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A comparative study of the performance of narrow linewidth erbium-doped fiber laser by incorporating different selective elements

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Tunable laser performance sources with requirements of higher optical power and narrower linewidth become widely demands due to massive usage of network capacity driven by new applications and services associated with web-scale networking. High optical power and narrow linewidth are seeking to transmit signals over a long distance and to increase data transmission rate. Employing wavelength selective element within the cavity usually used to reduce the linewidth, giving the outcome of significantly narrow linewidth. Hence, in this paper, the comparative study of erbium-doped fiber ring laser (EDFL) was experimentally performed by using different selective elements. The output optical power, tunability and the 3dB linewidth EDFL incorporating different wavelength selective elements such as the tunable-bandpass filter (TBF), arrayed waveguide grating (AWG) and ultra-narrow bandwidth tunable filter (UNB-tunable filter) was analyzed. The UNB-tunable filter produced the widest tuning capability of 37.7 nm, which covered the C-band region. The narrowest 3 dB linewidth was obtained by using an UNB-tunable filter, giving the linewidth value of 14 pm. The utilization of UNB-optical filter in EDFL configuration was proven to offers greater tunability, lower linewidth and better optical performance.

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Keywords: Narrow Linewidth, Wavelength selective element, Data transmission, Tunable laser, Erbium-doped fiber laser, Single wavelength fiber laser

1. Introduction

Reaching goal for the ideal optical sources that having a high optical signal-to-noise ratio (OSNR), moderate output powers (100 µW per channel), wide tunability and operate in single longitudinal mode are challenging task [1-3]. Versatile gain medium such as erbium-doped fiber (EDF) usually chosen to compare to semiconductor optical amplifiers (SOAs) as it offers low insertion loss, simple configuration, high extinction ratio and low cost. Thus, diversity of designs by using Erbium-doped fiber laser (EDFL) has been proposed and experimented to realize ideal optical oscillation. However, the unwanted homogenous broadening gains of EDFs preventing the stable multiwavelength lasing [4,5]. Therefore, plenty techniques have been introduced to mitigating or eliminate the mode competition between different wavelengths in EDFL at room temperature. Those techniques including cooling EDF in liquid nitrogen (77K) in which caused inconvenience for application [6], using various FBGs structure in the cavities [7,8], and utilized nonlinear effects such as four-wave mixing (FWM) [9] and cascaded stimulated Brillouin scattering [5,10]. Most likely, FBGs have advantages in term of low cost, ease to use and compatible that makes it an ideal component as wavelength selection for fiber laser after all.

Nevertheless, the ability to tune fiber laser become widely demand seeks to increase transmission capacity [10]. The effects of laser cavity such as the EDF length, output coupling ratio, pump power and intra-cavity loss on the laser performance have been studied extensively by theoretically and experimental analysis [11,12].

Experimental studies acknowledge the large tuning range could be obtained in ring cavity EDFL [13].

Despite that, fiber laser sources have become an alternative source and highly potential as narrow linewidth sources. Plenty of technique has been demonstrated in order to produce narrow linewidth and single longitudinal mode (SLM) in fiber laser. Generally, a basic configuration of fiber laser has typically 1-15 nm of optical linewidth, depending on the cavity and pumping condition. The lasing of a broad spectrum can occur with a primarily homogeneously broadened condition transition, caused by a broad gain broadening and spatial hole burning effect on gain medium. The form of standing-wave in laser cavity induced spatial hole burning, which reducing gain competition between axial modes. A wavelength selective element or filter within the cavity usually used to reduce the bandwidth, giving the outcome of significantly narrow linewidth. Hence, the wavelength selective elements are a necessary property to produce narrow-linewidth fiber laser.

In this paper, the basic configurations of EDFL incorporating the wavelength selective elements such as tunable-bandpass filter (TBF), arrayed waveguide grating (AWG) and ultra-narrow bandwidth tunable filter (UNB-tunable filter) was examined, using erbium-doped fiber amplifier (EDFA) as the predominant gain medium. The aspects that we were investigated included the tunability, the OSNR, efficiency and most importantly the range of linewidth of lasing output produced.

2. Experimental setup

The arrangement of the experimental setup is shown in Fig. 1. A 980 nm laser diode with pump power of 150 mW is connected to the 3 m EDF via 980/1550 nm wavelength-division multiplexer (WDM). The EDFA signal is directed toward Tunable bandpass filter (TBF) to be filtered. The wavelength of interest can be tuned from range of 1480 nm to 1560 nm, since the amplified spontaneous emission (ASE) power emitted within this region.

