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Performance of Multiwavelength Laser Utilizing Fabry-Pérot Interferometer in Different Cavity Configuration using Hybrid Raman-EDF Gains

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Abstract – **This paper presents on the design of multiwavelength laser for hybrid Raman-erbium doped fiber gains in three different cavities; single pass linear, bidirectional linear and ring laser. Multiwavelength laser has the potential for its simplicity and lower in cost. The 50% arm coupling ratio of ring laser structure with 0.2 nm line width, 20 lasing line and 5 mW lasing threshold is achieved and shown to be the best result for multiwavelength laser design compared to the single pass and bidirectional linear cavity. With an input power of 240 mW (EDFA) and 2000 mW (FRA), a 96% power conversion efficiency is obtained and produced a stable multiwavelength for L-band source with peak power of -10 dBm for ring laser, -25 dBm for single pass linear and -5 dBm for bidirectional linear laser. The lasing threshold obtained at 50% arm coupling ratio for ring laser is also slightly lower than other value reported previously. The interesting features of the proposed laser systems is the low threshold power, high output power, high number of lasing line and high pump conversion efficiency.**

Index Terms— **Fabry–Pérot interferometer; multiwavelength laser; hybrid Raman-EDF, Single Pass linear laser, Bidirectional linear laser, Ring laser.**

I. INTRODUCTION

MULTIWAVELENGTH fiber laser many potential in this era. It also has great potential in the optical communication system such as monitoring the Fiber to the Home (FTTH) network, optical fiber sensors, optical component testing and spectroscopy [1]. A fiber laser is created when a fiber amplifier is inserted in an optical resonator. The optical feedback provided by the resonator allows a light field (initially starting from spontaneous emission) to build upon itself until saturation effects arrest further growth: This describes a laser. The energy supply (pump source) must be provided by optical means and is therefore more complex than for laser diodes. On the other hand, fiber lasers are perfectly suited to coupling their light into a fiber.

Fiber lasers also offer great possibilities as multiwavelength sources and any modulation imposed on the pump power would be low-pass filtered; in the case of Erbium doped fiber lasers the time constant is τ = 10ms[2]. The main challenge of producing a multiline output with and erbium doped fiber laser (EDF) is the fact that the erbium ion saturates mostly homogeneously at room temperature, preventing stable multiwavelength operation. The requirements for such optical sources are, a high number of channels over the large wavelength span, moderate output powers with good optical signal to noise ratio (OSNR) and spectral flatness, single longitudinal mode operation of each laser line, tunability and accurate placement on the frequency grid [2], [3]. Achieving all these requirements simultaneously is a difficult undertaking, and many different approaches using semiconductor or erbium-doped fiber technology has been suggested and tested out in various experiment to obtain multiwavelength laser that stable at room temperature [3],[4],[5].

Design principle multiwavelength lasing has been produced with various gain mechanisms, including EDF amplification and Fiber Raman amplification (FRA) [4]. Multiwavelength output using EDFs have been study extensively due to their superiority such as higher power conversion efficiency. It is an intrinsic disadvantage that an EDF has a solid homogenous line broadening and cross-immersion gain at room temperature [5], [6]. The genuine addition rivalry among various lasing wavelengths (inside the large homogenous line broadening region) will constitute the multiwavelength laser unstable at room temperature. In order to make a multiwavelength laser stable at room temperature, different systems have been utilized, for example, employing a highly nonlinear fiber [7], [8], cooling the EDF to cryogenic temperature with liquid nitrogen, using some special fibers [9] and utilizing a frequency-shifted feedback technique in a laser cavity [11]. In this simulation, a multiwavelength fiber laser based on hybrid gain medium of EDF and Raman gain has been acquainted to suppress the homogenous line broadening of Erbium ions [12,

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13] using several methods that include single pass linear laser, bidirectional linear laser and ring laser.

The single pass linear cavity structure is the ones where light pass thru the Raman EDF gain medium. Fig. 1 demonstrates a schematic diagram of the multiwavelength fiber laser in view of a line structure of EDFA and FRA. Several alternatives exist to avoid passing the pump light through the dielectric mirrors. For example, one can take advantage of fiber couplers as shown in Fig. 1. It is possible to design a fiber coupler such that most of the pump power is coupled into the laser cavity. In this case, the single coupler design will partially reflect the laser beam while transmitting the pump.

The design of laser cavity is a key step in building a fiber laser with good performance. Various configurations based on two types of cavities; linear cavity and ring cavity have been studied [14, 15]. Among these designs, fiber ring lasers have been particularly attractive, because they have excellent lasing efficiency, and are able to eliminate back scattering and spatial hole- burning effects. Consequently, these lasers have better potential to achieve multiwavelength longitudinal mode. However, no technique is free from operating difficulties due to the problems of EDF amplifier fiber laser from environmental influences, such as vibrations and temperature drift [16, 17]. Most of these issues can be directed by applying some schemes, as will be demonstrated in this paper.

