Multi-wavelength thulium-doped fiber laser operating at slope efficiency of 16.57% in linear cavity configuration

H. SHAMSUDIN[a], A. A. LATIFF[a,b], N. N. RAZAK[a,b], H. AHMAD[a], S. W. HARUN[a,c]
[a]*Photonics Research Centre, Department of Physics, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[b]*Faculty of Electrical and Computer Engineering, Malaysia Technical University of Melaka (UTeM), 25566 Melaka, Malaysia*
[c]*Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*

A multi-wavelength thulium doped fiber laser (TDFL) with a slope efficiency of 16.57 % is demonstrated using a linear cavity consisting of a broadband mirror and a flat-cleaved fiber end in conjunction with 1552 nm pumping. The TDFL produces eleven lines within a wavelength range from 1895 to 1907 nm with a constant spacing of 1.2 nm and signal to noise ratio of more than 27 dB. The multi-wavelength TDFL is capable of generating pulses with a repetition rate of 11.62 MHz and average output power of 93 mW at the maximum pump power of 1100 mW. The proposed multi-wavelength TDFL is suitable for a multitude of real-world applications such as range-finding, medicine and spectroscopy due to its ability to operate in the eye-safe region of 2 micron.

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1. Introduction

Multiwavelength fiber lasers have attracted lots of interest in recent years due to their potential applications wavelength division multiplexing (WDM) communication, precise spectroscopy and optical fiber sensing. There are many different methods to realize stable multiwavelength fiber laser operation, such as liquid nitrogen cooling [1], multiple fiber Bragg gratings [2], anisotropic gain effects [3-4], nonlinear optical loop mirror [5], four-wave mixing (FWM) [6], comb filter [7], and nonlinear polarization rotation [8-9]. In the past two decades, most of the previous investigations of multiwavelength fiber lasers focus on 1 and 1.5 μm band. Since 2 μm lasers have lots of applications in LIDAR, communication and atmospheric sensing, they have also attracted broad attention in recent years. However, there are few reports on tunable or multiwavelength fiber lasers near 2 μm up to now [10-12].

Usually, the NPR mechanism is used in passively mode-locked lasers to generate ultrashort pulse trains [13]. However, the lasers based on NPR effect can also work in another operating regime to produce the continuous-wave multi-wavelength emission [14]. By adjusting the polarization in the ring-cavity, NPR can induce intensity-dependent loss (IDL) to alleviate mode competition caused by homogeneous broadening in the gain medium. In this paper, we propose and experimentally demonstrate a multi-wavelength Thulium-doped fiber laser operating at around 1.9 μm region based on NPR technique. Since, the TDF used in the cavity has a reasonably high nonlinearity, it produces sufficient NPR and four-wave mixing (FWM)-induced IDL effect in the laser cavity [15]. In this case, the transmission term varies too fast with the power and thus allows multi-wavelengths to oscillate in the linear cavity. In this work, a high-reflectivity optical mirror is used as a reflector to reduce the threshold pump power while a 1552 nm single-mode fiber laser is used as a pump source.

2. Working principle and experimental setup

Thulium (Tm) is a rare element with atomic number 69. Tm can be pumped at several different wavelength bands, which are located at 793 nm, 1210 nm and at 1640 nm. Tm-doped silica (Si)-fibers have a very broad emission spectrum for the $^3F_4$ to $^3H_6$ transition. The span is about 300 nm, ranging from 1800 nm to 2100 nm which provides a wide flexibility in operating wavelength. This is due to the Tm ions interaction with the local crystal field, its energy levels Stark split into broad energy bands, which is an inhomogeneous broadening effect [16]. The increased phonon energies due to temperature changes also contribute to this broadening [17]. The energy level diagram of the Tm ions in silica glass is shown in Fig. 1. The 2 micron emission and lasing are due to the the ion transition from $^3F_4$ to $^3H_6$. The emission is broad due to the line broadening mechanisms that create manifolds or sub-levels [18]. These sub-levels are susceptible to temperature changes, just as the phonon energy, which induce a redistribution of the populations. The ions relax down from the bottom of $^3F_4$, to the different sub-levels of $^3H_6$, thus enabling the broad emission spectrum. Since $^3H_6$ is the ground state, the transition of TDFL is considered to be a quasi-three level transition. However, at laser transitions beyond 2020-2030 nm, the sub-levels of the top of $^3H_6$ are not highly thermally populated, thus acting as a quasi-four level transition [18].

