. Optics express, 29(5), 6532-6541.

[10] Tehranchi, A., & Kashyap, R. (2019). Theoretical investigations of power fluctuations statistics in Brillouin erbium-doped fiber lasers. Optics Express, 27(26), 37508-37515

[11] Zhang, L., Xu, Y., Lu, P., Mihailov, S., Chen, L., & Bao, X. (2018). Multi-wavelength Brillouin random fiber laser via distributed feedback from a random fiber grating. Journal of Lightwave Technology, 36(11), 2122-2128.