In this simulation, OptiSystem software and design suite is used to plan, design, test and simulate the optical laser system and demonstrate various simulations to achieve the ideal gain for single linear laser, bidirectional linear laser and ring laser. In addition, the performance of the ring-cavity and linear-cavity laser will be discussed further in this paper in term of output power, SMSR, lasing threshold, spectral spacing and line width.

II. DESIGN SETUP AND PRINCIPLE OF MULTIWAVELENGTH LASER

A. *Single Pass Linear Laser*

Fig. 1 demonstrates a schematic diagram of the multiwavelength fiber laser in view of a line structure of EDFA and FRA. As displayed in Fig. 1, a section of DCF with distance of 10 km, which is originally used for compensating the dispersion of 20 km single mode fiber (SMF) is used as the Raman gain fiber. Two laser diodes; laser diode 2 and laser diode 3 are used as the Raman pumps with wavelength of 1450 nm, 1460 nm with 1000 mW pump power, respectively. A division of EDF with distance of 8 m and a Laser Diode 1 whose maximum output power and wavelength are 240 mW and 1480 nm from the EDF part of amplification. The used of DCF 10 km and Raman 8m was based on the simulation result shown in Fig. 5. The selection of the fiber length was based on the highest gain produced from the simulation result.

A Fabry–Pérot Filter [19], [20] and a Gain Flattening filter form a resonant cavity is to produce a stable multiwavelength output. The 50 %arm of an optical coupler is employed as the output port. The multi-reflection process that happens in the Fabry–Pérot (F–P) is unique and it produces a transfer function much different from the other filter such as Mach–Zehnder, Michelson and Sagnac configurations [20], [21]. The multiple passes along the fiber magnify the phase extremely high sensitivity [22]. The Fabry–Pérot has a greater sensitivity and one of the best results to produce multiwavelength laser compared to the other techniques.

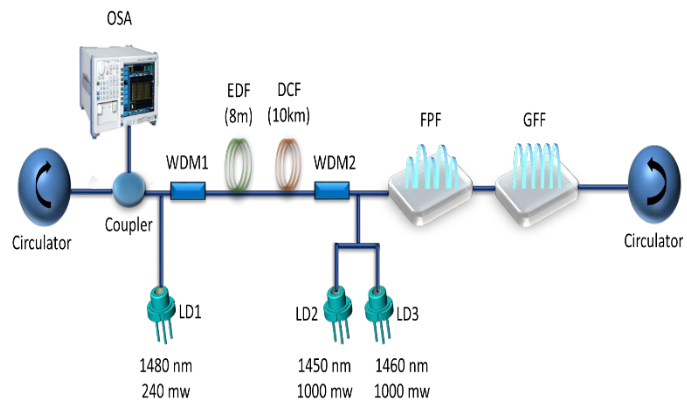


Fig. 1. Schematic configuration of the multiwavelength single pass linear cavity laser.

B. *Bidirectional Linear Laser*

Fig. 2 demonstrates a schematic diagram of the multiwavelength fiber laser in view of a line structure of EDFA and FRA. As expressed in Fig. 2, the DCF, laser diodes, 3-dBm optical coupler and pump powers are used as a gain medium identically to Fig. 1. The bidirectional linear cavity laser is designed with the circulator to make sure the direction of the cavity is bidirectional and overcome the different result. A Fabry–Pérot Filter and a Gain Flattening filter (GFF) form a resonant cavity is to produce a stable multiwavelength output. The 50% arm of an optical coupler (OC) is employed at the output port. The function of this design is to gain the best outcome in the linear laser cavity by using the bidirectional method and this will be discussed future in the result and discussion section.

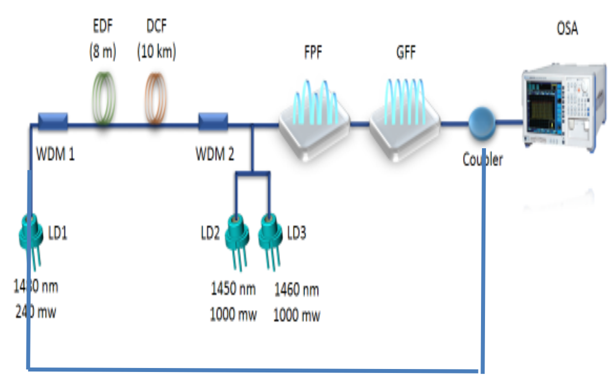


Fig. 2. Schematic configuration of the multiwavelength bidirectional linear cavity laser.

C. Ring Laser

Fig. 3 demonstrates a schematic diagram of the multiwavelength fiber laser in view of a line structure of EDFA and FRA. As expressed in Fig. 3, a section of DCF with a distance of 10 km, which is originally used for compensating the dispersion of 20 km SMF is used as the Raman gain fiber. Laser diode 2 and laser diode 3 are used as the Raman pumps, and their wavelengths are 1450nm and 1460nm with 1000 mW pump power respectively. A division of EDF with a distance of 8 m and a laser diode 1 (whose maximum output power and wavelength are 240 mW and 1480 nm and respectively) from the EDF part of amplification. A Fabry–Pérot Filter and a Gain Flattening filter form a resonant cavity is to produce a stable multiwavelength output. The 3-dBm optical coupler and 50% arm of an optical coupler (OC) is employed at the output port.