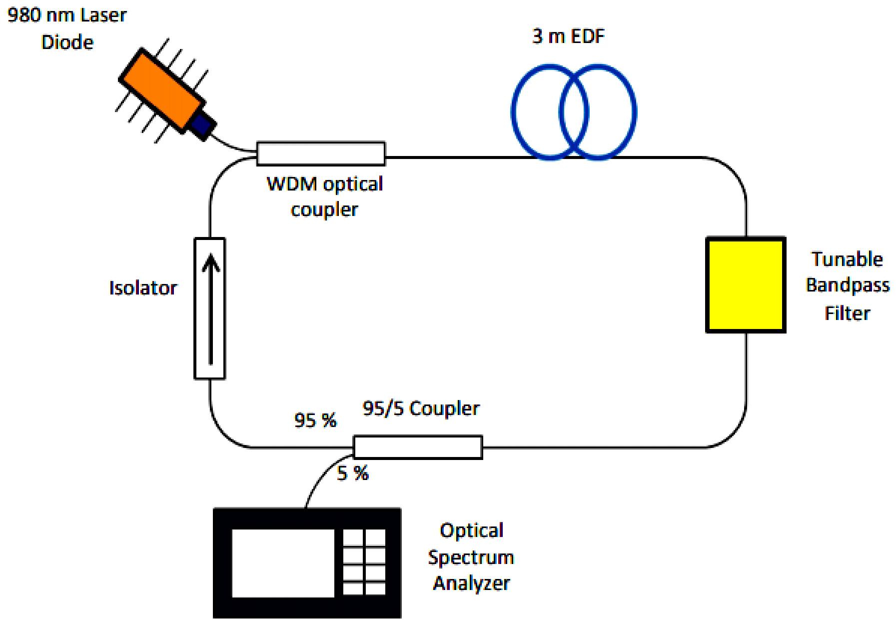


Fig. 1. Experimental setup of EDFL using tunable bandpass filter as wavelength selective element (color online)

The output spectrum, output power, optical signal-to-noise-ratio (OSNR) and linewidth of tunable fiber laser is examined and analyzed by using a ring cavity configuration with the insertion of TBF within the cavity. An isolator was inserted in between 95/5 coupler and WDM. The insertion of an isolator does affect the output power and width of the spectrum. By incorporating an isolator in the setup, the peak power obtained was higher and narrower than configuration without isolator. The lasing trace without isolator produced many oscillating longitudinal mode lasing at the same time. This is due the bidirectional propagation inside the cavity where propagation of back reflection emission also occurs. Thus, the used of an isolator does provide unidirectional propagation inside the laser cavity, in addition to lead higher stimulated emission. Higher intensity of stimulated emission generated higher lasing output power. The output power is extracted by using 5 % of 95/5 optical fused coupler that yields 0.63 mW of output power which is measured using optical power meter (OPM). The spectrum of transmitted wavelength was displayed through 0.02 nm Yokogawa AQ6370B OSA.

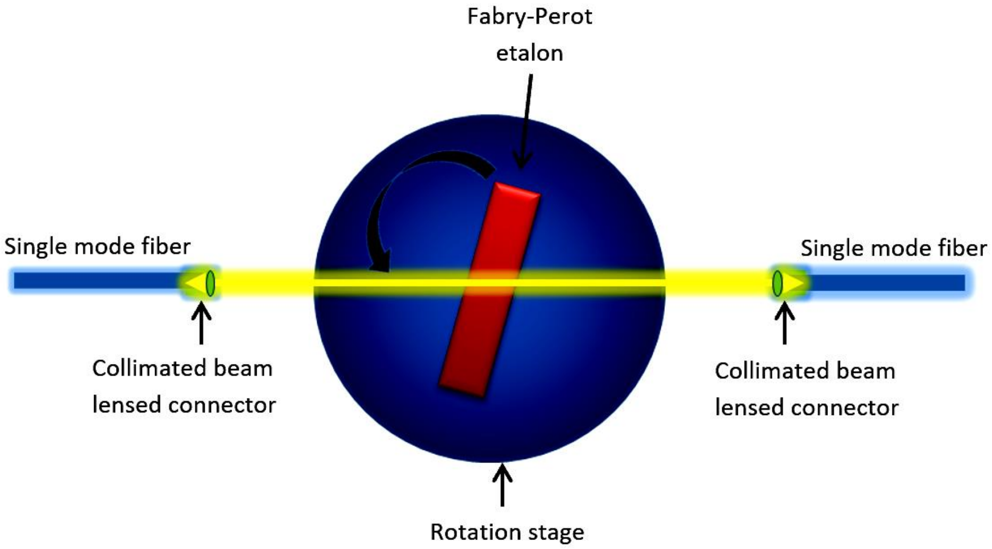


Fig. 2. The schematic diagram of Tunable Bandpass Filter (TBF) (color online)

Fig. 2 shows schematic diagram of fiber coupled TBF. When a stream of beam light of a plurality of wavelength from the single mode fiber (SMF) accident to an angled optical fiber collimator, beam become more aligned and refocused to etalon. The collimated beam will travel through the free-space region before encounter the Fabry-Perot Etalon. The Fabry-Perot Etalon will functionally as interference filter. The filtered beam will encounter second angled collimator before entering the second SMF.

