Performance comparison of single-mode single-cladding thulium doped and thulium/holmium co-doped fiber lasers in ring cavity

H. SHAMSUDIN[a], A. A. LATIFF[a,b], N. N. RAZAK[b], Z. JUSOH[c], H. AHMAD[a], S. W. HARUN[a,c]
[a]*Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia.*
[b]*Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100 Melaka, Malaysia.*
[c]*Faculty of Electrical Engineering, Universiti Teknologi MARA (Terengganu), 23000 Dungun, Terengganu, Malaysia*
[d]*Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.*

We investigate and compare the performance of the thulium-doped fiber laser (TDFL) and thulium holmium co-doped fiber laser (THDFL) based on 800 nm pumping. Both fiber lasers generated a broadband amplified spontaneous emission (ASE) across a wavelength range of 1720 - 2010 nm, with a threshold pump power of 155.58 mW. The THDFL and the TDFL are operating at single wavelength of 1908.87 nm and at dual wavelength of 1931.62 nm and 1937.09 nm respectively with a signal-to-noise ratio (SNR) of more than 30 dB. We also discuss the cross-relaxation process for TDFL and energy transfer for THDFL operations. With 1550 nm pumping, the THDFL operates at 1986.4 nm due to energy transfer from Tm^{3+} to Ho^{3+} in the active medium.

(Received November 23, 2015; accepted September 29, 2016)

Keywords: Thulium-doped fiber, Thulium-holmium doped fiber, Continuous-wave fiber laser

1. Introduction

Laser systems operating in 2 μm "eye safe" wavelength region have gained steadily increasing interest in recent years since they offer exceptional advantages especially for free space applications compared to the conventional systems that operate at shorter wavelengths. For instance, they are suitable for applications in LIDAR and gas sensing systems as well as in free-space optical communication [1, 2]. Strong water absorption in this wavelength range makes such lasers also very useful for medical applications. These 2 μm lasers can achieve a substantial heating of small areas and thus they allow for very precise cutting of biological tissue. The wavelength also overlaps with many absorption lines of several gas molecules such as hydrogen bromide (HBr) and carbon dioxide (CO_2), which creates the possibility of constructing cost-effective gas sensors. The development of 2 μm fiber laser can be realized based on radiative transitions in thulium and holmium trivalent cations, Tm3+ and Ho3+, respectively. However, there are still many issues to be addressed such as low quantum efficiency of generated laser in high-phonon energy glass host matrix such as silica-based glass fibers. Therefore, Thulium-doped fibers (TDFs) are normally employed low phonon energy glass hosts, eg. - fluoride glass, in which the up-conversion intensity is reported to be quite high in ultraviolet region [3]. Nevertheless, since the fluoride host is a rather soft type of glass, it is very hard to draw optical fiber from the preform due to its lower melting temperature. Recently, the interest has shifted back to silica based host TDFs as the phonon energy of silica glass can be reduced by incorporating silica network modifiers like Aluminum (Al) and Germanium (Ge). Thus TDFs with modified silica host have emerged as a promising gain medium for achieving an efficient TDF laser (TDFL) [4-7].

TDFLs and Holmium doped fiber lasers (HDFLs) provide an efficient method of generating high average power in the 1.8 – 2.2 μm spectral region. TDFLs typically operate efficiently in wavelength region between 1.85 – 2.09 μm [8]. However these systems are not able to efficiently access longer wavelengths due to the diminishing emission cross-section of thulium in silica. Singly-doped HDFLs present the most power scalable method for operation at 2.1 μm [9]. Both TDFL and HDFL operate based on quasi-four level system, and thus they possess a non-negligible population in the lower laser level. As such, they definitely present a challenge in this regard due to a significant level of pump excitation required to overcome the population in the lower laser level and achieve inversion. In this paper, we compare the performance of a thulium-doped fiber laser (TDFL) with the thulium holmium co-doped fiber laser (THDFL) as the gain medium which was pumped by an 800 nm pump laser in a ring cavity configuration. The performances of TDFL and THDFL are investigated with gain medium lengths of 2 m and 90 cm respectively. We also discuss the cross-relaxation process for TDFL and energy transfer for THDFL operations.