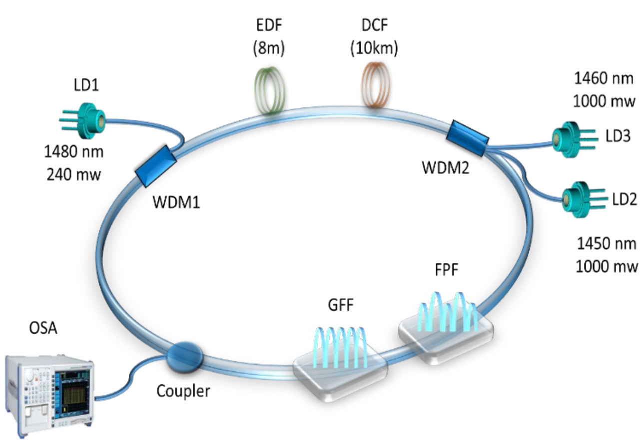


Fig. 3. Schematic configuration of the multiwavelength ring cavity laser.

The power conversion efficiency, η_{PCE} of an EDFA and FRA represents the efficiency with which the amplifier is able to convert power from the pump to the signal [22]. Suppose that $P_{P,\,in}$ is the pump power into the EDFA and FRA as shown in the Fig. 4, Fig. 5 and Fig. 6, where $P_{S,\,in}$ are $P_{S,\,out}$ the input and output powers, respectively. Then

$$\eta_{PCE} = \frac{P_{S,\,out} - P_{S in}}{P_{P,\,in}} \approx \frac{P_{S,\,out}}{P_{P,\,in}} \quad (1)$$

Suppose that the flux of photons from the pump is $\Phi_{P,\,in}$ and the signal input and output photon fluxes are $\Phi_{S,\,in}$ and $\Phi_{S,\,out}$. Since optical power is proportional to photons flux X hc/λ, where hc/λ is the photons energy, we can write the equation as.

$$\eta_{PCE} \approx \frac{\Phi_{S,\,out}}{\Phi_{S,\,in}} \text{X} \frac{\lambda_P}{\lambda_S} \quad (2)$$

III. RESULT AND DISCUSSION

The optical amplifier may be considered as a laser without feedback, or one in which the feedback is suppressed. There are distinctive physical systems that can be used to amplify the optical signal. In this design, an electrical pump; 240 mW, 1000 mW, and 1000 mW with respectively 1480 nm, 1450 nm and 1460 nm are used to achieve population inversion. Thus, the input signal photons are amplified. In this chapter, we focus mainly on two types of gain medium, Erbium Doped Fiber Amplifier (EDFA) and Raman Amplifier (FRA).

Fig. 4 and Fig. 5 show the output signal from EDF with different length of 2 m, 4 m, 6 m, 8 m, and 10 m and Raman amplifier with different length of 3 km, 5 km, 7 km, 10 km and 15 km utilized in ring cavity laser. From Fig. 4, it is shown that the best gain produced by the EDFA is when 8m length is applied. As the fiber length increases, this large number of excited electrons undergo stimulated emission and the output optical signal is a highly amplified signal.

However, as this process continues, the number of excited electrons in the metastable state starts decreasing and the population inversion condition starts depleting. As a result, the amplitude of the EDFA drops due to unavailability of sufficient excited electrons to undergo stimulated emissions. It can easily be seen from Fig. 4 at 8m fiber length, the EDFA provides the highest amplitude of about -20 dBm. But, as the fiber length about 2 m, the power drops to an insignificantly low value about -60 dBm, or in other words, there is no practical amplification of the input signal in the amplifier. This shows that the gain of the EDFA is dependent on length of the fiber.

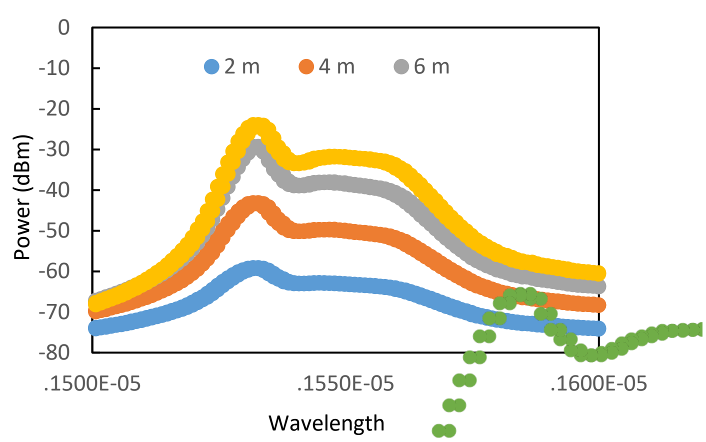


Fig. 4. Erbium Doped Fiber Amplifier (EDFA) amplitudes with different length.