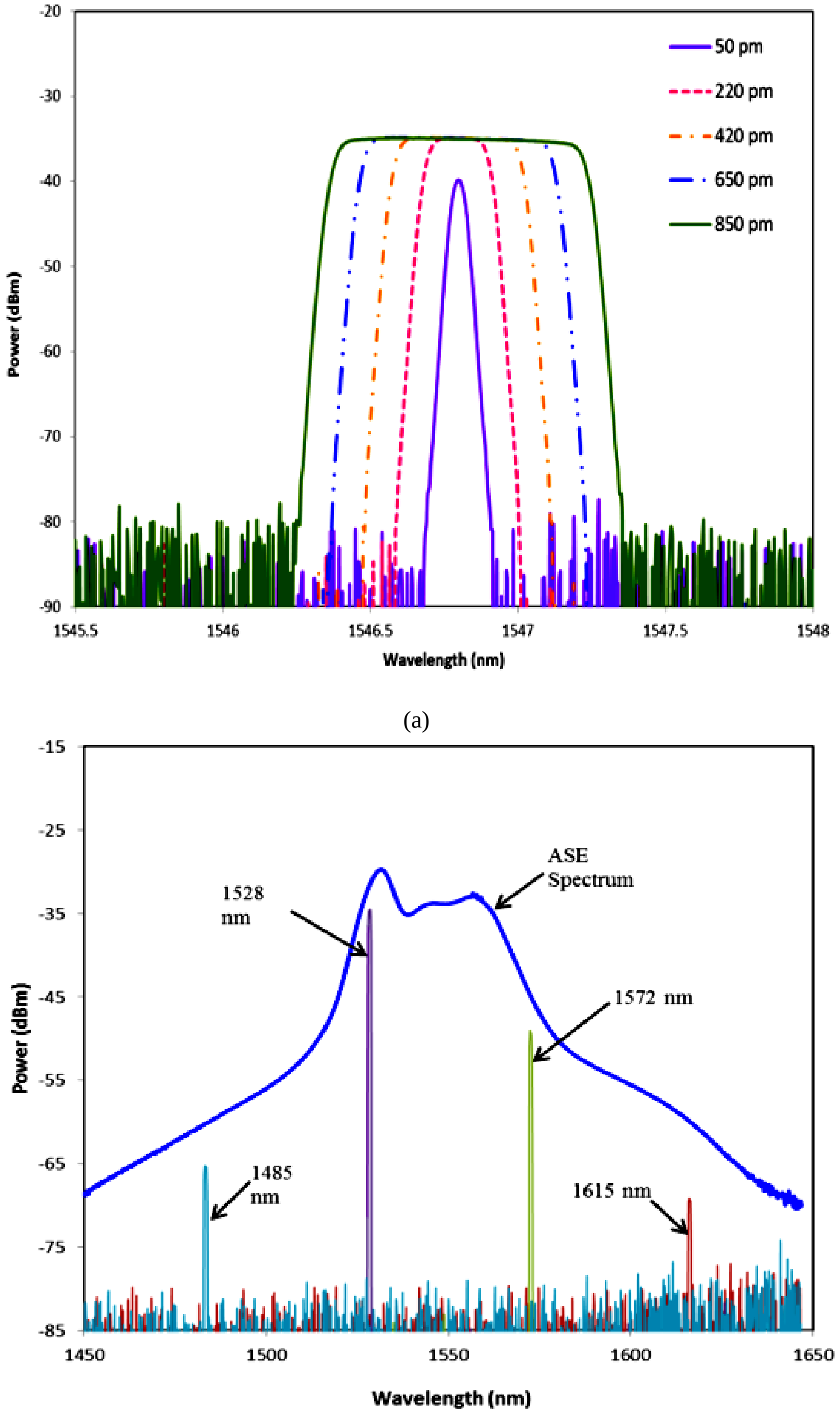
The Fabry-Perot Etalon consists of metallic layers that act as an interferences filter where certain spectral lines will be reflects and transmits others, at the same time coefficient of absorption is maintaining nearly zero for all desired wavelengths. The Fabry-Perot Etalon will selectively choose wavelength by virtue of the interference effects occurs resulting from incident and reflected waves at thin-film boundaries. The Fabry-Perot Etalon located on a rotational stage, thus allows TBF to be tunes up their center transmission wavelength by varying the angle of incident of propagating beam. The rotating of Fabry-Perot Etalon can be controlled by tuning the high precision micrometer, such that any desired wavelength region of TBF may operate [14].

The TBF was then changed to different wavelength selective elements: AWG. 1×16 channel of AWG is used intentionally to ‘slices' ASE into 24-wavelengths with about 0.8 nm inter-channel spacing from two adjacent channels. The AWG device becomes a tuning mechanism in the system and their operating principle can be refer to ref [15]. Subsequently, the AWG is combined with the optical channel selector (OCS) where OCS serves as channel selector which allows single channel out of 16 channels, to propagate through it. The OCS has low-polarization loss of 0.03 dB with cleanable and replaceable optical adapter.

The AWG was then replaced with the UNB-tunable filter. The UNB-tunable filter was used as wavelength selective element in which operates by filtering the ASE passing through and permits a single wavelength to be transmitted. The UNB-tunable filter was set to have the narrowest bandwidth of 50 pm. Ref [5,16] shows details characterization of the UNB-tunable filter device.

For this work, a Yenista XTM-50 ultra-narrow bandwidth optical filter was used as the mechanism to generate the desired SLM output. The optical filter consists of a triangular mirror, grating and a reflector, where the triangular mirror is the main component for controlling the wavelength and bandwidth tunability. The triangular mirror is a crucial component of the filter as it is used to select a portion of the spectrum, with the narrow end of the triangular mirror creating a narrow bandwidth filter while the wide end creates a wide bandwidth filter.

The analysis of the output spectrum is carried out by using an OSA with highest resolution specification of 0.02 nm.The spectrum of different bandwidth and wavelength from the characterization of the UNB- optical filter are shown in Fig. 3 (a) and (b). From Fig. 3, the bandwidth and wavelength of the output spectrum is changing variably with the screw graduation of a tunable filter. The bandwidth of the optical filter is tunable from 50 to 850 pm, which is shown in Fig. 3(a) while a wide wavelength tunability is observed from 1485 nm to 1615 nm and this is depicted in Fig. 3(b), with the power of the wavelengths, filtered corresponding to the relative power of that particular wavelength in the ASE spectrum.



(a)

(b)

Fig. 3. Characterization of optical filter (a) bandwidth tunability from 50 to 850 pm; (b) wavelength tunability from 1485 to 1615 nm (color online)

3. Result and discussion

Fig. 4 shows the spectrum of wavelength transmitted at C-band of EDFL. Output spectra of seven lasing wavelengths with the wavelength interval of ~5 nm are taken from the OSA. The wavelength range of 34.2 nm, spanning from 1525.8 nm to 1560.0 nm is cover by TBF but it is not limited to that scale as TBF (Newport) can be tune up to 100 mm. Ref [17] reported a continuously tunable single-frequency EDF laser the cover tuning range of 70 nm (from 1510 to 1580 nm) by incorporating three TBFs inside fiber ring laser cavity with the total cavity of 40 nm.