2. Working principles of the 2 micron fiber lasers

TDFL operating at around 1.9 μm region can be realized by laser diode pumping at wavelength near 800 nm ($^3H_4$) and 1560 nm ($^3F_4$). The 1.9 μm laser can be obtained in a singly doped TDF due the energy transition between the $^3F_4 \rightarrow$ $^3H_6$ states. The typical energy level diagram of the Tm^{3+} with possible laser transition and cross relaxation process is shown in Fig. 1. The $^3H_6 \rightarrow$ $^3F_4$ absorption band of silica TDF possesses an extremely broad line-width, close to 130 nm, it is one of the broadest in any of the trivalent rare earths [10]. The pump band mostly used is $^3H_6 \rightarrow$ $^3H_4$ transition at about 800 nm, which exhibits no significant excited-state absorption (ESA). The $^3H_6 \rightarrow$ $^3H_4$ transition is very broad, and it allows pumping at the strong peak near 790 nm with either AlGaAs laser diode or Sapphire laser. One important feature of this transition is the cross-relaxation between Tm^{3+} pairs, which takes place when the Tm^{3+} concentration is sufficiently high [11]. As shown in Fig. 1, the cross-relaxation process leads to energy transfer from a Tm^{3+} ion in the $^3H_4$ level (donor) to a neighbouring Tm^{3+} ion in the ground state (the acceptor). The latter is thus excited to the upper laser level ($^3F_4$ level), whereas the donor drops to the $^3F_4$ level, yielding two excited ions for one pump photon, or a quantum efficiency of 2 as shown in Fig. 1 [12]. The phenomenon of cross-relaxation can be used to produce an efficient 1.9 μm laser using a 800 nm pumping in conjunction with TDF with high Tm^{3+} concentration. Another pump band for Tm^{3+} is at 1560 nm, where lasing near 2 μm in the pure TDF occurs between the $^3F_4$ and $^3H_6$ states. The spectral bandwidth of the TDF also covers a very large range from 1.7 – 2.1 μm.

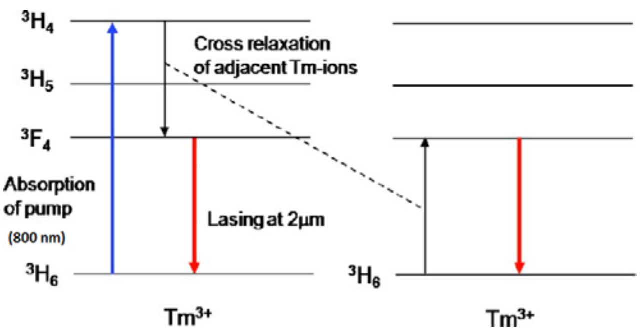


Fig. 1. Energy level diagram showing cross-relaxation of excited Tm3+ into the metastable level

The lasing wavelength can further extend to longer wavelength above 2.0 μm when Ho^{3+} is doped in the fused silica glass along with the thulium. The energy level diagram of THDF with possible transitions is as shown in Fig. 2. The approach of co-doping Ho^{3+} ions along with the Tm^{3+} in fused silica is to achieve lasing on the transition of $^5I_7 \rightarrow$ $^5I_8$ level of Ho^{3+} [13-14] due to energy transfer mechanisms through Tm^{3+} excitation. If the Tm^{3+} concentration is sufficiently high there is energy transfer from $^3F_4$ state of Tm^{3+} to $^5I_7$ state of Ho^{3+} leading to population inversion. The doping Tm:Ho ratio will determine the transparency level of the laser transition and the threshold power. It is believed that the high ratios will ensure that enough Ho^{3+} ions will be sufficiently excited to exceed the transparency level of the laser transition for a given pump power and hence decrease the thresholds [15].

