This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2712739, Journal of Lightwave Technology

1.5 μm low threshold, high efficiency random fiber laser with hybrid Erbium-Raman gain

Han Wu, Zinan Wang, *Senior Member, IEEE, Senior Member, OSA*, Wei Sun, Qiheng He, Zedong Wei, and Yun-Jiang Rao, *Fellow, IEEE, Fellow, OSA*

***Abstract*—In this paper, we proposed a novel approach to realize low-threshold, high-efficiency 1.5 μm random fiber laser by taking advantage of hybrid Erbium-Raman gain. The numerical model is established to optimize the proposed Erbium-Raman random fiber laser, revealing the route to generate high-efficiency random lasing. The experiment is conducted to verify the concept, in which the threshold of 1.55 μm random lasing has been reduced to 75 mW and its optical conversion efficiency has reached record high (65.5%). This simple and efficient random fiber laser could provide a platform for development of novel 1.5 μm light sources for diverse applications where stable random lasing output with high-efficiency is essential.**

***Index Terms*—Random lasers, fiber lasers, Erbium-doped gain, Raman gain, Rayleigh scattering**

I. Introduction

SINCE its first demonstration in 2010, random fiber laser (RFL) based on the random Rayleigh feedback has been widely studied [1,2]. This simple system can intrinsically provide the stable lasing and good directionality, making it a promising light source for optical communication [3,4], imaging [5-7] and high power applications [8-10]. In recent works, RFLs have been tailored to be multi-wavelength [11,12], widely tunable [13], narrow bandwidth [14, 15], polarized output [16, 17], high efficiency and high output power [18-20]. Besides, RFLs have been designed to generate pulsed output by means of internal modulation [21, 22], Q-switching [23] and graphene-based external modulation [24].

As for the efficiency performance, random Raman fiber laser (RRFL) has been explored to have the ability of high-efficiency generation [10, 18-20]. Short-cavity-based RRFLs have been theoretically predicted and then experimentally demonstrated to generate ultra-high optical conversion efficiency that even approaching quantum limit [10,16,17,19]. However, the RRFLs have relatively high thresholds (at least watt level), especially with the short cavity length [8,10,16,20]. Therefore, the operating wavelengths of the aforementioned high-efficiency RRFLs focus on the 1.1 μm regime, due to the availability of high power laser as the pump source[8,10,16,18-20]. On the other hand, 1.5 μm lasers are highly demanded as light sources to be used in optical communication & sensing, LIDAR, medical research, etc., as they lie in the fiber lowest-loss and eye-safe region. However, the reported optical conversion efficiency of the RRFL at 1.5μm is less than 45% (with 3.5 W pump power) due to the lack of commercial high power pump source at 1.45 μm [12].

An alternative way to generate the 1.5 μm RFL is by utilizing the active fiber, such as Erbium-doped fiber (EDF) [25-28]. However, till now, the way to generate high efficiency random lasing with the active fiber has not been reported either theoretically or experimentally. In ref. 25, a long single mode fiber (SMF) is connected after the EDF to provide sufficient Rayleigh feedback, with the forward-pumped half-opened cavity design and high efficiency gain of the EDF, the threshold of this Erbium-doped RFL is as low as 13 mW. However, the loss introduced in the long SMF will lower the laser efficiency, resulting in the low slope efficiency (less than 15%) in these configurations [25-27]. Also, the reported RFL by utilizing hybrid Erbium-Raman gain with the open cavity design [28] suffers from the low efficiency problem (the optical conversion efficiency is less than 10%), and two pumps are used to pump the EDF and SMF respectively, which will increase system's complexity and cost.

Here, in this paper, we propose and make a comprehensive analysis on a novel Erbium-Raman RFL (ERRFL) with a single 1455 nm pump, featuring both the low threshold and high efficiency. The 1455 nm pump can provide the Raman gain in the SMF and erbium-doped gain in EDF simultaneously, and the cavity is elaborately designed to tailor the lasing power distribution. Due to the high efficiency gain of EDF, the required pump power for stimulating random lasing can be significantly reduced. A segment of SMF is placed before EDF so that the backward-propagated lasing can be efficiently amplified along the SMF via the Raman gain, and finally reaches its power maximum at the output end. With this backward pumping scheme and the hybrid Erbium-Raman gain, this novel ERRFL exhibits the threshold as low as 75 mW and

This work was supported by the Natural Science Foundation of China (61635005,61290312,41527805,61205048), Fundamental Research Funds for the Central Universities (ZYGX2015J008), Sichuan Youth Science and Technology Foundation (2016JQ0034),the PCSIRT project (IRT1218), and the 111 project (B14039).

