Jurnal
Teknologi

Full Paper

TUNABLE ULTRA-LONG RANDOM DISTRIBUTED FEEDBACK FIBER LASER

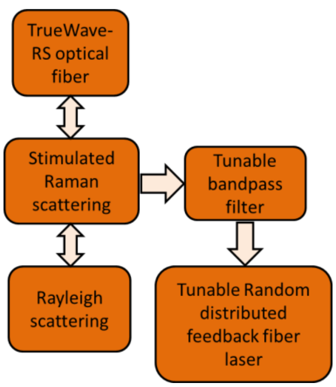
Nadiah H. Z. Abidin[a], M. H. Abu Bakar[a*], N. Tamchek[b], M. A. Mahdi[a]

[a]Wireless and Photonics Networks Research Center, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[b]Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

Article history
Received
15 August 2015
Received in revised form
15 November 2015
Accepted
30 December 2015

*Corresponding author
mhab@ieee.org

Graphical abstract



Abstract

A 72 km open-ended symmetrical tunable random distributed feedback fiber laser (RDB-FL) with different pumping schemes is presented in this study. The random distributed feedback was contributed by Rayleigh scattering in the single-mode fiber while distributed gain was provided by the effect of stimulated Raman scattering. The pumping schemes tested with the configuration was outward and inward pumping, where these would be backward and forward pumping in a non-symmetrical configuration of a fiber laser, respectively. The tuning range was also varied in conjunction with the different pumping schemes to determine the optimum performance. Random lasing in the RDB-FL was achieved by utilizing multiple scattering in the disordered gain medium to achieve resonance. With pump power limited to 1.5 W, the best threshold was measured as low as 1.4 W while the highest total output power was at 8 mW. In outward pumping configuration, the wavelengths that are within the maximum Raman gain (1555-1565 nm) show the best peak powers and total output power with a narrow linewidth, as low as 0.25 nm.

Keywords: Random distributed feedback fiber laser, fiber laser, Rayleigh scattering, stimulated Raman scattering, Raman gain, random laser

Abstrak

Laser gentian optik boleh tala sepanjang 72 km dengan maklum balas rawak dan teragih (RDB-FL) yang terbuka dan simetri menggunakan keadah pengepaman yang pelbagai, dibentangkan dalam kajian ini. Maklum balas rawak dan teragih disumbangkan oleh serakan Rayleigh dalam gentian mod-tunggal manakala gandaan teragih disumbangkan oleh efek daripada rangsangan serakan Raman. Kaedah pengepaman yang diuji dengan konfigurasi ini adalah pengepaman ke-luar dan ke-dalam yang akan menjadi pam ke-belakang dan ke-hadapan sekiranya dalam konfigurasi bukan simetri laser gentian optik. Julat penalaan juga telah diubah disamping dengan kaedah pengepaman untuk menentukan prestasi yang optimum. Laser rawak dalam RDB-FL dicapai menggunakan serakan yang berbilang dalam pengantara dengan gandaan yang tidak tertib, untuk mencapai resonans. Dengan kapasiti pam terhad sebanyak 1.5 W, ambang laser yang terbaik adalah serendah 1.4 W, manakala jumlah kuasa output yang tertinggi adalah sebanyak 8 mW. Dalam konfigurasi yang menggunakan kaedah pengepaman ke-luar, jarak gelombang yang berada dalam lingkungan gandaan Raman yang tertinggi (1555-1565 nm) menunjukkkan prestasi kuasa puncak dan kuasa output yang terbaik, dengan lebar garis yang sempit, serendah 0.25 nm

Kata kunci: Gentian optik dengan maklum balas rawak dan teragih laser, laser gentian, serakan Rayleigh, serakan Raman terangsang, gandaan Raman, laser rawak

1.0 INTRODUCTION

In 2010, a novel type of random laser utilizing standard optical communication fiber; random distributed feedback fiber laser (RDB-FL) was introduced [1] endowing the conventional fiber lasers and amplifiers as old technology [2-3]. RDB-FL is an extension to traditional random lasers, where the term 'random' represents a laser with feedback due to random scattering mechanism as opposed to the reflective feedback by the mirrors [4]. In order for a laser to acquire the characteristics of a random laser, there are two main components needed: 'scatterers' for the purpose of scattering mechanism and a gain medium. The advantage provided by the scatterers is that it increases the path length of the light before leaving the medium, giving rise to a larger optical gain to acquire the threshold condition.