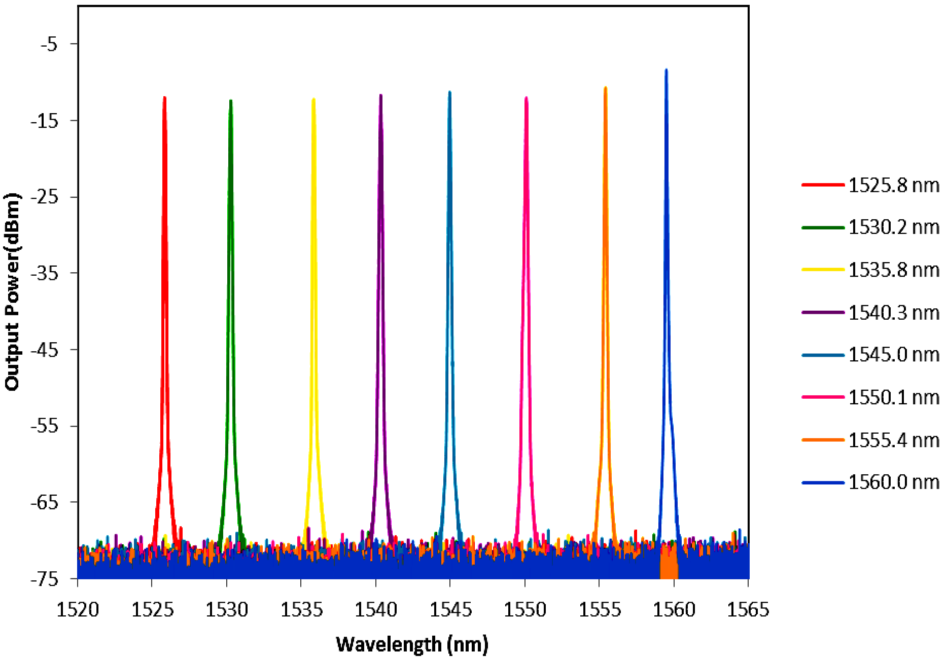


Fig. 4. Tunable single wavelength EDFL using TBF with C-band tuning range (color online)

The TBF still can be tuned to shorter or longer wavelengths, but the lasing output power might be low at shorter wavelength which may cause the limited population inversion in EDF itself. For example, at L-band region (1565 nm -1625 nm), the single-frequency operation becomes more difficult to deal with, since the laser has higher tendency to oscillate under multi-longitudinal modes. This happens in this region since the absorption of EDF too weak to build strong absorption grating. Therefore, laser mode hopping unable to be suppressed. The lasing wavelength is continuously adjustable within permitted TBF tuning range but limited by ASE spectrum of EDF used in the experiment. High stability of lasing was achieved throughout the experiment.

Further analyses were done by measuring the optical signal-to-noise ratio (OSNR) for each spectrum of wavelengths. The data plotted as depicted in Fig. 5. OSNR values slightly increased with the shifting of lasing wavelengths to the longer wavelengths. The average OSNR established is ~61.1 dB with the lowest OSNR is ~60.1 dB while the highest OSNR is ~63.7 dB. The different in OSNR's values might cause by the pattern of ASE spectrum of the EDF itself.

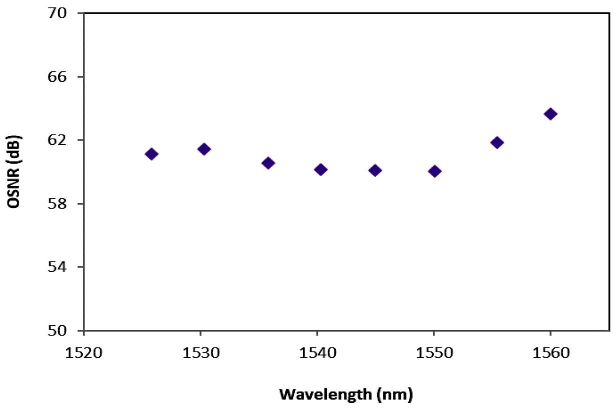


Fig. 5. The OSNR of each lasing wavelength of tunable fiber laser using TBF

Fig. 6 shows the average output power against the lasing wavelength for tunable fiber laser using TBF. The output power recorded by using optical power is performed at fix pump power of ~150 mW. The highest output power of -1.3 dBm is achieved at 1560.0 nm and the lowest output power of -3.1 dBm at 1525.8 nm. The result indicated that the small change of average output power when the TBF is tuned to perform the shifting to the longer wavelengths, where the maximum difference between highest and lowest average output power measured is 1.8 dBm.