Han Wu, Zinan Wang, Wei Sun, Qiheng He, Zedong Wei and Yun-Jiang Rao are with the Key Laboratory of Optical Fiber Sensing and Communications (Ministry of Education), University of Electronic Science and Technology of China, Chengdu, 611731, China. (E-mails: han.wu1990@hotmail.com, znwang@uestc.edu.cn, 1030926854@qq.com, heqiheng11@qq.com , 1530418884@qq.com, yjrao@uestc.edu.cn)

Zinan Wang is also with Center for Information Geoscience, University of Electronic Science and Technology of China, Chengdu 611731, China.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2712739, Journal of Lightwave Technology

the optical conversion efficiency as high as 65.5%, when the pump power is 2 W. To the best of our knowledge, this is the highest reported optical conversion efficiency of RFL operating at 1.5 µm. Recent research shows that the high power fiber laser amplifier with a clear sign of spectral broadening-free property can be achieved by utilizing the random fiber laser as the seed [9]. Therefore, the achieved 1.5µm random lasing also has the potential to serve as the seed in cladding-pumped Er-Yb-codoped high power fiber amplification systems.

II. Principle and the Numerical Modelling

To ensuring both the low threshold and high efficiency, the laser cavity is elaborately designed to take advantage of the hybrid gain and to tailor the power distribution [31]. The proposed cavity design for generating low threshold, high efficiency ERRFL is shown in Fig. 1. A 1455 nm pump is launched into 10 km-long single mode fiber (SMF, Corning SMF 28e+) through the 1455/1550 nm WDM (insert loss: 0.3 dB). The 1455 nm pump can provide Raman gain in the SMF and also remotely pump the 12 m EDF (EDFC-980-HP, Nufern) which is connected after the SMF. A FBG with the central wavelength at about 1550 nm and the reflection of 95% is spliced to the far-end of the EDF to form the backward-pumping scheme for the random lasing. All the fiber ends are angle cleaved to avoid the Fresnel reflection. The output of the laser is at the 1550 nm port of the WDM, and an isolator (insert loss: 0.2 dB) is used to further reduce the influence of parasitic reflection on the laser performance.

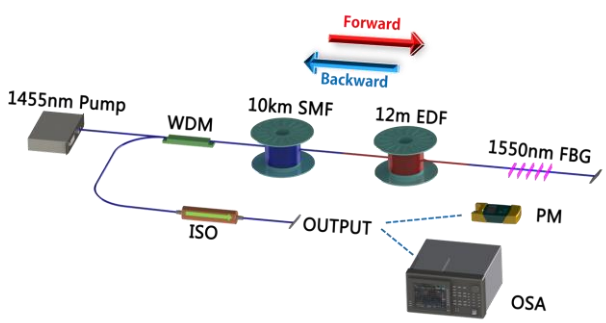


Fig.1. Configuration of proposed ERRFL.WDM-wavelength-division multiplexer with 1455 nm, 1550 nm and common ports; FBG- fiber Bragg grating with central wavelength at 1550 nm and the reflection of 95%; ISO-isolator.

With the 1455 nm remote pump, The ASE light around 1550 nm can be stimulated in EDF. The reflected 1550 nm light by the FBG will propagate backward to the SMF. The 1550 nm light can experience the Raman gain and the random distributed Rayleigh feedback in SMF. Therefore, in this way, by combining the point-reflector and the random distributed Rayleigh feedback, the 1550 nm random lasing can be stimulated with the help of the erbium-Raman hybrid gain. Moreover, in this configuration, the laser output is at the pump end of the SMF and the 1550 nm light is mainly amplified near the pump end of the fiber where the Raman gain is maximal. Therefore, the ERRFL in this configuration can feature both the low threshold and the high efficiency.

In order to make a more comprehensive analysis on the power performance of the Er-Raman RFL, we established the power balance model by considering both the EDF and the Raman gain. In the SMF section, we use the equation (1)-(3) by considering the Raman gain, fiber loss and the Rayleigh backscattering.

$$\frac{dP_p^{\pm}(z)}{dz} = \mp\alpha_p P_p^{\pm}(z) \mp g\frac{f_p}{f_s}P_p^{\pm}(z)\left(P_s^{+}(z)+P_s^{-}(z)+\Gamma_s\right) \pm \varepsilon_p P_p^{\mp}(z) \tag{1}$$

$$\frac{dP_s^{\pm}(z)}{dz} = \mp\alpha_s P_s^{\pm}(z) \pm g\left[P_s^{\pm}(z)+0.5\Gamma_s\right]\left(P_p^{+}(z)+P_p^{-}(z)\right) \pm \varepsilon_s P_s^{\mp}(z) \tag{2}$$

$$\Gamma_s = 4hf_s\Delta f_s\left\{1+\frac{1}{\exp\left[h(f_p-f_s)/(k_BT)\right]-1}\right\} \tag{3}$$

Subscripts 's' and 'p' stand for 1550 nm light and 1455 nm pump. Lower indexes'+' and '-' denotes the forward and backward waves, respectively. P denotes the optical power, f is the wave frequency. Γ_s stands for the population of phonon, where Δf_s = 0.1 THz is the lasing bandwidth, T (= 298K) is the absolute temperature and k_B is the Boltzmann's constant, h is the Plank's constant, $\alpha_{s,p}$ is the fiber loss, g is the Raman gain coefficient, $\varepsilon_{s,p}$ is the Rayleigh backscattering coefficient. The parameters used in the SMF are summarized in Table I.