Random lasers have been tested on various platforms such as: laser dye solution with nanoparticles [3], rare earth doped laser crystal powder [4], laser gas with two types of atom (one that amplifies light and the other that scatters) [6], direct band gap semiconductors [7] and also fiber based random laser with Rayleigh scattering feedback or RDB-FL [1, 8-16]. Fiber based random laser is deemed to have weaker random scattering compared to the rest of the traditional random lasers that utilize strong scattering. Fiber based random laser is also peculiar in the random laser class in a sense that one cannot simply introduce more scatterers to the optical fiber as needed but instead, the scatterers in the optical fiber are fixed. The weak multiple scattering induced by Rayleigh scattering (RS) in the optical fiber is due to the inhomogeneity of the refractive index. This property causes the operation of fiber based random laser to be distinctive as opposed to the other traditional random lasers. The effective reflection from RS is ~0.1 % within the fiber [1]. Additionally, the RS influences the outcome of the backscattered radiation coefficient which is averaged to be $\varepsilon \sim 5\text{x}10\text{-}5\ \text{km}^{-1}$ in a SMF [8]. The total backscattered radiation is negligibly small and continuous even in a very long passive fiber. However, the situation is dramatically changed when the multiply-scattered radiation is amplified via Raman gain.

As the Raman gain provides a relatively flat and broad spectral profile, a number of methods have been proposed to produce tunable RDB-FL. Some of them were formed by using different tunable filters such as manual tunable filter [11], bandpass filter [12,13], optical grating filter [14], multi-channel wavelength tunable component [15], F–P cavity [15,16] combined with a long-period fiber gratings based Mach–Zehnder interferometer [15] and with different gain mediums such as SMF [12-15], erbium-doped fiber in combination with SMF [16], and ytterbium-doped fiber in combination with SMF [11]. In this study, we propose a tunable RDB-FL where the gain medium is TrueWave-RS optical fiber while the tuning component is a tunable bandpass filter sandwiched between the fiber spools. The configuration was also tested and compared with different pumping schemes; outward and inward pumping. The random fiber laser gain media consists of a mirrorless open ended cavity made solely from the optical fiber and was pumped bidirectionally

2.0 EXPERIMENTAL

Figure 1 shows the schematic of the tunable RDB-FL employing both outward pumping and inward pumping. The main difference between the two configurations is the position of the fiber spools with respect to the pump signal. Outward pumping refers to when the setup is pumped centrally and bidirectional, while inward pumping is pumped peripherally and bidirectional. Both of the setups have a span of 72 km contributed by two fiber spools of Truewave-RS fiber (L= 2x36 km = 72 km). The loss coefficient of the fiber is 0.22 dB/km in the C-band transmission window. The Raman pump centered at wavelength 1455 nm with maximum power of 1.5 W is coupled to a 50/50 coupler to administer equal amount of power into the 1450/1550 WDM couplers. The WDM couplers multiplex the pump signal into the setup and demultiplex the pump signal from the output. The TrueWave fiber Raman gain coefficient is 0.67 $\text{W}^{-1}\text{km}^{-1}$. Furthermore, a tunable band pass filter (TBF) is incorporated at the center of both setups to provide the laser tunability at a broad range of transmission between 1535-1565 nm. The insertion loss of the TBF is 3.88 dB while the 3 dB linewidth measured by an ASE broadband source is 0.88 nm. Meanwhile, the isolators at each end serve to minimize end reflections to ensure that feedback is only due to Rayleigh scattering. The output port is spliced to a fiber pigtail to measure for laser output power and spectra using a power meter and optical spectrum analyzer (resolution: ~0.02 nm) respectively. Since the setups both have a symmetrical configuration, both sides of each setup were ensured to correspond equally in terms of power and spectral output.