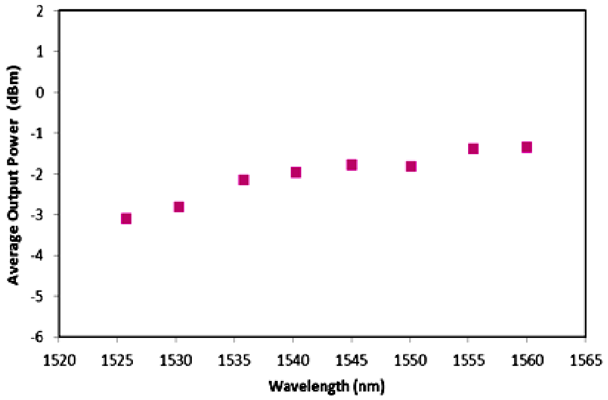


Fig. 6. Average output power against lasing wavelength

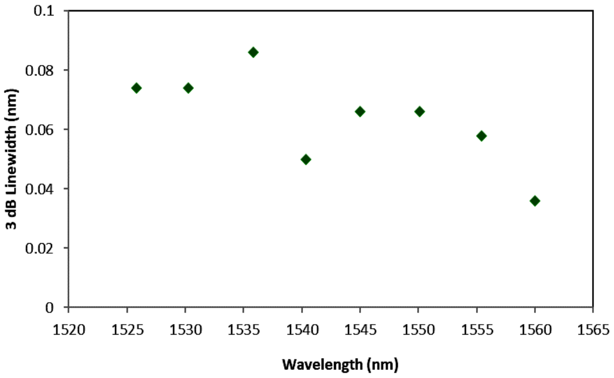


Fig. 7. The 3 dB linewidth against wavelengths

Fig. 7 shows the graph of 3 dB linewidth of single-wavelength fiber laser using TBF against their lasing wavelengths. In this experiment, lasing single wavelength at 1560.0 nm achieved the narrowest linewidth of 0.036 nm while broadest linewidth of 0.086 nm is obtained for single-wavelength laser at 1535.8 nm. The maximum difference between the narrowest and broadest linewidth is 0.05 nm.

Fig. 8 shows the shape of output spectrum and tunability performance of fiber laser by using an AWG at a fixed pump power of 150 mW. As shown in figure, approximately the tuning by 16-AWG channels can cover a wavelength range of 11.7 nm, which can span from channel 1 with wavelength of 1527.4 nm to channel 16 with wavelength of 1539.1 nm. The spacing between each channel of wavelengths approximately 0.8 nm. This spacing can be tuned by selecting distinct channel on AWG with maximum distance between two wavelengths can be obtained is 11.7 nm. The tuning range may be extended by using 1×24 AWG. The peak power of all wavelengths is slightly varying with each other.

As seen in Fig. 8, the peak power of measured channels displayed shows fluctuation. Theoretically, the long wavelength is relatively easier to achieve their threshold power before start lasing. This is due to the energies needed for longer wavelength is lower than the shorter wavelength. However, higher spectral curve of EDF at range of 1530 nm caused a slightly lowered threshold power for this range of wavelength. Thus, the reduced threshold power raised the tendency of lasing.

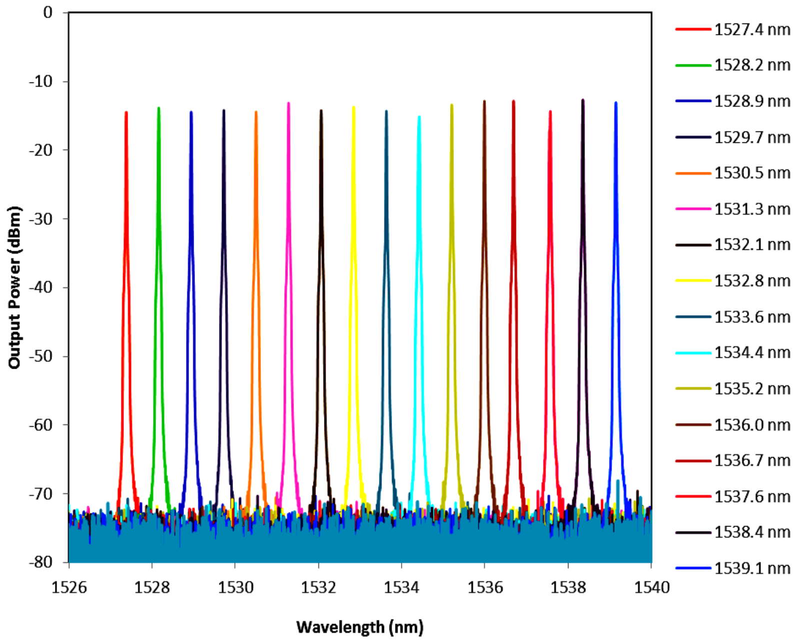


Fig. 8. Tunability of laser spectrum by using an AWG for 16 tuning wavelengths (color online)

Fig. 9 shows the values of OSNR that measured and recorded from tunable single wavelength fiber laser by using totally 16-channel of AWG using fix pump power. The maximum value of OSNR obtained is 61.66 dB from lasing at 1539.1 nm and the minimum value acquired is 59.24 dB from lasing at 1534.4 nm. By the result, the maximum difference between highest OSNR and lowest OSNR is 2.42 dB with average calculation of OSNR is 60.55 dB. As seen in Fig. 9, longer wavelengths have higher OSNR since energy needed to achieve threshold power is lower at longer wavelengths. However, there was reduction in OSNR level at 1534.4 nm and 1537.6 nm lasing wavelength. That might be caused of uneven response of losses inside connector and different wavelengths response of AWG.

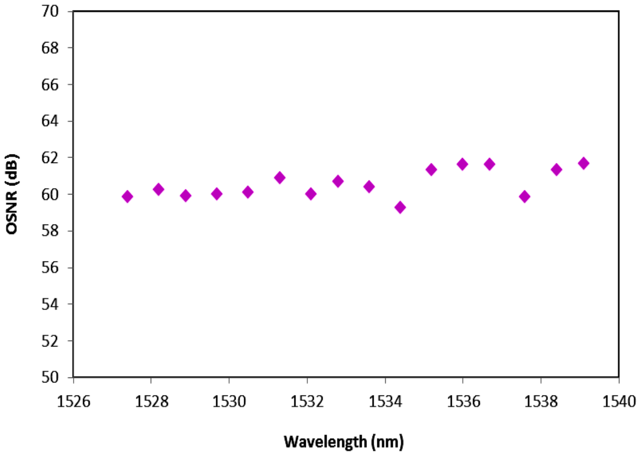


Fig. 9. The values of OSNR of tunable single wavelength tunable fiber laser incorporating 16 different channel of AWG

Fig. 10 shows the received power or output power of 16-different wavelength of AWG recorded by using OPM. 9.05 dBm was the highest output power obtained from the lasing wavelength of 1538.4 nm while the lowest output power recorded is -10.79 dBm at 1529.7 nm. These results giving the different output power of 1.74 dBm and average output power of -9.84 dBm. The output power received by each channel was slightly different.