Likened to an EDFA, the primary advantages of Raman amplification are an improved noise Fig. and improved gain flatness. Nevertheless, additional issues arise in Raman amplification that are not present in EDFA. These include spontaneous Raman scattering added to the amplified signal and comes out as a disturbance because of random phases associated with all spontaneously generated photons. It depends on the photons population in the vibrational state, which depends on the fiber length of the Dispersion Composition Fiber (DCF) used. In Fig. 5, the signal gain is increasing proportionally with increases of fiber length. The best Raman gain is produced when 10 km fiber length is used. Moreover, further along the fiber, the pump becomes too weak, the gain reduced, and the fiber attenuates the signal, which is highly undesirable. In addition, the signal and pump are combined using a fiber coupler and the combined signal is launched into the fiber.

For a signal wavelength at 1550nm, the pump wavelength should be about 1450nm to ensure the highest gain, corresponding to a frequency difference of about 14 THz. To achieve a gain flatness over a broad range of signal frequencies, multiple pumps is usually used in practical systems. The signal is higher than Raman amplifier due to their advantages such as higher power conversion efficiency. It is an intrinsic disadvantage that an EDF has a strong homogenous line broadening and cross-saturation gain at room temperature.

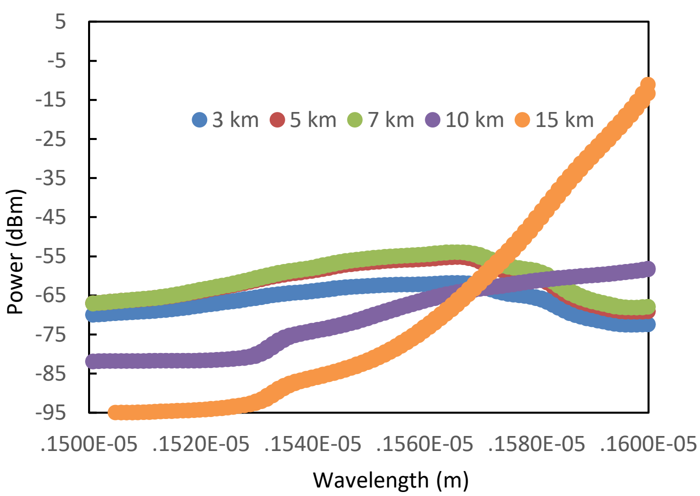
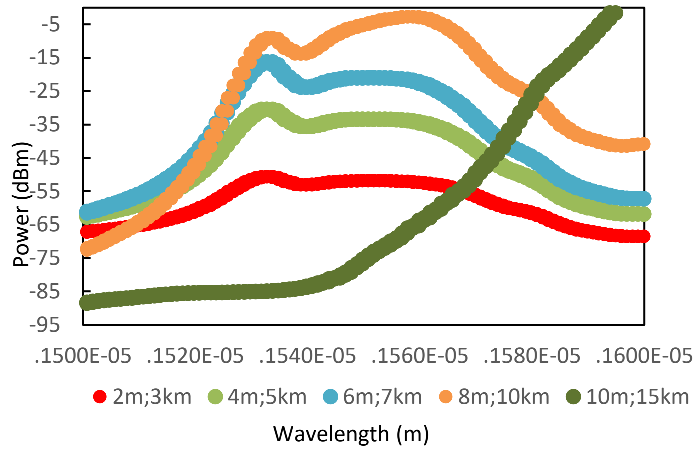


Fig. 5. Raman Amplifier (FRA) gain with different length.

Fig. 6 shows Hybrid Raman-EDF gain. The main reason of this combination between two gains medium is to create a multiwavelength laser with higher gain and more stable at room temperature. In this design, a multiwavelength fiber laser based on a hybrid gain medium of EDFA with 8 m length and FRA with 10 km length has been introduced to suppress the homogenous line broadening of Erbium ions. As we can see from the Fig. 6, the output power of Hybrid Raman-EDF gain is higher compared to the single Raman or EDFA. This shows the combination between this two medium at the right fiber length can produce higher medium gains and more stable multiwavelength laser at room temperature.

From Fig. 4, Fig. 5 and Fig. 6, it can be observed that the amplifier gain becomes maximum at the length of 8 m EDF and



10 km DCF. For the given pump power, gain increases with distance initially and then it decreases. This is because the pump decays as it propagates through the EDF and at a certain length. Physically, when the pump power is less than its threshold level, erbium ions pumped to level 2 (via level 3) are not adequate to cause population inversion. In this design, multiwavelength fiber performance parameters to consider are peak wavelength shifting, high Side-Mode Suppression Ratio (SMSR), Free Spectral Range (FSR), narrow line width, lasing threshold and maximum peak power. The result was chosen based on the Hybrid Raman EDF simulation result. The combination of 8 m EDF and 10 km DCF shown to be the best output for Hybrid Raman EDF simulation as shown in Fig. 6.

Fig. 6. Hybrid Raman-EDF gain with different length of EDF and DCF.