The fundamental principle behind the operation of random distributed feedback fiber is by using the optical fiber as a gain medium without the presence of any physical reflectors and taking advantage of stimulated Raman scattering for amplification and Rayleigh scattering as distributed feedback. The multiple scattering occurring continuously and amplified by Raman gain grows increasingly significant and forms the distributed virtual feedback as it accumulates over the long length fiber.

The distributed virtual feedback induced by the RS forms the transverse confinement needed to sustain light oscillation. The integration of the tunable band pass filter at the center of the configuration suppresses modes that are outside of the filter bandwidth which results in a controllable lasing wavelength. However, the downside to this is wastage of optical power. The oscillating radiated light that is outside the spectral bandwidth of the TBF is attenuated every time it passes through, generating a narrower spectral output but with less total power. This will cause a laser configuration with a narrow bandpass filter to reach threshold lasing at a higher pump power compared to a laser configuration with none.

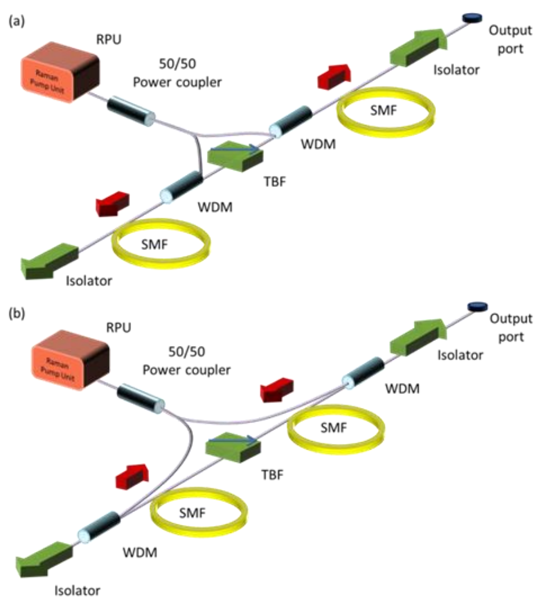


Figure 1 Schematic of tunable RDB-FL employing (a) outward pumping and (b) inward pumping

3.0 RESULTS AND DISCUSSION

Figure 2 shows the output power development at different tuning wavelengths with varying pump power. The TBF was tuned at every 5 nm in the range of 1535-1565 nm while the pump power was varied from 80 mW to 1650 mW. The results show that both pumping configuration have the highest output power at the wavelength 1555 nm (red). The highest output power recorded for outward and inward pumping was measured to be approximately 4 mW and 0.26 mW respectively at pumping power of 1500 mW. This is due to the tuning wavelength being at the highest spectral Raman gain maximum. Within the pump range, the wavelengths that manage an output laser power well above the threshold are between 1555-1565 nm for outward pumping configuration. The three wavelengths ({1555, 1560, 1565} nm) all display a threshold condition at approximately 1400 mW. This behavior is similar to open-ended tunable RDB-FL employing SMF [10] where the threshold condition recorded was at approximately 1500 mW. The slightly lower threshold of the proposed setup with outward pumping can be attributed to the higher Raman gain of the TrueWave fiber compared to the Raman gain of a standard single mode fiber. Subsequently, the rest of the wavelengths for outward and inward pumping setups (other than outward: 1555-1565 nm) are observed to yield output powers below 0.3 mW. It is concluded that the wavelengths have not reached the threshold condition even at the maximum pump power (1.5W). The reasoning behind the lower threshold of outward pumped configuration will be discussed in section 4.0.

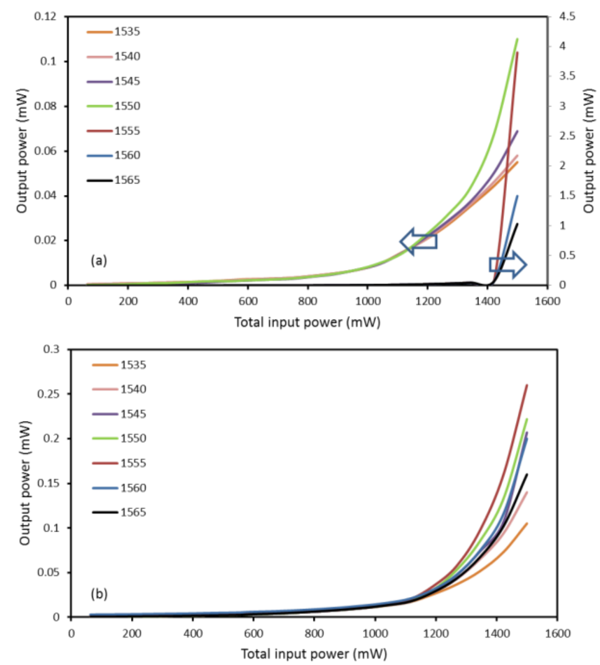


Figure 2 Laser output for (a) outward and (b) inward pumping with varying pump power