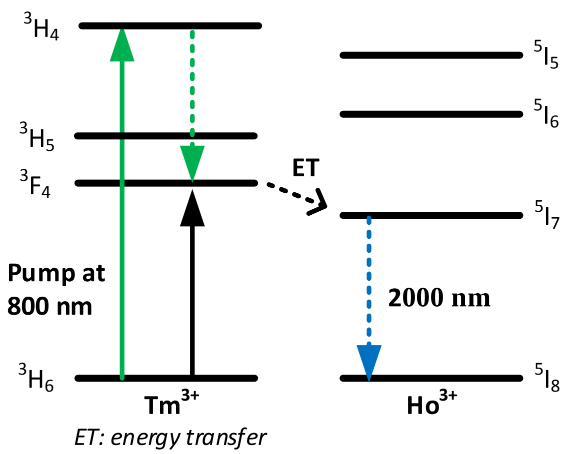


Fig. 2. Energy level schematic of THDF indicating Tm/Ho energy transfer process.

3. Experimental setup

The experimental setup of the proposed 2 micron fiber lasers is shown in Fig. 3.

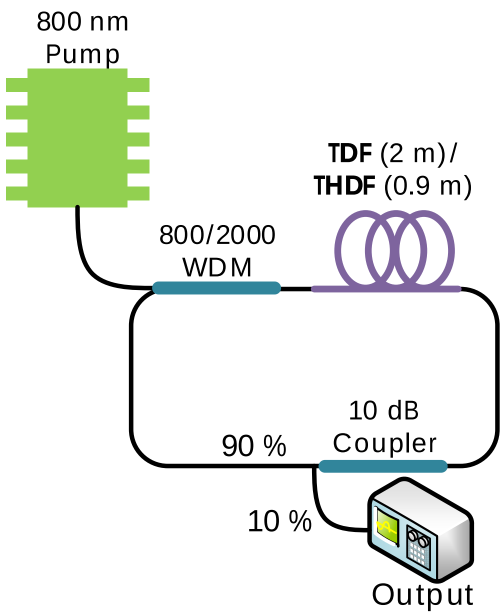


Fig. 3. Experimental for the TDFL/THDFL based on a ring cavity configuration.

Two gain media with single-mode and single cladding structure are tested in the configuration; 2 m long TDF (Nufern SM-TSF-9/125) and 0.9 m long THDF (CorActive TH550). Tables 1 and 2 summarize the optical and physical specifications, respectively, for both fibers. A 800 nm laser diode with the maximum output power of 182 mW is used as a pumping source for the proposed ring laser. It is launched into the active fiber via 800 / 2000nm Wavelength Division Multiplexer (WDM). The output laser is tapped out from a 10% port of a 90:10 coupler. The remaining signal is channelled through the 90% port of the tap coupler where it will now come into contact with the 2000-nm port of the WDM, thereby completing the ring cavity. The 10% port of the 90:10 coupler are connected into a digital power meter (ThorLabs PM100D/S302C) and two units of optical spectrum analyser (OSA1: Yokogawa AQ6370B and OSA2: Yokogawa AQ6375). OSA1 and OSA2 have an operating wavelength in a range of 600 - 1700 nm and 1200 - 2400 nm respectively.

Table 1. Optical Specification of the TDF and THDF.

Model	Operating Wavelength (nm)	Core NA	Mode Field Diameter (μm)	Cutoff Wavelength (nm)	Core Absorption
Nufern SM-TSF-9/125 (TDF)	1900 – 2100	0.15	10.5 @ 2.0	1750 $\pm$ 100	9.00 ± 2.00 dB/m at 1180 nm 27.00 dB/m at 793 nm
CorActive TH550 (THDF)	1900 – 2100	0.14	NA	NA	> 100.00 dB/m at 790 nm

Table 2. Geometrical & Mechanical Specification of the TDF and THDF.