TABLE I
The parameters of SMF used in the model

Wavelength(nm)	α(dB/km)	ε(km^{-1})	g($W^{-1}km^{-1}$)
1455	0.24	6×10^{-5}	0.44
1550	0.2	4.3×10^{-5}	/

In the EDF section, we calculated the power evolution through Giles model which is commonly used in erbium-doped fiber laser and amplifiers [29].

$$\frac{dP_p^{\pm}(z)}{dz} = \pm\left(\alpha_p^{*}+g_p^{*}\right)\frac{\bar{n}_2}{\bar{n}_t}P_p^{\pm}(z) \pm 2g_p^{*}\frac{\bar{n}_2}{\bar{n}_t}h\nu_p\Delta\nu_p \mp \left(\alpha_p^{*}+l_p\right)P_p^{\pm}(z) \tag{4}$$

$$\frac{dP_s^{\pm}(z)}{dz} = \pm\left(\alpha_s^{*}+g_s^{*}\right)\frac{\bar{n}_2}{\bar{n}_t}P_s^{\pm}(z) \pm 2g_s^{*}\frac{\bar{n}_2}{\bar{n}_t}h\nu_s\Delta\nu_s \mp \left(\alpha_s^{*}+l_s\right)P_s^{\pm}(z) \tag{5}$$

$$\frac{\bar{n}_2}{\bar{n}_t} = \frac{\dfrac{\left(P_s^{+}(z)+P_s^{-}(z)\right)\alpha_s^{*}}{h\nu_s\zeta}+\dfrac{\left(P_p^{+}(z)+P_p^{-}(z)\right)\alpha_p^{*}}{h\nu_p\zeta}}{1+\dfrac{\left(P_s^{+}(z)+P_s^{-}(z)\right)\left(\alpha_s^{*}+g_s^{*}\right)}{h\nu_s\zeta}+\dfrac{\left(P_p^{+}(z)+P_p^{-}(z)\right)\left(\alpha_p^{*}+g_p^{*}\right)}{h\nu_p\zeta}} \tag{6}$$

$\bar{n}_2$ is the erbium ion population of the upper energy level, and $\bar{n}_t$ is the total erbium ion population of the ground state and

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2712739, Journal of Lightwave Technology

the upper energy levels. ν, $\Delta\nu$ stand for the light frequency and the noise bandwidth. ζ (=3.87×10^{15}m^{-1}s^{-1}) is the saturation parameter, and $l_{s,p}$(= 0.01 dB/m) is the background loss. The value of absorption coefficient α* and gain coefficient g* is provided by Nufern and summarized in Table II.

TABLE II
The parameters of SMF used in the model

Wavelength(nm)	α*(m^{-1})	g* (m^{-1})
1455	0.21	0.054
1550	0.68	0.988

In simulation, we set the SMF length as L_1 and the EDF length as L_2. The total fiber length L=L_1+L_2. The boundary conditions are as follows: $P_p^+(0) = P_{in}$, $P_s^+(0) = R_L P_s^-(0)$ and $P_s^-(L) = R_R P_s^+(L)$, where P_{in} denotes the pump power, and R_L, R_R are the reflectivity at the left and right fiber end. In our configuration, R_R is set to 0.95 and R_L is set to 1×10^{-6} by considering the parasitic reflection in the experiment, which is also the typical value in previous works [10,19].

To show the EDF section's function to reduce the laser's threshold, we numerically calculate the lasing power distributions just above the thresholds for the cases with and without EDF, respectively, the results are shown in Fig. 2. For the case with 12 m EDF (Fig. 2(a)), the 1455 nm pump is set at 0.1 W, which is slightly above the threshold. The propagated 1455 nm pump through the 10 km SMF would be absorbed in EDF and provides efficient Erbium-doped gain for 1550 nm light. Therefore, it can be seen that the power of backward 1550 nm random lasing boosts rapidly in the EDF section. As a comparison, the power distribution near threshold for the case without EDF is also calculated in Fig. 2 (b), the threshold for this case is as high as 1.68 W. The power of generated random lasing is mainly distributed in the region near the pump end of the fiber where the maximal Raman gain is located. It is clearly seen that the EDF section plays significant role in reducing laser's threshold.

Figure 3 shows the numerical calculated power distribution of 1455 nm pump and 1550 nm lasing at 1 W pump power. The insert in Fig. 3(b) shows the detailed lasing power distribution within the EDF. The 1455 nm pump power decreases along the 10 km SMF and is further absorbed in the 12 m EDF. Due to the high gain in the EDF and the reflection of FBG, the power of backward 1550 nm random lasing can increase rapidly inside the EDF and reach the value of 103 mW when enters into the SMF. The backward lasing power can be further increased with the assistance of Raman gain in the 10 km SMF, and finally the laser power reaches its maximum at the output end of the SMF. The power distribution manifests the high efficiency generation because the backward-propagating 1550nm wave is sufficiently amplified in the region near the output end where the Raman gain is highest. In this way, the generated 1550nm photons near the output end would experience less loss and thus enabling the high efficiency operation.