In this work, the pumping was carried out using a 1552 nm single-mode fiber laser, which is available in medium power, easily obtained and relatively cheaper compared to other wavelength range. The pump propagates inside the fiber core to interacts with Tm ions and produces 2 micron laser. As the pump photons are absorbed by the thulium ions, it excites the ions from ground state $^2F_4$ to $^3H_6$. As the ion relaxes to ground state, energy transfer process happens to neighboring thulium ions. When the thulium ions in ground state ($^3H_6$) absorb the donated photons it got elevated to $^3H_5$ level before it irradiatively relaxes to $^3F_4$. Thulium ions that populate this state level drops to ground state again generating the 2 µm laser.

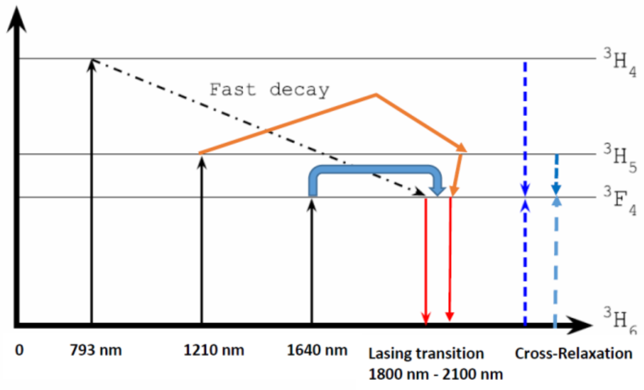


Fig. 1. Energy diagram levels for thulium ions in TDF showing an energy transfer

Fig. 2 shows the experimental setup of the proposed multi-wavelength TDFL using using a simple half-opened linear cavity, which is formed by the broadband mirror and an output coupler reflector. The 5 m long TDF is used as the gain medium of the fiber laser. It has numerical aperture (NA) of 0.15, core and cladding diameters of 9 and 125 µm, respectively, loss of less than 0.2 dB/km at 1900 nm, and peak core absorption at 1180 and 793 nm are 9.3 and 27 dB/m, respectively. The TDF is pumped by a 1552 nm fiber laser via a wavelength division multiplexer (WDM, 1550/2000). The output coupler reflector is formed by the perpendicular cleaved fiber end, which has a 4% Fresnel reflection. The multi-wavelength output spectrum and power of the TDFL are analyzed by using an optical spectrum analyzer (OSA) with a resolution of 0.02 nm and optical power meter (OPM), respectively. The temporal characteristic of the laser is investigated using a 500 MHz digital oscilloscope and RF spectrum analyser via a fast photodetector. Total cavity length is measured as 16.2 m which specify 2 times of a single trip length of 8.1 m.

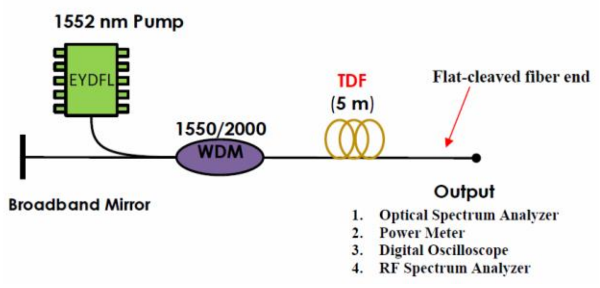
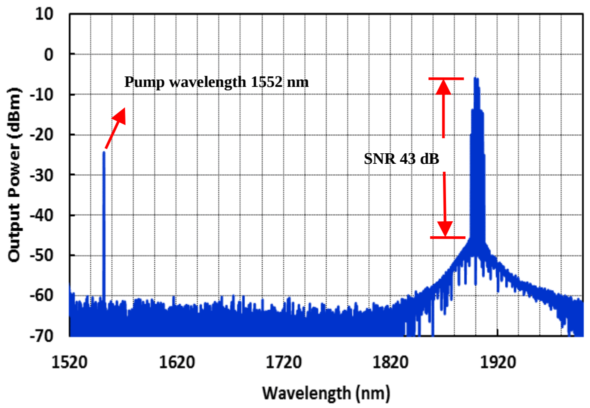


Fig. 2. Experimental setup of the proposed multi-wavelength TDFL

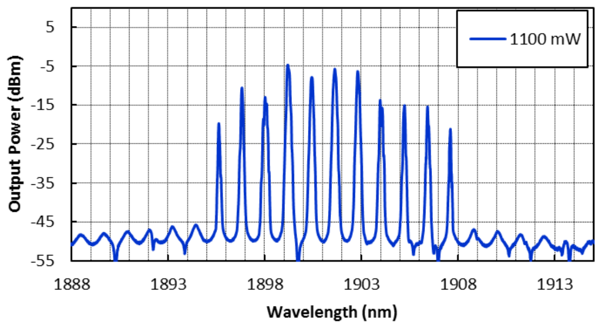
The laser operation is supposed to be grounded on the TDF gain and the resonance between broadband mirror and a 4% Fresnel reflection from the perpendicular cleaved fiber end. When the TDF is pumped by a 1552 nm laser to generate population inversion of thulium ions, the emitted energy is then transferred to thulium ions to generate an amplified spontaneous emission (ASE) in 2 µm region via spontaneous and stimulated emission process. The ASE oscillates in the linear cavity to generate laser when the gain overcomes the total cavity loss. With increasing power of the pump, the multi-wavelength laser is generated due to the effect of the TDF birefringence, which induced round-trip phase variation in the linear laser cavity based on nonlinear polarization rotation (NPR) effect.