Model	Cladding Diameter (μm)	Core Diameter (μm)	Coating Diameter (μm)	Coating Concentricity (μm)	Core / Clad Offset (μm)
Nufern SM-TSF-9/125 (TDF)	125.0 ± 1.0	9.0	245.0 ± 15.0	< 20.0	≤ 0.50
CorActive TH550 (THDF)	125.0 ± 1.0	11.5 ± 1.0	245.0 ± 15.0	< 1.0	NA

4. Result and discussion

The amplified spontaneous emission (ASE) emission was investigated for both TDF and THDF using a 800 nm single-mode pumping scheme. In the experiment, TDF and THDF lengths were fixed at 2 m and 0.9 m, respectively while the 800 nm pump power is fixed at 155.58 mW. The pump is launched into the fiber when the 10 dB coupler is removed from the cavity and the forward ASE is monitored using both OSAs. Fig. 4 compares the ASE spectra within a wavelength range from 600 nm to 2400 nm. The residual pump is observed at wavelength of 804.61 nm while the 1614.09 nm line is a second order pump from the laser diode. As seen in the figure, the TDF and THDF emit broadband ASE at 1720 - 2020 nm region as pumped by 800 nm photons. The ASE output spectra for both TDF and TDHF are almost similar where the peak emission is obtained at centre wavelength of 1872 nm. However, the ASE peak powers are obtained at -61 dBm and -58 dBm with THDF and TDF, respectively, which indicates that the TDF exhibits better performance than THDF. This is attributed to the insufficient 800 nm pump power to excite all the Tm^{3+} in the TDF. It is also observed that a broad ASE peaking at 2060 nm is achieved by the 800 nm pumped TDF. This is most probably due to the shorter wavelength TDF's ASE, which is absorbed and emits at around 2060 nm region. We could conclude that the broad ASE emission in the 1750 - 2010 nm region is achieved through the transition of a thulium ion from $^3F_4$ to $^3H_6$ level and also from an active holmium ion from $^3I_7$ to $^3I_8$. In addition to cross-relaxation process between thulium ions, the 800 nm pump is expected to provide effective energy transfer channels from holmium to thulium.

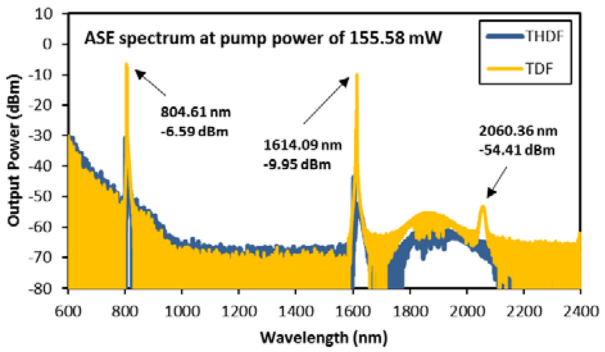
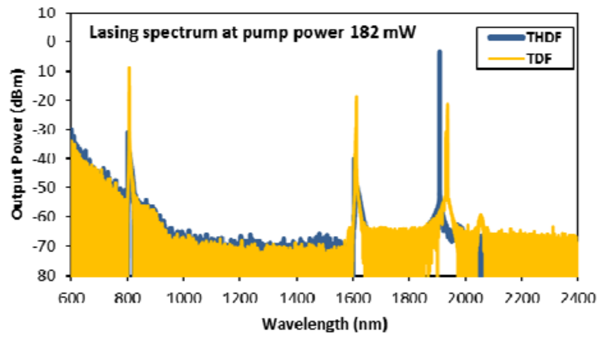
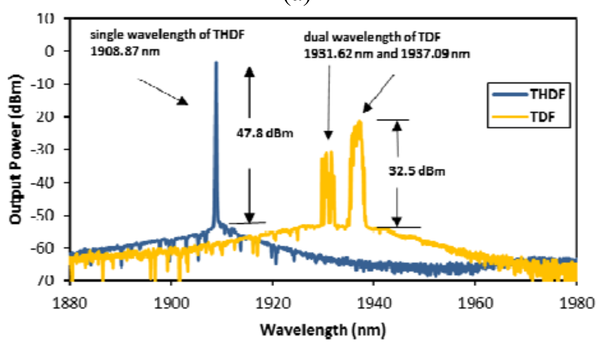


Fig. 4. ASE spectrum of TDF and THDF at pump power of 155.58 mW.