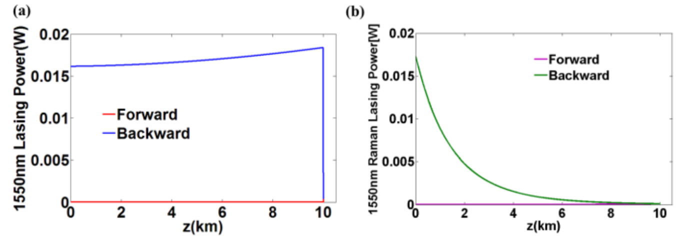


Fig.2. The calculated lasing power distributions just above the thresholds: (a) with 12 m EDF, the 1455 nm pump is set at 0.1 W (b) without EDF, the 1455nm pump is set at 1.7 W

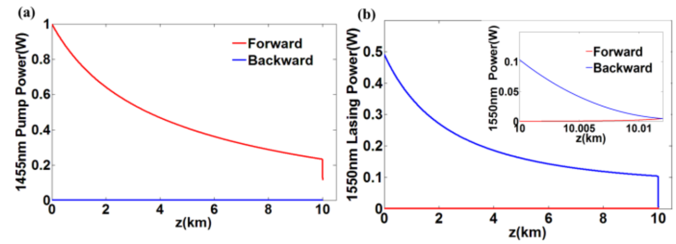
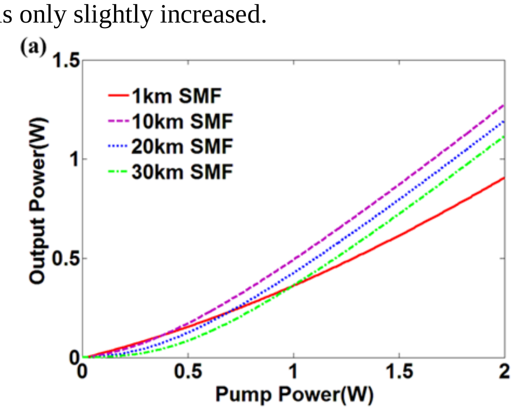


Fig.3. The power distribution calculated by the numerical simulation at 1 W of pump power: (a) 1455 nm pump; (b) 1550 nm random lasing; Insert: the detailed lasing power distribution within the EDF.

To make the optimization of this laser system, we numerically investigate the influence of the length of SMF or EDF on the laser performance. Fig. 4(a) shows the effect of the SMF's length when the EDF's length is fixed to 12 m. When the SMF is relatively short (1 km), the Raman amplification for 1550 nm light in SMF would be insufficient, thus significantly reducing the slope efficiency. One the other hand, if the SMF is too long (20 km or 30 km), the 1455 nm pump would experience higher loss before entering the EDF, resulting in the higher threshold. Fig. 4(b) shows the effect of the EDF's length when the SMF's length is fixed to 10 km. With 5 m EDF, the absorption of 1455 nm pump in the EDF is insufficient, and the relatively low EDF gain will increase the threshold significantly. With the reduction of threshold, the output power increases continually when the EDF length increases from 5 m to 12 m. Further increasing the EDF length to 15 m, the output power is only slightly increased.



This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2712739, Journal of Lightwave Technology

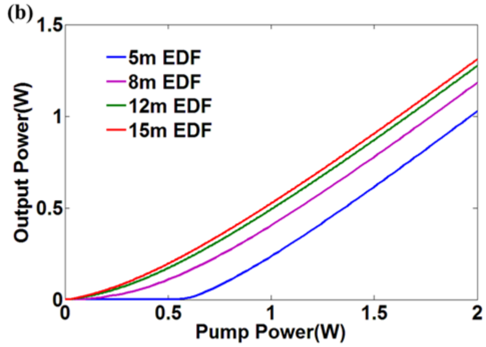


Fig.4. The output power versus pump power curve calculated by the numerical simulations with different fiber length: (a) the length of SMF is varied from 1 km to 30 km when the EDF's length is fixed to 12 m;(b) the length of EDF is varied from 5 m to 15 m when the SMF's length is fixed to 10 km.