3. Result and discussion

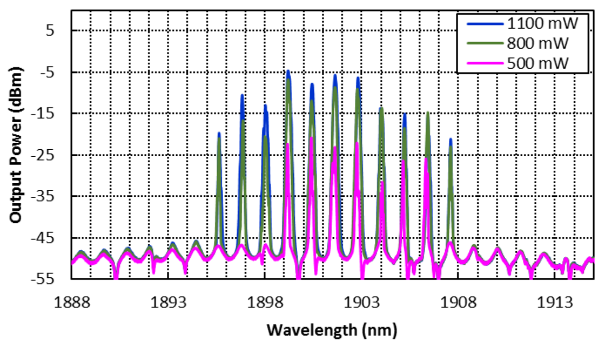
The output spectrum of the proposed TDFL is recorded by an OSA and the result is shown in Fig. 3. At the maximum 1552 nm pump power of 1100 mW, the output spectrum shows two peaks centered at 1901.60 nm and 1552 nm, which represents the multi-wavelength laser and residual pump respectively within the scanning wavelength from 1520 to 2000 nm as shown in Fig. 3(a). The lasing peak and residual pump powers are obtained at -6.2 dBm and -24.4 dBm, respectively and thus the difference is 18.2 dB. The output power of the TDFL is measured to be 93 mW by the OPM at pump power of 1100 mW. Based on the ratio between the peak laser power and the residual pump (18.2 dB), it is obtained that the measured output power is mostly contributed by the multi-wavelength laser. Fig. 3 (b) shows the multi-wavelength laser spectrum, which is obtained within the wavelength region from 1888 nm to 1915 nm. As seen in the Fig. 3 (b), eleven multi-wavelength output lines are obtained at a range of 1895 and 1907 nm with a constant spacing of 1.2 nm. The lasing wavelength has a signal to noise ratio (SNR) of more than 27 dB with a 3 dB bandwidth of of less than 0.1 nm. The Fig. 3 (c) shows the spectra of multi-wavelength TDFL at three different pump powers of 500, 800 and 1100 mW. As shown in the figure, the equal spacing of all spectra are maintained at 1.2 nm while the number of lines are increased from 7 to 11 as the pump power is increased from the threshold power of 500 mW to 1100 mW. The peak power of each lines is also increased with the pump power.



(a)



(b)



(c)

Fig. 3. Output spectrum of the TDFL (a) at 1100 mW within large wavelength range (b) Multi-wavelength output spectrum at 1100 mW (c) at three different pump powers

Fig. 4 shows the output power characteristic of the multi-wavelength laser against the 1552 nm pump power. As shown in the figure, the TDFL starts to lase at threshold pump power of 500 mW to generate a laser operating around 1907 nm region. The output power of the laser is observed to increase linearly with the increment of single mode 1552 nm pump power up to 1100 mW. The slope efficiency of the multi–wavelength laser is measured to be around 16.57 %. For single mode TDFL system, this is the highest slope efficiency, which has been reported so far for the linear cavity configuration. At the single mode pump power of 1100 mW, the multi-wavelength laser produces the maximum total output power of 93 mW. The output spectra of the TDFL is investigated within 60 minutes for a stability test at maximum pump power of 1100 mW. The result is depicted in Fig. 5, which indicates a consistent multi-wavelength lines with the same spacing are obtained within the period.

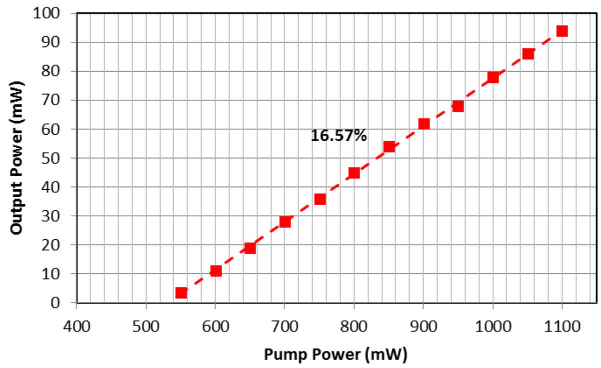


Fig. 4. The output power of the multi-wavelength laser against the 1552 nm single mode pump power for the proposed TDFL in the linear cavity configuration