A. Single Pass Linear Laser

Fig. 7 shows the number of lasing line with the various pump power. It is observed, the number of lasing line started to increase to 9 lines when 50 mW pump power is applied. The number of lasing line is slowly increasing as the pump power increase until it reached the optimum number of lasing lines. This parameter is defined as the efficiency of the fiber laser to convert pump energy into lasing signal energy. The optimum number of lasing lines achieved was about 17 lines at pump power of 1000 mW for the single pass linear cavity system. The 50%, 25%, 10% and 1% arm coupling ratio produce the output signal with constant line width 0.2 nm. SMSR represent the ratio between higher peak power and the second highest peak power in the multiwavelength laser signal output. From table 1, the higher value of SMSR produce when 1% arm coupling ratio is applied and the 50% of coupling ratio represent the lowest value of SMSR. Higher value of lasing line, and lowest value of spectral spacing defined as a good performance for Ethernet passive optical network (EPON) in FTTH network, optical fiber sensor, dense wavelength division multiplexing (DWDM) system and optical component testing.

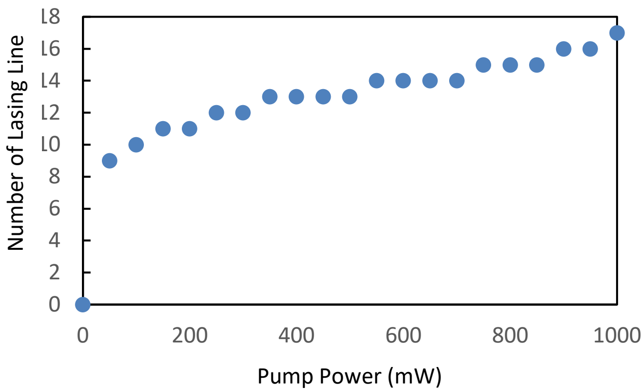


Fig. 7. Number of lasing line versus pump power for single pass linear laser.

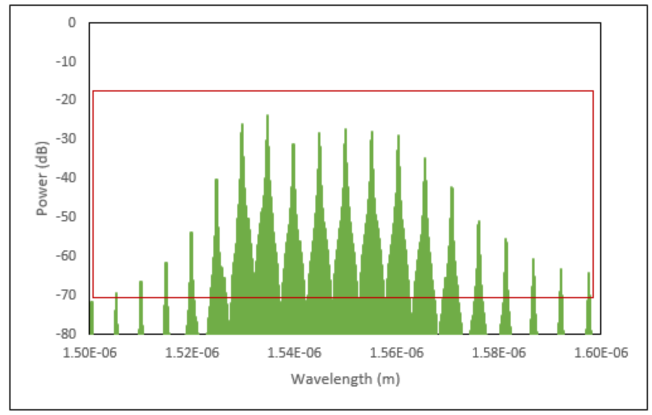


Fig. 8. Multiwavelength output signal from single pass linear laser with 50% arm of an optical coupler (OC).

TABLE 1
MULTIWAVELENGTH LASER SPECIFICATION WITH DIFFERENT COUPLING RATIO SINGLE PASS LINEAR LASER

Coupling Ratio (%)	Lasing line	Spectral Spacing (nm)	Line Width (nm)	SMSR (dBm)	Peak Power (dBm)	Lasing Threshold (mW)
50:50	15	4.25	0.2	18	-25	9
75:25	14	4.5	0.2	20	-28	8.9
90:10	13	4.75	0.2	22	-29	8.2
99:1	12	5.0	0.2	24	-30	7.8

Fig. 8 shows the output of multiwavelength signal that is produced from the single pas linear laser. In the first section, Fabry-Pérot filter is obtained by the amplifying medium itself, which functions as the comb filter. The second section is when the flattening filter takes place as the last part to smother the output signal produced by the Fabry-Pérot filters to produce multiwavelength single pass linear laser setup to generate multiwavelength laser in the C-band region. Number of lasing lines are counted for laser above -70 dBm as the reference. It is shown that the number of lasing lines is inversely proportional to the spectral spacing value. This happens due to the high monochromic oscillation wavelength and the change upon the temperature and variety.

B. Bidirectional Linear Laser

From the bidirectional linear cavity result in Table 2, it can be seen that the higher value of SMSR produce when 1% arm coupling ratio is applied and the 50% of coupling ratio represent the lowest value of SMSR. Higher value of SMSR, and lowest value of spectral spacing defined as a good performance for the multiwavelength fiber laser. However, in this design we prefer the highest value of lasing line as the main factor to define as a good performance for the multiwavelength fiber laser due to widely apply of multiwavelength spectrum.