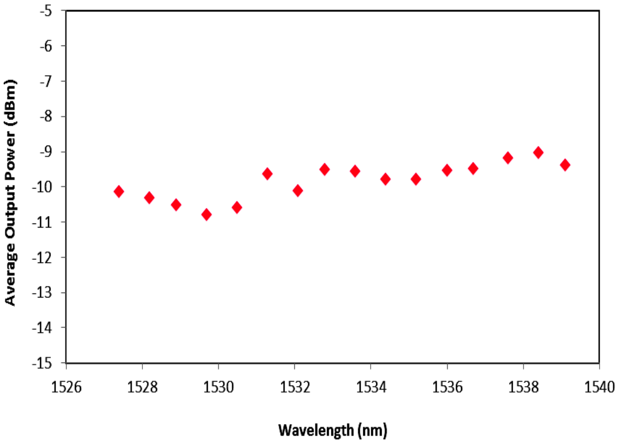


Fig. 10. The average output power of tunable fiber laser of 16-different channel of AWG

In long-haul optical transmission system, the imbalanced in accumulated power and OSNR have significant effect in reducing and limiting the system performance in many ways. Such as, the uneven power received can exceed the limitation of receiver range. The OSNR with different level at certain wavelength might lead to the bit error rate (BER), falling below required levels. Therefore, the tunable fiber laser needed to get flatten at the signal range so that adequate OSNR at each wavelength receives.

In multichannel system, the flat gain spectrum is required. However, EDFA has intrinsic non-uniform gain which typically transmission of signal takes place at 1530 nm. Hence, present gain peaking at the range of 1530 nm. The slight fluctuation in OSNR might also cause by EDFA that exhibit non-uniform gain spectrum [18].

Fig. 11 shows the linewidth of 16 lasing fiber laser by using AWG. The narrowest 3 dB linewidth of 0.016 nm produced at lasing wavelength of 1536 nm, 1536.7 nm, 1540 nm, 1542.3 nm and 1543.1 nm. While the broadest 3 dB linewidth produced is 0.032 nm at lasing wavelength of 1538.4 nm thus giving the linewidth different of 0.016 nm. From wavelength of 1528.9 nm to 1531.3 nm, the 3 dB linewidth produced have almost comparable values.

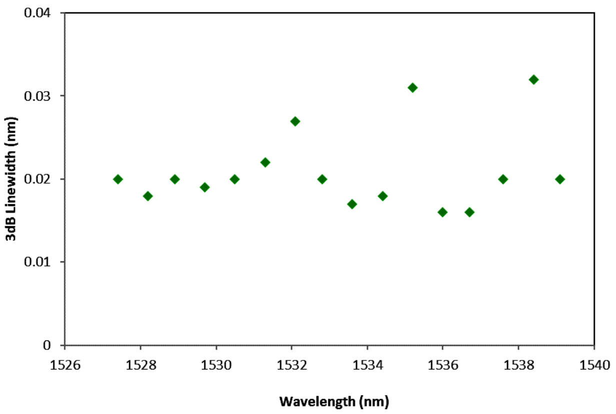


Fig. 11. The linewidth of each lasing wavelength using AWG

Fig. 12 shows the single wavelength fiber laser tunability using the UNB-tunable filter as wavelength selective element. The output spectrum is tuned randomly to 7 different wavelengths filtering from ASE produced and exhibit gain in the 1550 nm region. The output spectrum was taken at fixed pump power of 150 mW with pump wavelength at 980 nm. The range is subjected to the gain bandwidth of the ASE, which is basically depends on the laser active gain medium. From Fig. 12, the tuning range measured is about 37.7 nm, which spanning from 1527.7 nm to 1565.4 nm covering the C-band region. It can be depicted that the power variation across the transmitted wavelengths is relatively high. The amplitude of maximum peak power measured is -30.9 dBm at 1529.8 nm and the minimum peak power measured is -37.4 dBm at 1565.4 nm, giving a total different of ±6.5 dBm. The high excitation level at 1530 nm because of high gain occurs at this region explained the maximum peak power observed at 1529.8 nm. A small degradation of output power is observed as the wavelength is tuned to the longer wavelength which occurs because the absorption of pump power gets low. The output power can be further enhance by supplying higher pump power.

