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ALL-FIBER WAVELENGTH SWITCHABLE THULIUM DOPED FIBER LASERS INCORPORATING AN ARRAYED WAVEGUIDE GRATING

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ABSTRACT

We demonstrate an all-fiber wavelength switchable Thulium-doped fiber laser (TDFL) incorporating an arrayed wavelength grating (AWG) as the tuning element. The AWG consists of 16 switchable channels with approximately 0.96 nm inter-channel wavelength spacing. By switching the AWG channels using an optical channel selector (OSC), this setup is capable of generating 16 different wavelengths ranging from 1874.47 nm to 1888.92 nm with an average output power of 4.56 dBm. Narrow linewidth laser output is achieved with an average 3 dB bandwidth of approximately 0.06 nm. Measurement of side mode suppression ratio (SMSR) gives a value of between 57.32 dB and 60.18 dB, with a low variation of only 2.86 dB across the wavelength range, indicating a good stability and high quality of the laser output.

Keywords: switchable wavelength; TDF laser, two-micron, AWG

INTRODUCTION

In recent years, 2 μm laser sources operating in the eye-safe region are of great interest owing to their superior properties such as simple thermal management, wide tunable range and high nonlinear threshold [1–4], which are highly desirable and beneficial in various potential applications including light detection and ranging sensor (LIDAR), microsurgery, spectroscopy and remote sensing and nonlinear frequency conversion [1]. The exponential growth in bandwidth demand for telecommunication network services has also motivate many researchers to look into possibility of using this region as an alternative to the existing band for future communication window. Currently, the most effective approach to produce lasers at the wavelength of 1.8 to 2.1 μm is by employing thulium or holmium-doped fibers. Emission in this regime is achieved based on Tm^{3+} ions and Ho^{3+} direct energy level transitions of $^3F_4 \rightarrow {}^3H_6$ and $^5I_7 \rightarrow {}^5I_8$ respectively [5].

In principle, fiber laser has numerous attractive properties as compared to bulk or solid states lasers. Due to its long length geometrical attributes, fiber laser allows rather simple heat dissipation management resulting to higher lasing efficiency and lower possibility of the laser being damaged by the heat. Furthermore, the core of the optical fiber acts as an excellent waveguide, which enables a high quality laser beam being produced without the requirements of intricate intra-cavity alignments. Nevertheless, previous works on 2 μm region, mostly use free space designs and bulk components [6–8] since the components of optical fiber in the 2 μm range is scarce, which eventually increases the system complexity [5]. Thus, all-fiber laser operating in the 2 μm region is becoming all the necessary, which would give advantage in terms of compactness, simplicity, low cost and reliability.

One of the attractive qualities of thulium doped fiber laser is its potential for wide wavelength tunability due to the broad transition line widths of thulium ions in glass hosts [1,9,10]. In this regards, intensive research have been conducted on wavelength tunable thulium doped fiber laser by using various approaches to achieve the wavelength tunability such as by integrating volume Bragg gratings (VBGs) [8,10,11], diffraction gratings [12], Sagnac loop mirror [13] or even by multimode interference (MMI) [14]. However, all the above demonstrations were still using bulk optic components in the laser cavity whereby brittle free-space coupling were utilized to pump the gain fibers. On the other hand, many demonstrations have also been proposed for all-fiber tunable thulium doped fiber laser by employing several types of wavelength tuning mechanisms, such as Fabry-Perot tunable filter in Y. Wei et al (2012) and J.Geng et al (2011) [5,15], manual grating-based tunable filter [1,15], fiber taper filter [16], fiber Bragg gratings (FBGs) [10,17] and polarization controller (PC) [18]. However, the use of FBGs as the tuning mechanism such as reported in A. Pal et al (2012) [17] has a shortcoming of limited and narrow tuning range, making it less attractive for specific applications. As for a Fabry-Perot tunable filter such was employed in Y. Wei et al (2012) [5] and J. Geng et al (2011) [15], the incorporation of a voltage supply for controlling the input voltage entering the Fabry Perot tunable filter is necessary for the tuning purpose. Wavelength tuning by using a fiber taper filter in K. Kieu et al (2011) [16] is also a difficult process since it requires careful and fine stretching of the fiber taper.

In this work, we use a new approach of using an arrayed waveguide grating (AWG) as the wavelength slicing mechanism to demonstrate an all-fiber wavelength switchable thulium doped fiber laser. The use of AWG as the wavelength slicing mechanism has been previously demonstrated in development of switchable wavelength fiber laser in erbium doped fiber laser operating in the C-band region and in depressed cladding erbium doped fiber laser operating in the S-band region [19] with a spacing of between 100 GHz between adjacent channels. Besides that, the AWG has also been proven to work well in the L-band region [20]. However, to date, there is still no report on the use of AWG for generating wavelength tunability in thulium doped fiber laser operating in 2 μm region in spite of its advantages such as easy handing, low insertion loss and low power consumption. To the best of our knowledge, this is the first demonstration of a switchable fiber laser in 2 μm region using an AWG as the wavelength selective element as well as to provide the wavelength tunability. The AWG consists of 16 switchable channels with an approximately 0.96 nm inter-channel wavelength spacing. By switching the AWG channels using an optical channel selector (OCS), this setup is capable of generating 16 different wavelengths ranging from 1874.47 nm to 1888.92 nm with an average output power of 4.69 dBm. Narrow linewidth laser output is achieved with an average 3 dB bandwidth of approximately 0.06 nm. Measurement of side mode suppression ratio (SMSR) gives a value of between 57.32 dB and 60.18 dB, with a low variation of only 2.86 dB across the wavelength range, indicating a good stability and high quality of the laser output.