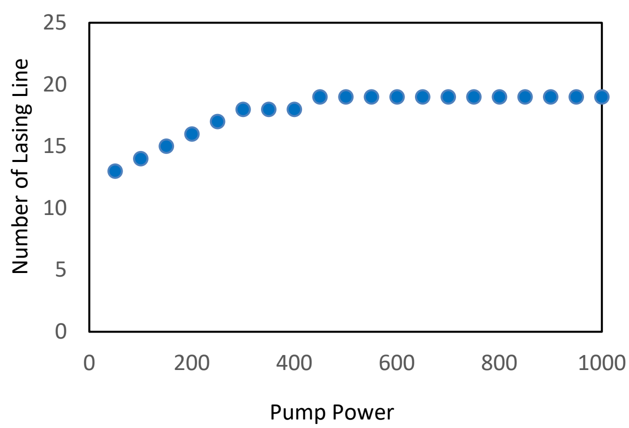


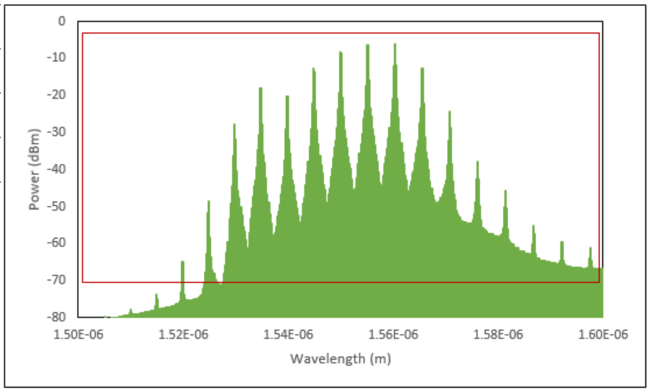
Fig. 9. Number of lasing line versus pump power for bidirectional linear laser.

TABLE II
MULTIWAVELENGTH LASER SPECIFICATION WITH DIFFERENT COUPLING RATIO BIDIRECTIONAL LINEAR LASER

Coupling Ratio (%)	Lasing line	Spectral Spacing (nm)	Line Width (nm)	SMSR (dBm)	Peak Power (dBm)	Lasing Threshold (mW)
50:50	19	4.25	0.2	20	-5	13
75:25	17	4.5	0.2	24	-10	10
90:10	14	4.75	0.2	28	-15	8.6
99:1	13	5.0	0.2	30	-20	8

Fig. 10 shows the output of multiwavelength signal that produce from the bidirectional linear cavity laser with the number of lasing line directly proportional to the pump power apply. As we can see, the value of pump power started increasing to 12 when 50 mW power is applied. However, the

Coupling Ratio (%)	Lasing line	Spectral Spacing (nm)	Line Width (nm)	SMSR (dBm)	Peak Power (dBm)	Lasing Threshold (mW)

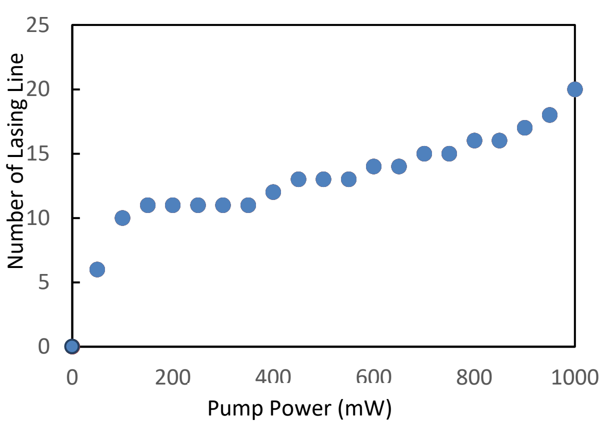


number of lasing line become static at the 450mW as it achieves the optimum gain.

Fig. 10: Multiwavelength output signal from bidirectional linear laser with 50% arm of an optical coupler (OC).

C. Ring Laser

In this design, multiwavelength laser with a different coupling ratio of 50%, 25%, 10% and 1% are applied to the ring cavity structure to measure the lasing line, spectral spacing, line width, SMSR, peak power and the lasing threshold. Number of lasing lines are counted for laser above -70 dBm as the



reference. From Table 3, the higher value of of SMSR produce when 1% (35 dBm) arm coupling ratio is used and the 50% (25 dBm) of coupling ratio gives the lowest value of SMSR.

Fig. 11. Number of lasing lines versus pump power for ring laser.

TABLE III
MULTIWAVELENGTH LASER SPECIFICATION WITH DIFFERENT COUPLING RATIO RING LASER

Fig. 12 shows the output of multiwavelength signal that is produced from the ring cavity laser in the C-band region with wavelength range from 1530 nm-1565 nm.

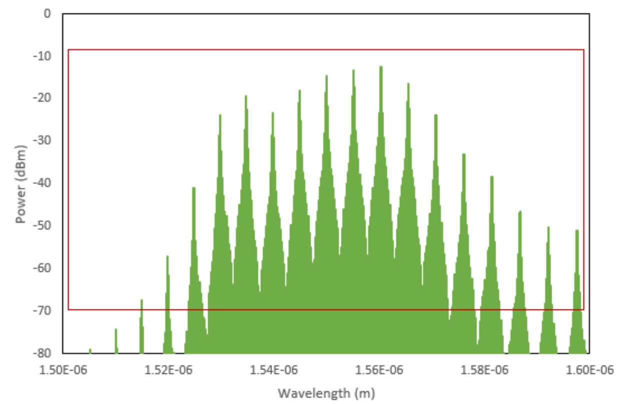


Fig. 12. Multiwavelength output signal from ring laser with 50% arm of an optical coupler (OC).