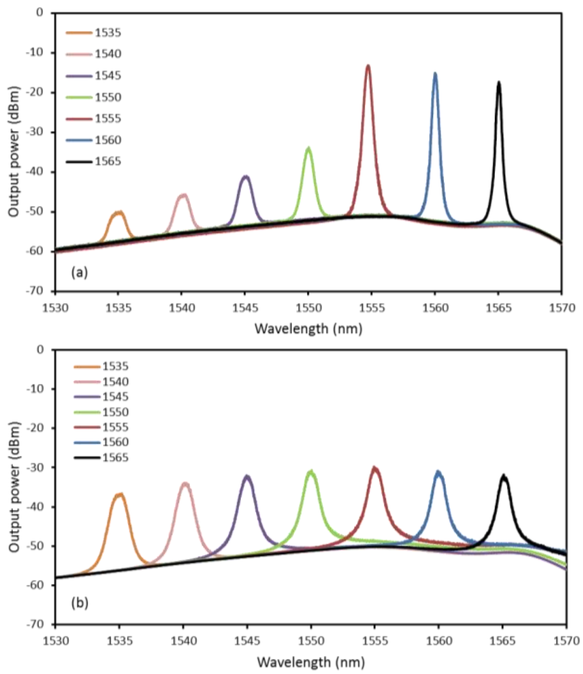


Figure 3 Spectral output for (a) inward pumping and (b) outward pumping configuration at different wavelengths and at maximum pump power

Figure 3 shows the spectral output for both pumping configurations as a function of the tunable bandpass filter wavelength. In outward pumping configuration, the wavelengths that are within the maximum Raman gain (1555-1565 nm) show better spectral peak powers compared to the rest of the wavelengths. The same behavior is not observed for inward pumping setup as no specific spectra shows dominancy over the rest. To further observe the spectral power, the spectral output was plotted in linear scale in Figure 4.

From Figure 4, it is evidently clear that in outward pumping configuration, the 1555-1565 nm wavelengths show that the laser has already reached beyond the threshold condition. This is exhibited by the characteristics of a stable clean spectrum [12-16]. Meanwhile, in inward pumping configuration, the lasers have taken form but show unstable noisy characteristics; thus proving that they are still below the threshold condition region. This is also the case for the other wavelengths in the outward pumping configuration (1535-1550 nm). For both setups, the 1555 nm wavelength shows the best performance in terms of spectral peak power. Again, this is because the filter is tuned at the maximum Raman gain.

The reasoning behind the difference in threshold condition between outward and inward configuration is explained as the following. The highest Rayleigh scattering feedback will be situated near the highest longitudinal distribution of the signal. The location of the highest longitudinal signal gain is called L_{RS} or the amplification region and is calculated to be ~35 km according to [1]. This point with the highest RS will form the main virtual feedback. According to longitudinal distribution of inward pumping, the amplification region will end at 35 km from both ends of the cavity forming the main virtual feedback around the center of the cavity. Hence, the radiation propagating into the TBF is multiply-scattered in lossy region while impeded by the main virtual feedback. This attenuates it severely on both ends of the filter. Thus, more pump power is needed to reach the threshold condition. On the other hand, for outward pumping, the end of amplification region will be situated at the near the ends of the laser cavity, establishing confinement for the whole 72 km cavity. The propagating light within the virtual cavity is able to oscillate while simultaneously amplified via Raman gain. This justifies the reason where outward pumping was able to achieve lasing at lower pump power than inward pumping configuration.