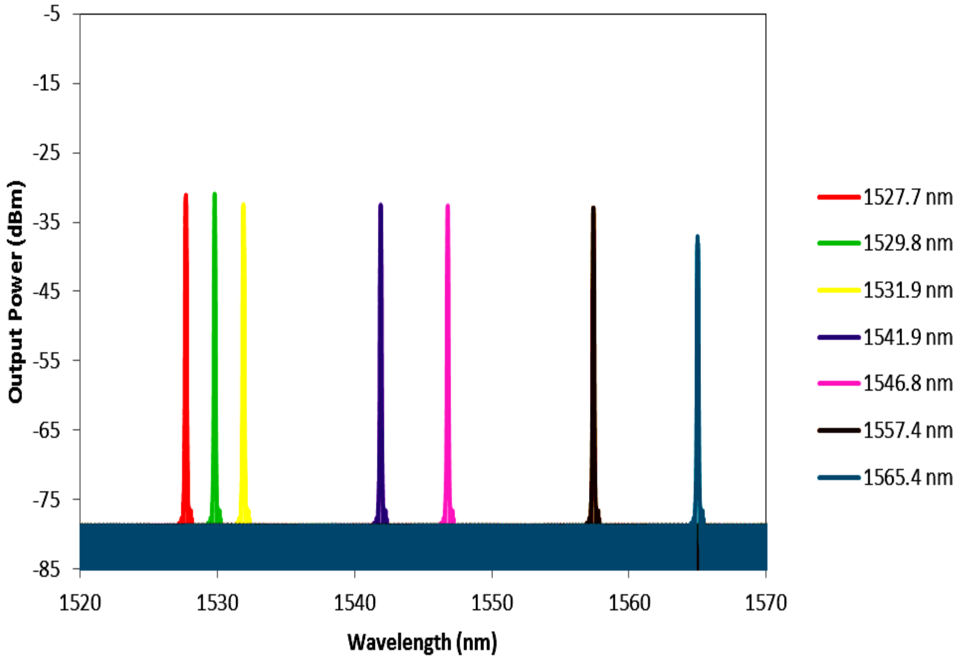


Fig. 12. Tunable single-wavelength fiber laser using UNB-tunable filter in which wavelengths randomly selected over large spectra (color online)

The variation of optical signal-to-noise variation (OSNR) of the proposed tunable single wavelength fiber laser setup against the tuned wavelengths is depicted in Fig. 13. The OSNR with respect to the acquired wavelengths follows the pattern of the output spectrum shows in Fig. 11, dropping initially from 33.4 dB at 1527.7 nm to 22.1 dB at 1531.9 nm and increased to 35.1 dB as wavelength tuned to 1546.8 nm. Subsequently, the OSNR is lowering to 31.2 dB at wavelength of 1565.4 nm. Based on Fig. 13, it can be seen that the averages OSNR for all wavelengths is ±33.0 dB except at wavelength of 1531.9 nm, the OSNR is at worst which is 22.1 dB giving the total different of ±10 dB. The low OSNR at 1531.9 nm was caused by the high excitation level at this wavelength;

hence the ASE noise level is higher compared to other wavelengths even though the presence of emission wavelength signal at 1531.9 reduces the ASE noise level.

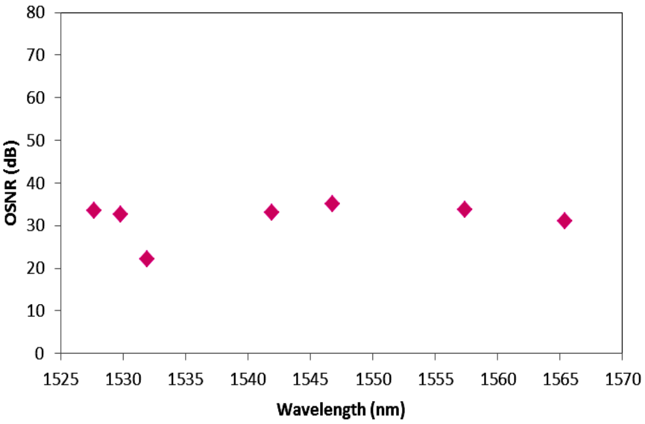


Fig. 13. OSNR variation versus the tuned of output wavelengths

The average output power of the proposed fiber laser against the tuned wavelengths is illustrated in Fig. 14. The output power received at 5% of 95/5 optical fused coupler using OPM. Roughly, output power recorded corresponding to each tuned wavelength is stable and flatten at power approximately in range of -10.8 dBm to -13.3 dBm. The highest output power obtained is -10.8 dBm at 1541.9 nm and minimum output power of -13.3 dBm at 1531.9 nm giving average output power of 12.1 dBm. The low averages output power majorly caused by power loss as the signal propagating through UNB-tunable filter, instead of passive loss made up by spliced loss, connector loss and fiber loss. The slightly different power obtained indicated the loss due to change in wavelength.

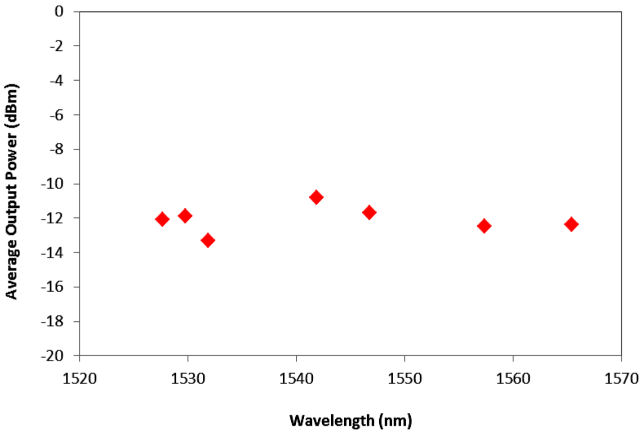


Fig. 14. The average output power against the tuned single-wavelengths using UNB-tunable filter

The data is further analyzed in terms of its 3 dB linewidth against the tuned wavelength as plotted as shown in Fig. 15.