Fig. 13 shows the total pump power versus total output power for single pass, bidirectional and ring laser structure from the simulation. The total pump power and output power behavior is initially linear but saturates at high input signal powers. For an optical laser source, efficiency represents the ratio of the lasing output power over the pump power, in other words, the conversion of the pump energy to the lasing energy. For example, efficiency of a Bidirectional laser cavity with 50% coupling ratio laser system has been reported to be about 80%. This value can be obtained from the slope of the transfer characteristic curve as shown in Figure 13. Efficiency is also being used to refer to the power launching or power coupling efficiency between the source and the input end of the fiber. The minimum amount of pump power required for a laser source to begin lasing is defined as the threshold power. When the pump power is below the threshold power, the output power of the laser source is incoherent and spontaneous. The total pump power and output power behavior is initially linear but saturates at high input signal powers. This situation is depending by the power conversion efficiency (PCE) of RPU in hybrid Raman-EDF gains that had been used in this design. The total pump power and output power behavior is initially linear but saturates at high input signal powers. This situation is depending by the power conversion efficiency (PCE) of EDFA and FRA that had been used in this design. From the equation (1) and (2), the total PCE produce by FRA and EDFA is 96% with 1450 nm, 1460 nm and 1480 nm pumping. The result shows PCE has a maximum value of λp/λs, which corresponds to each pump photon yielding one additional signal output.

The interesting features of the proposed laser systems are low threshold power, high output power, high number of lasing line and high pump conversion efficiency. For the ring laser system, the threshold power was measured to be 5mW and for linear cavity system, the threshold power was between 6 mW and 12 mW, for all the reflectivity values. These values are slightly lower than other values reported previously [15-17, 22-23]. It is believed that this is ascribable to the higher gains of the chosen mode in the EDF-Raman amplification in the pit. Furthermore, the comb filters suppress the oscillation of the unwanted ASE in both ways. Therefore, the competition between the modes in the lasing process has been reduced effectively as shows in Fig. 13.

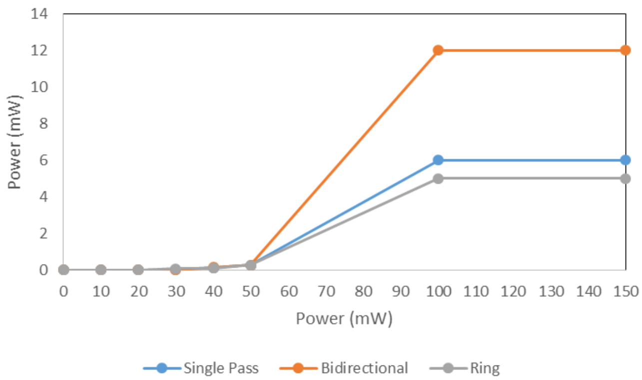


Fig. 13. Total pump power versus Total output power.

The effect of reflecting on the threshold pump power is not very significant, however, the output power and the slope efficiency of the proposed lasers increase in tandem with the reflectivity. For the ring laser system, the maximum output power for 50% arm coupling was -10 dBm and for linear cavity system, the maximum output power was -5 dBm for bidirectional and -25 dBm for single pass cavity laser. Both were measured at a 3 different pump power 1480 nm (450 mW), 1450 nm (1000 mW), and 1460 nm (1000 mW).

Lasing line is one of the critical factors to determine the laser performance. The highest lasing line has the greatest potential in the optical communication system such as monitoring the Fiber to the Home (FTTH) network, optical fiber sensors, optical component testing and spectroscopy. In this design, ring laser shows the highest lasing line (20) compared to the single pass (15) and bidirectional laser cavity (19). The result shows that number of lasing lines is inversely proportional to the spectral spacing value. This happens due to the high monochromic oscillation wavelength and the change upon the temperature and variety.

The result also shows that the spectral spacing for ring structure is becoming narrow compared to the single pass and bidirectional linear laser. This happens due to the counterclockwise oscillation that happen in the ring cavity laser that reduces the unwanted back reflection signal and preventing signal disturbance in the cavity.

IV. CONCLUSION

In conclusion, a stable multiwavelength fiber laser of hybrid Raman-EDF has been demonstrated. Three structures has been simulated to generate multiwavelength laser; single pass linear laser, bidirectional laser and ring laser. The 50% arm coupling ratio of ring laser structure has shown the best result comparable to other arm coupling ratio that has been used in this design. The ring laser structure produced the best result with 20 lasing lines with line width of 0.2 nm and 4 nm spectral spacing. With an input power of 240 mW (EDFA) and 2000 mW (FRA), a 96% power conversion efficiency is obtained and produced a stable multiwavelength for L-band source with peak power of -10 dBm for ring laser, -25 dBm for single pass linear and -5 dBm for bidirectional linear laser. From the result, it can be concluded that the ring laser cavity produced the best performance for multiwavelength laser in terms of lasing line, spectral spacing and lasing threshold compares to the single pass and bidirectional linear cavity laser.