III. Experimental Results and Discussions

According to the numerical calculations, we choose the length of SMF as 10 km and the length of EDF as 12 m in our experimental setup. Fig. 5 shows the output power of 1550 nm random lasing versus the launched pump power (the pump power measured after the WDM). The output power is measured after the isolator with the compensation of the insert loss of isolator and WDM (total insertion loss: 0.5 dB). Due to the high gain coefficient of the EDF, the random laser's threshold is only 75 mW. After the pump power exceeds the threshold, the output lasing power increases nonlinearly and the slope efficiency (defined as dP_{out}/dP_{pump}) increases continually at first. When the pump power exceeds 0.6 W, the output power increases almost linearly with the pump power (see the insert in Figure 5). With the linear fitting, the calculated slope efficiency is as high as 80% when the pump power is in the range of 0.6-2 W. As a result, the generated random lasing is 1.31 W with 2 W of pump power, corresponding to the 65.5% of optical conversion efficiency. To the best of our knowledge, this is the highest achieved optical conversion efficiency of RFL operating at 1.5 μm. The 1660 nm Stokes component induced by the 1.5 μm random lasing has not been stimulated at the maximum pump power, because for the 1660nm random lasing, the cavity is fully open without any strong point-reflector, the laser threshold with 10km SMF is much higher than the generated 1.5 μm lasing power [2]. The solid line corresponds to the numerically calculated output power, the numerical results can make a good agreement with the experimental results. We have measured the residual pump power after the FBG is about 110 mW at 2 W pump power. It should be noted that the quantum limit ($\eta = \lambda_p/\lambda_s$) is about 93.8% in this system, the obtained efficiency is lower than the ideal value because of the insufficient absorption of the pump in EDF section and the fiber loss for the generated 1550 nm photons.

The spectra evolution with the increase of pump power is shown in Fig. 6. Fig. 6(a) shows that when pump power reaches 0.075 W, narrow spikes appear in the relatively narrow spectrum range around 1550 nm, which suggests the generation of random lasing. These narrow spectral components are unstable because of the gain competition and the cooperative Rayleigh-Brillouin scattering [30]. The peak power of the spectrum increases but the spectrum is still unstable at 0.15 W pump power. By further increasing the pump power to 0.74 W, the spectrum becomes stabilized with a single peak localized at 1549.97 nm. The 3 dB bandwidth (BW) of the peak is only about 0.1 nm at 0.74 W pump power, which is much less than the 3 dB BW of the FBG (0.2 nm). Fig. 6(b) shows the spectra variation when pump power increases from 1.07 W to 2 W. It can be seen that the wings of the spectrum broaden continually. We record the BW values after the spectrum has been stabilized. The variations of the 3 dB and 20 dB BW with the pump power are plotted in Fig. 6(c) and Fig.6(d), respectively. With the pump power increases from 0.74 W to 2 W, the 3dB BW of random lasing increases slowly from 0.1 nm to 0.19 nm, which is still less than the bandwidth of FBG. However, the 20 dB bandwidth of the laser spectrum increases continually in the ERRFL, increases almost linearly from 1.3 nm to 4.3 nm when pump power varies from 0.74 W to 2 W. The evolution of 3 dB and 20 dB bandwidth with pump power could be attributed to the complex nonlinear interactions such as four-wave mixing, self-phase modulation (SPM) and cross-phase modulation (XPM) [30] in this Erbium-Raman hybrid gain system. Indeed, to fully understand this spectral behavior, the numerical model accounting these nonlinear interactions needs to be built, which is worth to be further investigated with extensive efforts. Fig.7 shows the spectral evolution of the residual 1455 nm pump. The spectrum of residual pump also exhibits unstable spikes and dips at relatively low pump power and is stable when pump power increases to 0.74 W. Further increasing the pump power, the residual pump's spectrum broadens continually, the 3 dB BW value increases from 0.9 nm to 1.9 nm when pump power increases from 0.74 W to 2 W.

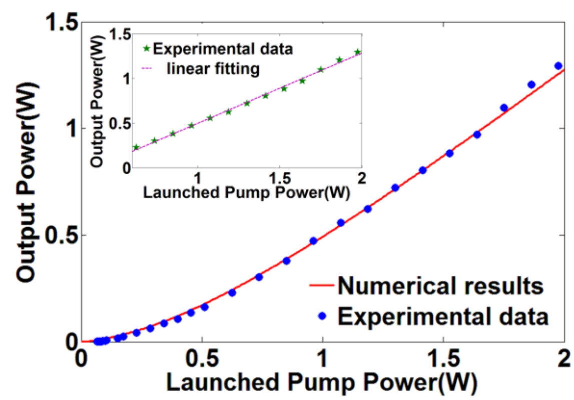
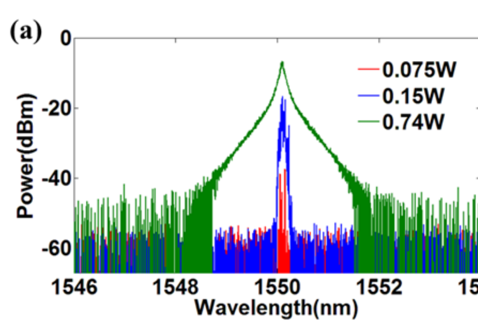


Fig. 5 Output power of the random lasing versus pump power (dots: experimental data; solid line: numerical simulation result).Insert: The linear fitting of experimental data when pump power is in the range of 0.6-2 W.