The 3 dB linewidth of both pumping configurations are exhibited in Figure 5 as above. The 3 dB linewidth decreases with increasing wavelength. Once the modes with particular wavelength have reached beyond the threshold condition, the linewidth is narrowed considerably as manifested by the wavelengths 1555-1565 in the outward pumping configuration. The narrowest linewidth is attained by the 1560 nm wavelength in the outward pumping configuration.

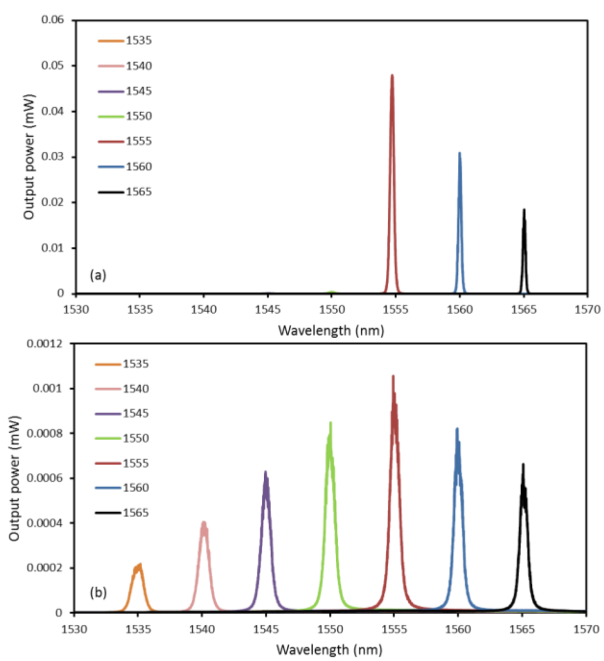


Figure 4 Spectral output for (a) outward pumping and (b) inward pumping configuration at different wavelengths with maximum pumping power in linear scale

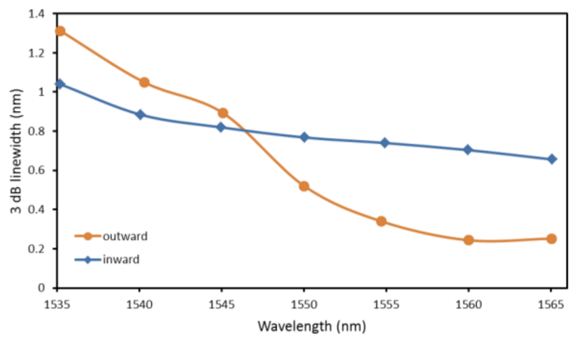


Figure 5 3 dB linewidth of the spectral output (every 5 nm in the range 1535-1565 nm) for outward pumping and inward pumping configuration

It can also be seen that the 3 dB linewidth of outward pumped configuration is wider than inward pumped configuration before it reaches lasing threshold. This can be simply explained from the direction of the pump. In inward pumping, majority of pump light that is converted into Stokes signal propagates towards the TBF even though it is backscattered by Rayleigh in the optical fiber. This causes majority of the modes to conform to the spectral width of the filter. On the other hand, in outward pumping, majority of the Stokes signal propagates towards the output end and only a partial amount is backscattered into the TBF and is tailored to the TBF bandwidth as it passes through. However, as light from the output end oscillates, the minority tailored modes will compete with the non-tailored modes. This causes the spectral width to be wider.

5.0 CONCLUSION

It can be concluded from the results and discussion that inward and outward pumping affects the laser formation differently due to the distinctive virtual feedback arrangement according to the Raman gain distribution. The Raman gain distribution influences the strength of the Rayleigh scattering which impacts the virtual feedback as well as the formation of virtual cavities. For power efficiency and threshold condition at a limited pump power (1.5W), outward pumping is considered the preferable scheme.

Acknowledgement

This work is funded by UPM Research University Grant Scheme (RUGS) #05-02-12-2307RU and partly funded by three years scholarship of Academic Training Scheme for Institutions of Higher Education (SLAI), Ministry of Higher Education (MOHE) Malaysia. The authors would also like to acknowledge contribution from MOHE High Impact Research grant #A000007-50001.