Fig. 5 shows the lasing spectrum of the TDF and THDF recorded by both OSA1 and OSA2 when a 10 dB coupler is incorporated in the cavity as shown in Fig. 3. In the experiment, the TDF and THDF length was fixed at 2 m and 0.9 m respectively while the maximum power of the 800 nm pump was 182 mW. The THDFL and dual-wavelength of the TDFL are operating at 1908.87 nm, 1931.62 nm and 1937.09 nm respectively with a signal-to-noise ratio of more than 30 dB as depicted in Figs. 5(a) and (b). It is shown that the power of the peak wavelength of the residual pump at 800 nm is about 12 dB lower than the peak power of the lasing wavelength. This shows that the output power measured by a power meter is mainly from the contribution of the lasing wavelength at 1908.87 nm, 1931.62 nm and 1937.09 nm. The 800 nm pumping allows only ground state absorption to contribute to the stimulated emission and lasing. In this process, Tm^{3+} ions absorb pump photons and are excited to upper laser level $^3I_4$, which causes population inversion between $^3H_6$ and $^3I_4$ level. As the Tm^{3+} ions drop back to the ground state they emit photons in the 2 μm region. On the other hand, 800 nm pumping creates excitation of photons for both active holmium and Tm^{3+} ions. Thulium ions at the $^3H_6$ level absorb pump photons and are excited to the upper laser level of $^3H_4$. The excited ions are then transferred non-radiatively to the $^3F_4$ level before they relax at the $^3H_6$ level to emit photons in the 2 μm region. The high thulium doping concentration may increase the possibility of Tm cross-relaxation to occur, by pumping Tm^{3+} ions with 800nm pump, the 'two for one' cross relaxation process may contribute to the population inversion at $^3F_4$ level. As sufficient number of Tm^{3+} ions occupy the ground state, some of the neighbouring ions will absorb the emitted photons, which are the result of other Tm^{3+} ions going through the transition from $^3H_4$ to $^3I_4$ level. Consequently, two ions can be excited to $^3F_4$ level using only one pump photon and this enhances the emission in the 2 μm region.



(a)



(b)

Fig. 5. The lasing spectrum of TDF and THDF at pump power of 182 mW in a scanning range of (a) 600 - 2400 nm. (b) The enlarged lasing spectrum within 1880 -1980 nm.

Fig. 6 shows the laser output power against the total pump power for a 0.9-m long of the THDF and a 2-m long of the TDF. As shown in the figure, the efficiency of the proposed THDFL and TDFL increases linearly as the input power increased gradually. The slope efficiency of 7.02% and 16.11% are obtained for THDFL and TDFL respectively with the maximum input power of 182 mW. The threshold pump power for the THDFL and TDF are 155.85 mW. The result shows that the TDF yields better performance due to the high thulium doping concentration in the gain medium, which supports the cross-relaxation process in the TDFL. Thus, the TDFL requires a smaller pump power to initiate lasing. High thulium doping concentration in the TDF increases the cross-relaxation process such that the optimum length for lasing is comparatively short. To avoid clustering from high concentration of rare-earth ion doping, Aluminium is added as a host modifier to reduce phonon energy of the core glass in the fiber. This in turn increases the probability of radiative emission and improves lasing efficiency.