This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2712739, Journal of Lightwave Technology

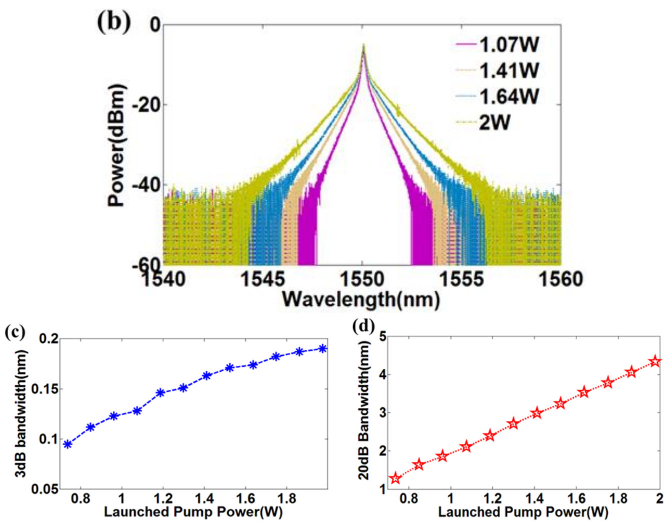


Fig. 6. Spectra information of random lasing: (a) spectra evolution of random lasing when pump power is in the range of 0.075 W-0.74 W; (b) spectra evolution of random lasing when pump power is in the range of 1.07-2 W; (c) The variation of the 3 dB BW with the pump power; (d) The variation of the 20 dB BW with the pump power;

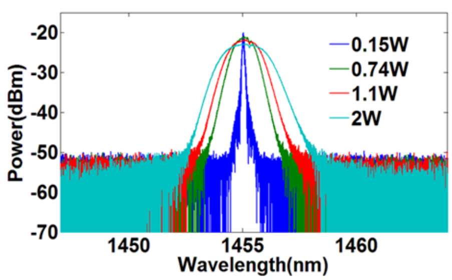


Fig.7. Spectra of the residual pump at different pump power.

To validate the random lasing behavior in our experimental scheme, we measure the radio frequency (RF) spectrum at 1.07 W pump power, which is shown in Fig. 8. It is clear that there is no longitudinal mode beating corresponding to $c/2nl \approx 10$ kHz spacing, which can validate the random lasing behavior.

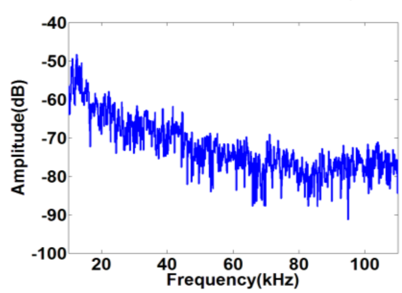


Fig.8. The RF spectrum measurements of output lasing.

IV. Summary

In conclusion, we have proposed a new approach to realize 1.5 μm RFL featuring both low-threshold and high-efficiency, by utilizing Erbium-Raman hybrid gain and the backward-pumping scheme. The theoretical model is established based on the power balance equations by considering both the Raman and EDF gains. With the hybrid gain, the threshold can be significantly reduced, and with the backward-pumping, the random lasing power can reach its maximum at the output, ensuring the high efficiency operation. The power performance of the proposed ERRFL can be well described and optimized by the theoretical model. With the proper choose of the fiber length, the experimentally achieved laser threshold can be reduced to 75 mW. Remarkably, the experimentally demonstrated optical conversion efficiency is of record high in the 1.5 μm regime, reaching 65.5% when pump power is 2 W. With these features, this work provides an effective way to generate watt-level 1.5 μm random lasing with relatively low pump power. Moreover, the concept of using hybrid gain is benefit to tailor the power distribution more flexibly, which could inspire the new explorations to enhance the performances of fiber lasers and amplifiers based on the combinations of passive fibers and active fibers.

References

[1] S. K. Turitsyn, S. A. Babin, A. E. El-Taher, P. Harper, D. V. Churkin, S. I. Kablukov, J. D. Ania-Castanon, V. Karalekas, and E. V. Podivilov, "Random distributed feedback fibre laser," *Nat. Photonics*, vol. 4, pp. 231–235 , 2010.

[2] S.K. Turitsyn, S.A. Babin, D.V. Churkin, I.D. Vatnik, M. Nikulin, E.V. Podivilov, "Random distributed feedback fibre lasers," *Physics Reports*, vol. 542, pp.133–193,2014.

[3] J. Nuño, M. Alcon-Camas, and J.D. Ania-Castañón, "RIN transfer in random distributed feedback fiber lasers," *Opt. Express*, vol. 20, pp. 27376-27381, 2012.

[4] M. Tan, P. Rosa, S. T. Le, Md. A. Iqbal, I. D. Phillips, and P. Harper, "Transmission performance improvement using random DFB laser based Raman amplification and bidirectional second-order pumping," *Opt. Express* , vol. 24, pp. 2215-2221, 2016.

[5] B. Redding, M. A. Choma, and H. Cao, "Speckle-free laser imaging using random laser illumination", *Nat. Photonics*, vol. 6, pp. 355, 2012.