References

[1] Turitsyn, S. K., Babin, A. A., El-Taher, A. E., Harper, P., Churkin, D. V, Kablukov, S. I., Ania- Castanon, J. D., Karalekas, K., and Podivilov, E. V. 2010. Random Distributed Feedback Fibre Laser. *Nature Photonics*. 4: 231-235.

[2] Bakar, M. H., Mahdi, M. A., Mokhtar, M., Abas, A. F., and Yusoff, N. M. 2009. Investigation on the Effect of Stimulated Raman Scattering in Remotely-Pumped L-Band Erbium-Doped Fiber Amplifier. *Laser Physics Letters*. 6(8): 602-606.

[3] Bakar, M. A., Abas, A. F., Mokhtar, M., Mohamad, H., and Mahdi, M. A. 2011. Utilization of Stimulated Raman Scattering as Secondary Pump on Hybrid Remotely-Pump L-Band Raman/Erbium-Doped Fiber Amplifier. *Laser Physics*. 21(4): 722-728.

[4] Cao, H., Xu, J. Y., Ling, Y., Burin, A. L., Seeling, E. W., Liu, X., and Chang, R. P. 2003. Random Lasers with Coherent Feedback. *IEEE Journal of Selected Topics in Quantum Electronics*. 9(1): 111-119.

[5] Markushev, V. M., Zolin, V. F., and Briskina, C. M. 1986. Luminescence and Stimulated Emission of Neodymium in Sodium Lanthanum Molybdate Powders. *Soviet Journal of Quantum Electronics*. 16(2): 281.

[6] Vuletic, V. 2013. Lasers: Amplified by Randomness. *Nature Physics*. 9(6): 325-326.

[7] Noginov, M. A., Zhu, G., Fowlkes, I., and Bahoura, M. 2004. GaAs Random Laser. *Laser Physics Letters*. 1(6): 291.

[8] Turitsyn, S. K., Babin, S. A., Churkin, D. V., Vatnik, I. D., Nikulin, M., and Podivilov, E. V. 2014. Random Distributed Feedback Fibre Lasers. *Physics Reports*. 542(2): 133-193.

[9] Sarmani, A. R., Abu Bakar, M. H., Bakar, A. A. A., Adikan, F. R., and Mahdi, M. A. 2011. Spectral Variations of the Output Spectrum in a Random Distributed Feedback Raman Fiber Laser. *Optics express*. 19(15): 14152-14159.

[10] Sarmani, A. R., Abu Bakar, M. H., Adikan, F. M., and Mahdi, M. A. 2012. Laser Parameter Variations in a Rayleigh Scattering-Based Raman Fiber Laser with Single Fiber Bragg Grating Reflector. *IEEE Photonics Journal*. 4(2): 461-466.

[11] Du, X., Zhang, H., Wang, X., and Zhou, P. 2015. Tunable Random Distributed Feedback Fiber Laser Operating at 1 μm. *Applied optics*. 54(4): 908-911.

[12] Babin, S. A., El-Taher, A. E., Harper, P., Podivilov, E. V., and Turitsyn, S. K. 2012. Broadly Tunable High-Power Random Fibre Laser. *International Society for Optics and Photonics in SPIE LASE*. 82373E-82373E.

[13] Babin, S. A., El-Taher, A. E., Harper, P., Podivilov, E. V., and Turitsyn, S. K. 2011. Tunable Random Fiber Laser. *Physical Review A*. 84(2): 021805.

[14] Sarmani, A. R., Zamiri, R., Bakar, M. A., Azmi, B. Z., Zaidan, A. W., and Mahdi, M. A. 2011. Tunable Raman Fiber Laser Induced by Rayleigh Backscattering in an Ultra-Long Cavity. *Journal of the European Optical Society-Rapid Publications*. 6.

[15] Zhu, Y. Y., Zhang, W. L., and Jiang, Y. 2013. Tunable Multi-Wavelength Fiber Laser Based on Random Rayleigh Back-Scattering. *IEEE Photonics Technology Letters*. 25(16): 1559-1561.

[16] Wang, L., Dong, X., Shum, P. P., and Su, H. 2014. Tunable Erbium-doped Fiber Laser Based on Random Distributed Feedback. *IEEE Photonics Journal*. 6(5): 1-5.