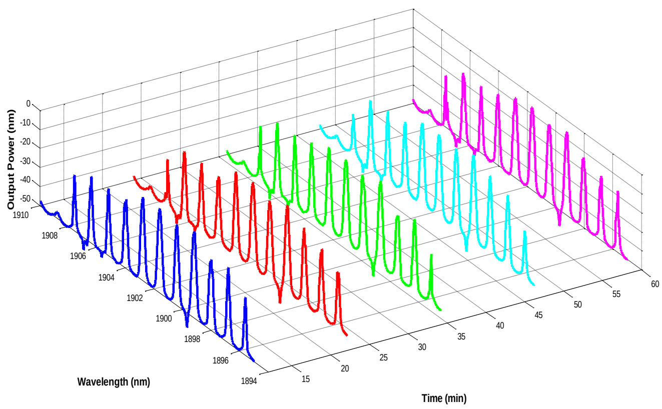


Fig. 5. Stability of output spectrum within 60 minutes under the pump power of 1100 mW

The temporal characteristic of the multi-wavelength laser is also investigated using an oscilloscope with the help of photo-detector. Fig. 6 shows the typical characteristic of the pulse train emitted from the TDFL at a maximum pump power of 1100 mW. The pulse train has a period of 86 ns with a pulse width of less than 3 ns as observes in oscilloscope. The RF spectrum of the multi-wavelength laser is also recorded by RF spectrum analyzer as shown in Fig. 7. It shows a pulse fundamental repetition rate of 11.62 MHz, which agrees very well with pulse period of 86 ns in Fig. 6 and corresponds to double trips cavity length of 16.2 m. The SNR of the RF spectrum is more than 36 dB, which indicates a stable mode-locking operation of the TDFL in the linear cavity. Inset of Fig. 7

shows the harmonic spectrum of the TDFL within 200 MHz span. The mode-locking operation is most probably due to the NPR effect in the linear laser cavity.

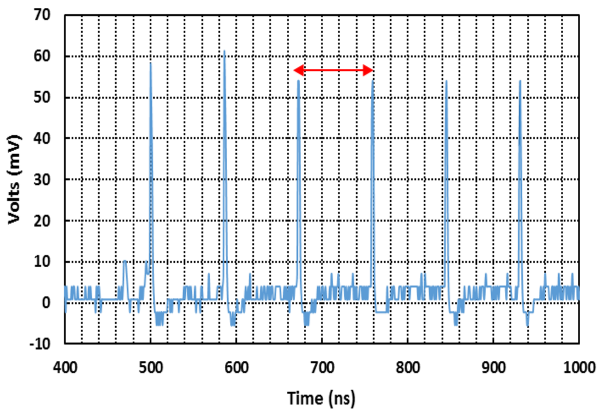


Fig. 6. Pulse train of the TDFL at pump power of 1100 mW

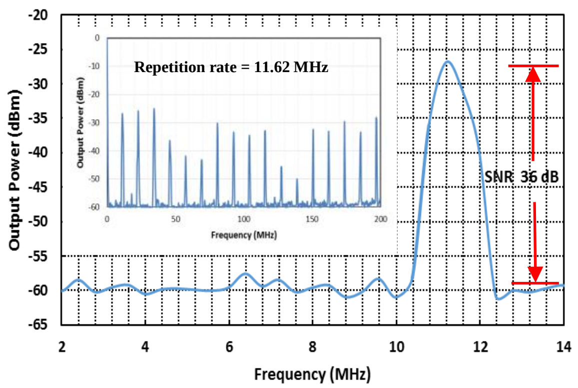


Fig. 7. RF profile of the fundamental pulse of the TDFL at the pump power of 1100 mW. Inset shows the harmonic spectrum within 200 MHz span

4. Conclusion

We have demonstrated the multiwavelength TDFL operating in 2 micron region using a linear cavity consisting of a broadband mirror and a flat-cleaved fiber end in conjunction with 1552 nm pumping. 5 m long highly nonlinear TDF is used as a gain medium as well as to produce sufficient NPR and four-wave mixing (FWM)-induced IDL effect in the laser cavity for both multi-wavelength and mode-locking operations. The TDFL achieved eleven output lines within a wavelength range from 1895 to 1907 nm with a constant spacing of 1.2 nm and signal to noise ratio of more than 27 dB at the maximum pump power of 1100 mW. The slope efficiency of the laser is 16.57 % with the maximum output power of 93 mW at pump power of 1100 mW. In addition, the experimental results indicate that the proposed multiwavelength fiber can also generate stable pulse train with a repetition rate of 11.62 MHz.

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*Corresponding author: swharun@um.edu.my