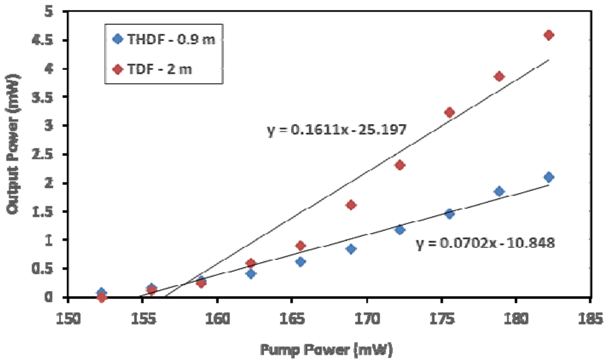


Fig. 6. The comparison of performance of the output power of a 0.9-m long of the THDF with a 2-m long TDF.

The efficiency of the THDFL is lower than the TDFL due to insufficient 800 nm pump power to allow the process of energy transfer happen in the THDFL. The unused Ho^{3+} absorbs the photons at 2 micron region and reduces the efficiency of the laser. Furthermore, the 800 nm pumped THDFL operates at 1908.87 nm and this indicates there is no energy transfer from Tm^{3+} to Ho^{3+} to generate photons at longer wavelength. To show the effect of energy transfer, we repeat the experiment by replacing the 800 nm laser diode with 1550 nm fiber laser for pumping. Figs. 7(a) and (b) show the ASE spectrum and the lasing for the 1550 nm pumped THDFL. The ASE is generated at wavelength region from 1960 nm to 2180 nm, which is shifted to a longer wavelength as compared to 800 nm pumping. Fig. 7(b) shows the lasing spectrum of the THDFL, which indicates that the laser operates at 1986.4 nm due to the energy transfer from Tm^{3+} to Ho^{3+}. Inset of Fig. 7(b) shows output power against the pump power for the 1550 nm pumped THDFL. It shows the laser has a higher efficiency of 5.78% compared to the 800 nm pumping. The maximum peak power of 31 mW is obtained at 1550 nm pump power of 1100 mW. It is expected that the efficiency of the laser output can be further improved by optimization of the THDF length, cavity loss and the amount of Tm-Ho co-doped in fiber core. The benefit of the proposed 2 µm laser system is that it operates in eye-safer wavelengths, where permissible free space transmission levels can be several orders of magnitude greater than 1 µm.

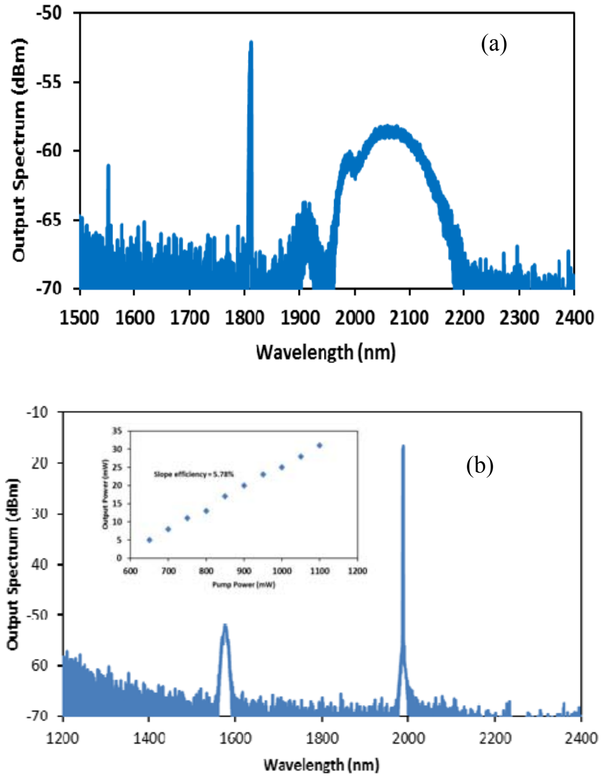


Fig. 7. Performance of 1550 nm pumped THDFL (a) ASE spectrum (b) Lasing spectrum. Inset of (b) shows the output power against 1550 nm pump power.