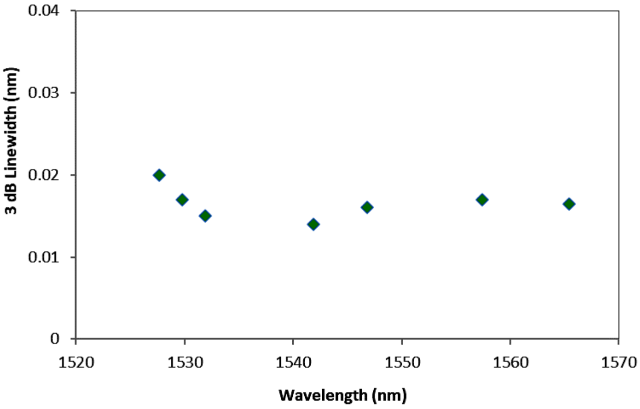


Fig. 15. The 3 dB linewidth against the tuned wavelength

As pointed before this, the bandwidth of UNB-tunable filter used in this experimental design is 50 pm. Based on Fig. 15, the narrowest 3 dB linewidth obtained is 14 pm while the broadest 3 dB linewidth is 20 pm, in which measured directly through 0.02 nm resolution OSA. The narrow bandwidth produced by this experimental setup due to election of narrowest bandwidth tuning of UNB-tunable filter, thus it is not compatible with OSA's resolution and the results of linewidth obtained might be narrower than stated in the graph. The linewidth can be further minimized by suppressing the external noise and optimizing the laser design. Broader and narrower 3 dB bandwidth can be produced using by adjusting the bandwidth of the UNB-tunable filter. However, the resolution of common OSA might show imprecise measurement. Thus, the determination of the laser linewidth using ‘delayed self-heterodyne method' can rely. This technique has been used, giving a measured linewidth of 61.5 kHz [5,16,17].

4. Conclusion

The tuning characterization of single fiber laser by using different wavelength selective elements is presented. The UNB-tunable filter obtained the widest tuning capability of 37.7 nm, which covered the C-band region. Moreover, the desired wavelengths can be selectively chosen at any range within ASE bandwidth giving advantageous to UNB-tunable filter. TBF device has the same capability of selectable wavelength, which is within ASE range, having tunability of 34.2 nm. Both devices can moderately tune to precise wavelengths. While AWG have limited tuning range of 11.7 nm with fixed 16 wavelengths. However, instead of small tuning range, the AWG is built with 16 channels that can easily select precise wavelength where a fixed gap of 0.08 nm from adjacent channels giving it a significant advantage as tuning elements. 3dB linewidth measured from 0.02 nm resolution OSA enthrone UNB-tunable filter as a great mechanism to produce narrow linewidth fiber laser. By using UNB-tunable filter, the average 3 dB linewidth measured was 16.5 pm, while TBF and AWG giving the result of 0.06 nm and 0.02 nm linewidth, respectively. However, the linewidth of fiber laser using UNB-tunable filter cannot be fully relied upon since the limited resolution of OSA. The linewidth produced might be narrower than stated above.

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References

[1] X. Feng, H. W. Tam, H. Liu, P. K. A. Wai, Optics Communications **268**, 2 (2006).

[2] A. A. Al Mukhtar, A. A. Al-Azzawi, Z. Jusoh, N. F. Razak, P. H. Reddy, D. Dutta, S. Das, A. Dhar, M. C. Paul, H. Ahmad, M. Yasin, S. W. Harun, Optoelectron. Adv. Mat. **13**, 7 (2019).

[3] X. Liu, L. Zhan, S. Luo, Z. Gu, J. Liu, Y. Wang, Q. Shen, Optics Express **20**, 7(2012).

[4] H. Ahmad, M. R. K. Soltanian, C. H. Pua, M. Z. Zulkifli, S. W. Harun, IEEE Photonics Journal **5**, 6 (2013).

[5] H. Ahmad, N. F. Razak, M. Z. Zulkifli, F. D. Muhammad, Y Munajat, S. W. Harun, Laser Phys. Lett. **10**, 105105 (2013).

[6] S. Yamashita, K. Hotate, Electron. Lett. **32**, 1298-1299 (1996).

[7] A. Lokman, A. Hamzah, N. A. D. Huri, H. Arof, F. Ahmad, H. Ahmad, S. W. Harun, Optoelectron. Adv. Mat. **4**, 11 (2010).

[8] H. Wei, Z. Jiaqi, D. Mingli, M. Fanyong, Z. Lianqing, Optics & Laser Technology **127**, 106026 (2020).

[9] Y. G. Han, T. V. A. Tran, S. B. Lee, Optics Letters **31**, 6 (2006).

[10] H. Ahmad, N. F. Razak, M. Z. Zulkifli, M. F. Ismail, Y. Munajat, S. W. Harun, Applied Optics **53**, 29 (2014).

[11] Th. Pfeiffer, H. Schmuck, H. Bülow, IEEE Photon. Technol. Lett. **4**, 8 (2002).

[12] A. Bellemare, M. Karasek, C. Riviere, F. Babin, G. He, V. Roy, G. W. Schinn, IEEE J. Select. Topics Quantum Electron **7**, 4 (2001).

[13] Y. Lv, S. Lou, Z. Tang, X. Liu, X. Wang, Optics & Laser Technology **128**, 106269 (2020).

[14] G. R. Lin, J. R. Wu, Applied Optics **42**, 27 (2003).

[15] P. Munoz, D. Pastor, J. Capmany, J. Lightwave Technol. **20**, 4 (2002).

[16] N. F. Razak, H. Ahmad, M. Z. Zulkifli, F. D. Muhammad, Y. Munajat, S. W. Harun, Optik **126**, 2 (2015).

[17] H. Chen, F. Babin, M. Leblanc, G. W. Schinn, IEEE Photonics Technology Letters **15**, 2 (2003).

[18] B. A. Hamida, S. Azooz, A. A. Jasim, T. Eltaif, J. Eur. Opt. Soc. **10**, 15015 (2015).

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