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REFERENCES

[1] M.I. Md Ali, Nani Fadzlina Naim, Muhammad Faiz Ibrahim, “Single-pump multiwavelength hybrid Raman-EDF laser using a non-adiabatic microfiber interferometer”, Indonesian Journal of Electrical Engineering and Computer Science, Vol. 18, No. 3, June 2020, pp. 1446~1453

[2] Muhammad Faiz Ibrahim, M.I. Md Ali, Nani Fadzlina Naim, “Multi Wavelength Laser Utilizing Fabry-Pérot Interferometer in Hybrid Raman and Erbium Doped Fiber Gains”, IEEE Student Conference on Research and Development, 2016 IEEE Student Conference.

[3] L. J. Cox, Solid-State Laser Engineering, vol. 24, no. 9. 2017.

[4] S. C. Singh, H. Zeng, C. Guo, and W. Cai, “Lasers: Fundamentals, Types, and Operations,” Process. Charact with Lasers, pp. 1–34, 2012.

[5] H. S. Al-Raweshidy and D. Uttamchandani, Spread spectrum technique for passive multiplexing of interferometric optical fiber sensors, vol. 80, no. 1. 2002.

[6] L. Classification, “Laser Classification,” Image (Rochester, N.Y.).2015

[7] U. Tiwari, K. Thyagarajan, and M. R. Shenoy, “Simulation and experimental characterization of Raman/EDFA hybrid amplifier with enhanced performance,” Opt. Commun., vol. 282, no. 8, pp. 1563–1566, 2009.

[8] S. Kotiyal, H. Thapliyal, and N. Ranganathan, “Mach-Zehnder Interferometer Based All Optical Reversible NOR Gates,” 2012 IEEE Comput. Soc. Annu. Symp. VLSI, pp. 207–212, 2012.

[9] P. Jain, D. Tanaka, and H. Tsuda, “Mach Zehnder Interferometer Optical Switch Using Phase-Change Material,” pp. 3–5.2003

[10] S. Singh and R. S. Kaler, “Flat-gain L-band raman-EDFA hybrid optical amplifier for dense wavelength division multiplexed system,” IEEE Photonics Technol. Lett., vol. 25, no. 3, pp. 250–252, 2013.

[11] F. Laser, G. Leader, N. I. Facility, and P. S. Directorate, “Fiber Lasers : Technology, Applications and Associated Laser Safety,” 2012.

[12] F. Lasers and T. Digest, “Fiber Lasers: Technical digest,” Ind. Laser Solut.

[13] E. Bash, fiber optic sensor second edition, vol. 1. 2015.

[14] J. L. Rasmussen and C. Springs, “new method of comb filter,” pp. 792–796, 2012.

[15] P. L. Scrivener, E. J. Tarbox, and P. D. Maton, Narrow linewidth tunable operation of Er doped single-mode fiber laser, Electron. Lett 25, 549-550, (2004).

[16] Th. Pfeiffer, H. Schmuck, and H. Bülow, Output power characteristics of Erbium-doped fiber ring laser, IEEE Photon. Technol. Lett. 4, 847-849 (2002).

[17] A. Bellemare, M. Karasek, C. Riviere, F. Babin, G. He, V. Roy, and G. W. Schinn, A broadly tunable Erbium-doped fiber ring laser: experimentation and modeling, IEEE J. Select. Topics Quantum Electron.7, 22-29 (2001).

[18] H. Chen, F. Babin, M. Leblanc, and G. W. Schinn, Widely tunable single-frequency Er-doped fiber laser with long linear cavity, IEEE Photon. Technol. Lett., vol. 13, no. 4, pp. 287289, (2001).

[19] S. Yamashita, and M. Nishihara, Widely tunable erbium-doped fiber ring laser covering both C-band and L-band, IEEE J.Select Topics Quantum Electron. 7, 41-43 (2001).

[20] H. Chen, F. Babin, M. Leblanc, and G. W. Schinn, Widely tunable single-frequency Erbium-doped fiber lasers,” IEEE Photon. Technol. Lett., vol. 15, no. 2, pp. 185-187, (2003).

[21] S. L. Pan, C. Y. Lou, and Y. Z. Gao, "Multiwavelength Erbium-doped fiber laser based on inhomogeneous loss mechanism by use of a highly nonlinear fiber and a Fabry-Perot filter," Opt. Express 14, 1113-1118 (2006). Erbium-doped fiber lasers anchored on the ITU frequency grid," J. Lightw. Photon. Technol., 18, 825-831 (2006)

[22] D. N. Wang, F. W. Tong, X. Fang, W. Jin, P. K. A.Wai, and J. M. Gong, "Multiwavelength Erbium-doped fiber ring laser source with a hybrid gain medium," Opt. Commun. 228, 295-301 (2003).

[23] Y. G. Han, G. Kim, J. H. Lee, S. H. Kim, and S. B. Lee, "Lasing wavelength and spacing switchable multiwavelength fiber laser from 1510 to 1620 nm," IEEE Photon. Technol. Lett. 17, 989-991 (2005).