5. Conclusion

A single mode laser operating at 2 µm region has been successfully demonstrated by employing a commercial THDF and TDF as the gain medium. The THDF and TDF are pumped by 800 nm photons to generate ASE in the 1720-2020 nm region via the transition of thulium ions from $^3I_4$ to $^3H_6$. The ASE oscillates in a ring cavity to generate laser output with the optimum gain medium length of 2 m and 0.9 m for TDF and THDF, respectively. The THDFL and TDFL generate a laser with a slope efficiency of 7.02% and 16.11% respectively and the threshold pump power for both lasers is 155.85 mW. The maximum output power of 2.1 mW and 4.58 mW are obtained at the maximum pump power of 182 mW. With 1550 nm pumping, the THDFL generates laser at 1986.4 nm due to energy transfer from Tm^{3+} to Ho^{3+} in the active medium.

Acknowledgement

This work is supported by Ministry of Higher Education (Grant No: FRGS/1/2015/SG02/UITM/03/3) and University of Malaya (Grant No: PG105-2014B).

References

[1] J.-P. Cariou, B. Augere, M. Valla, Comptes Rendus Physique **7**, 213 (2006).
[2] K. Scholle, S. Lamrini, P. Koopmann, P. Fuhrberg, "2 µm Laser Sources and Their Possible Applications," in Frontiers in Guided Wave Optics and Optoelectronics, B. Pal, Ed., ed Croatia: InTech, 2010.
[3] F. J. McAleavey, J. O'Gorman, J. F. Donegan, B. D. MacCraith, J. Hegarty, G. Maze, IEEE J. Selected Topics in Quantum Electronics **3**, 1103 (1997).
[4] H. Shamsudin, A. A. Latiff, N. N. Razak, H. Ahmad, S. W. Harun, Optoelectron. Adv. M. **10**, 129 (2016).
[5] S. W. Harun, A. Halder, M. C. Paul, S. M. M. Ali, N. Saidin, S. S. A. Damanhuri, H. Ahmad, S. Das, M. Pal, S. K. Bhadra, Chinese Optics Lett. **10**, 101401 (2012).
[6] N. Saidin, D. I. M. Zen, F. Ahmad, S. S. A. Damanhuri, H. Ahmad, K. Dimyati, S. W. Harun, IET Optoelectronics. **8**, 150 (2014).
[7] S. M. Azooz, S. W. Harun, H. Ahmad, A. Halder, M. C. Paul, M.Pal, S. K. Bhadra, Chin. Phys. Lett. **32**, 14204 (2015).
[8] W. Clarkson, N. Barnes, P. Turner, J. Nilsson, D. Hanna, Optics letters **27**, 1989 (2002).
[9] A. Hemming, N. Simakov, A. Davidson, S. Bennetts, M. Hughes, N. Carmody, et al., "A monolithic cladding pumped holmium-doped fibre laser," in CLEO: Science and Innovations, 2013, p. CW1M. 1.
[10] M. J. Digonnet, Rare-earth-doped fiber lasers and amplifiers, revised and expanded: CRC press, 2001.
[11] A. C. Tropper, R. G. Smart, I. R. Perry, D. C. Hanna, J. R. Lincoln, W. S. Brocklesby, "Thulium-doped silica fiber lasers," in San Jose-DL tentative, 1991, pp. 152-157.
[12] P. F. Moulton, G. Rines, E. V. Slobodtchikov, K. F. Wall, G. Frith, B. Samson, et al., Selected Topics in Quantum Electronics, IEEE Journal of **15**, 85 (2009).
[13] K. Oh, T. Morse, P. Weber, A. Kilian, L. Reinhart, Optics letters **19**, 278 (1994).
[14] C. Ghisler, W. Lüthy, H. Weber, J. Morel, A. Woodtli, R. Dändliker, et al., Optics communications **109**, 279 (1994).
[15] S. D. Jackson, T. King, Quantum Electronics, IEEE Journal of **34**, 1578 (1998).

*Corresponding author: swharun@um.edu.my, hanafi62@siswa.um.edu.my