[6] B. Redding, P. Ahmadi, V. Mokan, M.Seifert, M. A. Choma, and H. Cao, "Low-spatial-coherence high-radiance broadband fiber source for speckle free imaging," *Opt. Lett*, vol. 40, pp. 4607-4610, 2015.

[7] A.S. L. Gomes, B. C. Lima, P. I. R. Pincheira, A. L. Moura, M. Gagné, E. P. Raposo, Cid B. de Araújo, and R. Kashyap, "Glassy behavior in a one-dimensional continuous-wave erbium-doped random fiber laser", *Phys. Rev. A*, vol. 94, pp. 011801(R),2016

[8] H. Zhang, P. Zhou, X. Wang, X. Du, H. Xiao, and X. Xu, "Hundred-watt-level high power random distributed feedback Raman fiber laser at 1150 nm and its application in mid-infrared laser generation," *Opt. Express*, vol. 23, pp. 17138-17144 ,2015.

[9] X. Du, H. Zhang, P. Ma, H. Xiao, X. Wang, P. Zhou, and Z. Liu, "Kilowatt-level fiber amplifier with spectral-broadening-free property, seeded by a random fiber laser," *Opt. Lett*, vol. 40, pp. 5311-5314 , 2015.

[10] Z. Wang, H. Wu, M. Fan, L. Zhang, Y. Rao, W. Zhang, and X. Jia, "High power random fiber laser with short cavity length: theoretical and experimental investigations," *IEEE J. Sel. Top. Quantum Electron*., vol. 21, pp. 0900506, 2015.

[11] S. Sugavanam, Z. Yan, V. Kamynin, A. Kurkov, L. Zhang, and D. Churkin, "Multiwavelength generation in a random distributed feedback fiber laser using an all fiber Lyot filter," *Opt. Express*, vol. 22, pp. 2839–2844 , 2014.

[12] A. E. El-Taher, P. Harper, S. A. Babin, D. V. Churkin, E. V. Podivilov, J. D.Ania-Castanon, and S. K. Turitsyn, "Effect of Rayleigh-scattering distributed feedback on multiwavelength Raman fiber laser generation," *Opt. Lett*, vol. 36, pp. 130–132 , 2011.

[13] L. Zhang, H. Jiang, X. Yang, W. Pan, and Y. Feng, "Ultra-wide wavelength tuning of a cascaded Raman random fiber laser," *Opt. Lett*, vol. 41, pp. 215-218, 2016.

[14] D. Leandro, S. Rota-Rodrigo, D. Ardanaz, and M. Lopez-Amo, "Narrow-Linewidth Multi-Wavelength Random Distributed Feedback Laser," *J. Lightwave Technol*. Vol. 33, pp. 3591-3596 , 2015.

[15] T. Zhu, X. Bao, and L. Chen, "A self-gain random distributed feedback fiber laser based on stimulated Rayleigh scattering," *Opt. Commun*, vol. 285, pp. 1371, 2012.

[16] E. A. Zlobina, S. I. Kablukov, and S. A. Babin, “Linearly polarized random fiber laser with ultimate efficiency,” *Opt. Lett*, vol. 40, pp. 4074-4077, 2015.
[17] S. A. Babin, E. A. Zlobina, S. I. Kablukov , and E. V. Podivilov, “High-order random Raman lasing in a PM fiber with ultimate efficiency and narrow bandwidth,” *Sci. Rep*,vol. 6, pp. 22625 , 2016.
[18] I. D. Vatnik, D. V. Churkin, E. V. Podivilov, and S. A. Babin, “High efficiency generation in a short random fiber laser,” *Laser Phys. Lett*, vol. 11, pp. 075101, 2014.
[19] X. Du, H. Zhang, X. Wang, P. Zhou, and Z. Liu, “Short cavity-length random fiber laser with record power and ultrahigh efficiency,” *Opt. Lett*, vol. 41, pp.571-574, 2016.
[20] H. Wu, Z. Wang, M. Fan, L. Zhang, W. Zhang, and Y. Rao, “Role of the mirror’s reflectivity in forward-pumped random fiber laser,” *Opt. Express*, vol. 23, pp. 1421-1427, 2015.
[21] M. Bravo, M. Fernandez-Vallejo, and M. Lopez-Amo, “Internal modulation of a random fiber laser,” *Opt. Lett*, vol. 38, no. 9, pp. 1542-1544, 2013.
[22] H. Wu, Z. Wang, Q. He, M. Fan, Y. Li, W. Sun, L. Zhang, Y. Li and Y. Rao, “Polarization-modulated random fiber laser,” *Laser Phys. Lett*, vol. 13, pp. 055101, 2016.
[23] Y. Tang and J. Xu, “A random Q-switched fiber laser,” *Sci. Rep*, vol. 5, pp. 9338 , 2015.
[24] B. C. Yao, Y. J. Rao, Z. N. Wang, Y. Wu, J. H. Zhou, H. Wu, M. Q. Fan, X. L. Cao, W. L. Zhang, Y. F. Chen, Y. R. Li, D. Churkin, S. Turitsyn, and C. W. Wong, “Graphene based widely-tunable and singly-polarized pulse generation with random fiber lasers,” *Sci. Rep*, vol. 5, pp. 18526, 2015.
[25] L. Wang, X. Dong, P. P. Shum, and H. Su, “Tunable erbium-doped fiber laser based on random distributed feedback,” *IEEE Photon. J*, vol. 6, pp. 1501705, 2014.
[26] L. Wang, X. Dong, P.P. Shum, C. Huang, H. Su, “Erbium-doped fiber laser with distributed Rayleigh output mirror,” *Laser Physics*, vol, 24, no. 11, pp. 115101, 2014.
[27] S. Sugavanam, M. Z. Zulkifli and D. V. Churkin, “Multi-wavelength erbium/Raman gain based random distributed feedback fiber laser”, *Laser Physics*, vol. 26, pp. 015101, 2016.
[28] W. L. Zhang, S. W. Li, R. Ma, Y. J. Rao, Y. Y. Zhu, Z. N. Wang, X. H. Jia, and J. Li, “Random distributed feedback fiber laser based on combination of Er-doped fiber and single-mode fiber,” *IEEE J. Sel. Top. Quantum Electron*, vol. 21, pp. 44–49, 2015.
[29] C. R. Giles and E. Desurvire, “Modeling erbium-doped fiber amplifiers,” *J. Lightwave Technol.* vol. 9, pp.271–283,1992.
[30] I. A. Lobach, S. I. Kablukov, M. I. Skvortsov, E. V. Podivilov, M. A. Melkumov, S. A. Babin, and E. M. Dianov, “Narrowband random lasing in a Bismuth-doped active fiber,” *Sci. Rep.* vol. 6, pp. 30083, 2016
[31] H. Wu, Z. N. Wang, W. Sun, Q. H. He, Y. J. Rao, “1.5-μm low threshold, high efficiency Erbium-Raman random fiber laser,” *Proc. SPIE 10323*, 25th International Conference on Optical Fiber Sensors, 103237M, 2017

Han Wu is now working toward the Ph.D. degree for optical engineering at the Key Lab of Optical Fiber Sensing & Communications (Education Ministry of China), University of Electronic Science & Technology of China, Chengdu, China. He received the B.S. degree and M.S. degree from University of Electronic Science & Technology of China in 2012 and 2015, respectively. His current interests include random fiber laser and nonlinear fiber optics.

Zinan Wang received the PhD degree from Beijing University of Posts and Telecommunications, China, in 2009 (During 2007-2009, he was with Alcatel-Lucent Bell Labs as a visiting student). He was with Cornell University, as a postdoctoral research associate during 2009-2010. He joined University of Electronic Science and Technology in 2010, and became a full professor since 2015. His research interests include distributed fiber sensing and nonlinear fiber optics. He has published more than 100 papers in international journals and conference proceedings, and he is holding 10 Chinese patents and 1 US patent. He has given more than 10 invited talks at international conferences, and his research was highlighted in 'Optics in 2014' by OSA Optics and Photonics News. Zinan Wang is an Associate Editor for IEEE Photonics Technology Letters, and a Senior Member of IEEE & OSA.

Wei Sun is now working toward the Master’s degree for optical engineering at the Key Lab of Optical Fiber Sensing & Communications (Education Ministry of China), University of Electronic Science & Technology of China, Chengdu, P.R China. She received the B.S. degree from University of Electronic Science & Technology of China in 2014. Her research interests include random fiber laser and optical fiber amplification.

Qiheng He is now working toward the Master’s degree for optical engineering at the Key Lab of Optical Fiber Sensing & Communications (Education Ministry of China), University of Electronic Science & Technology of China, Chengdu, P.R China. His current interests include random fiber laser and amplifier.

Zedong Wei is now working toward the Master’s degree for optical engineering at the Key Lab of Optical Fiber Sensing & Communications (Education Ministry of China), University of Electronic Science & Technology of China. He received the B.S. degree from Anhui University in 2015. His current interests include random fiber laser and fiber sensing.

Yunjiang Rao received the Ph.D. degree in optoelectronic engineering from Chongqing University, Chongqing, China, in 1990. He joined the Electric and Electronic Engineering

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2712739, Journal of Lightwave Technology

Department at Strathclyde University, U.K. as a Postdoctoral Research Fellow during 1991–1992 and Applied Optics Group of the Physics Department at Kent University, U.K. as a Research Fellow and then a Senior Research Fellow during 1992–1999. From 1999 to 2004, he was a Chang-Jiang Chair Professor in Chongqing University. From 2004, he held the Chang-Jiang Chair Professor in University of Electronic Science and Technology of China. He is currently the Director of the Key Lab of Optical Fiber Sensing and Communications (Ministry of Education), University of Electronic Science and Technology of China. Prof. Rao is a Fellow of IEEE, OSA and SPIE. His research interests include fiber-optic sensors and lasers.