EXPERIMENTAL

Figure 1 shows the experimental setup of the proposed switchable wavelength thulium doped fiber laser. The proposed setup uses a 2 m Nufern SM-TSF-9/125 thulium doped fiber with an absorption coefficient of 27 dB/m at 793 nm as the gain medium. A 1550 nm laser diode from Princeton Lightwave with a maximum 220 mW pump power is coupled to the thulium doped fiber via a 1550/2000 nm wavelength division multiplexer (WDM) coupler. The pump light that propagates from the laser diode into the thulium doped fiber at the wavelength of 1550 nm provides adequate pump energy to excite the thulium ions, which then generates an Amplified Spontaneous Emission (ASE) circulating inside the cavity. An isolator is inserted into the cavity to enforce a clockwise unidirectional ring. This isolator also helps in compressing the backward ASE, thus enhancing the side mode suppression ratio (SMSR). The output of the isolator is then connected to the input port of an arrayed waveguide gratings (AWG), whereby the ASE is filtered and sliced into 16 different channels of the AWG. The interval between two adjacent channels of the AWG is 0.96 nm.

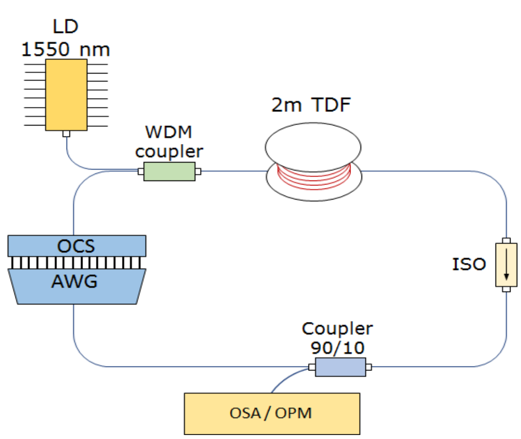

Figure 1: Switchable wavelength thulium doped fiber laser configuration

In general, the incident beam that passes through the AWG will be diffracted into multiple wavelengths, similar to the way a prism diffracts the incoming visible light. In this case, the input waveguide of the AWG distributes the ASE into an array of waveguides via an input coupler. Each array of waveguide differs in length with a constant increase in each length. Subsequently, the ASE propagates through these arrays of waveguides to the receiver waveguides via an output coupler. Since light travels at different path length along different array waveguides and arrive the output coupler with equal phase, the diffraction and interference at the output coupler will refocus the incoming beams, slightly offsetting each beam to be coupled to different receiver waveguides. As a result, the ASE travelling through the AWG will be sliced into a number of different wavelengths. The insertion loss of the AWG is about 3 to 4 dB. To provide switching, the output signal from 16 channels of the AWG are connected to a 16-channel optical channel selector (OCS), which is used to select one of the possible wavelengths at a time. As such, the combination of both AWG and OCS will provide the wavelength selectivity inside the cavity. The output of the OCS is then tapped from the laser cavity via the 10% port of a 10 dB coupler that feeds back the remaining 90% of the signal into the cavity via the signal port of the WDM, thereby completing the laser cavity.

RESULTS AND DISCUSSION

The amplified spontaneous emission (ASE) of the thulium-doped fiber pumped by the 793 nm laser diode at a maximum pump power of 220 mW is shown in Figure 2. From the figure, it can be seen that the ASE spectrum has a well-defined bandwidth of about 450 nm, stretching from approximately 1750 nm to 2200 nm at the floor level of -70 dBm. The highest ASE level is observed at a wavelength range of between 1888 nm and 1896 nm, with the output power ranging from -48.00 dBm to -47.95 dBm. The peak wavelength of the ASE spectrum is influenced by the length of the TDF, whereby it will shift towards longer wavelength by increasing the length of the TDF. Besides the TDF length, the core diameter of TDF is another factor that determines the peak wavelength of the ASE spectrum, such that the larger the core diameter of the TDF, the longer the peak wavelength that will be observed in the ASE spectrum. In general, it is expected that a broader bandwidth of the ASE spectrum would result in a wider wavelength range of the tunable laser.

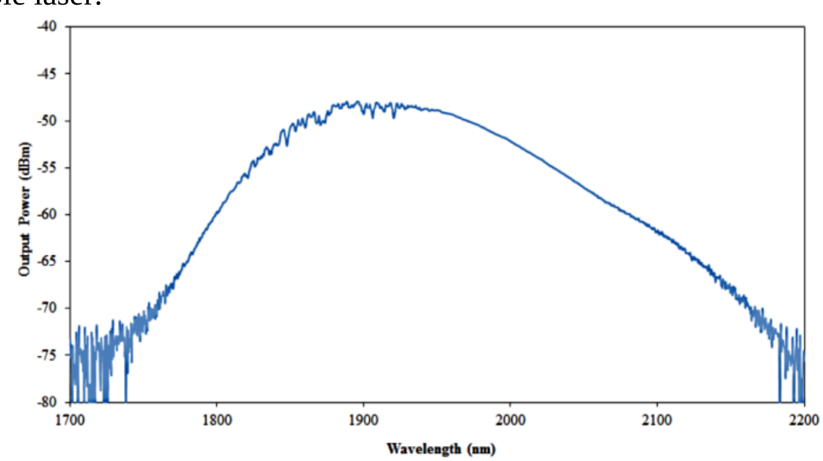

Figure 2: ASE spectrum of the TDF at the pump power of 220 mW

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Figure 3 shows the single wavelength output spectrum of the proposed switchable TDFL taken at channel 1 of the AWG at the pump power of 220 mW, with the peak wavelength equivalent to 1888.93 nm. The peak power and 3 dB bandwidth of the output spectrum as measured from the OSA are -10.98 dBm and 0.06 nm respectively. The SMSR of the laser output obtained in this work is also high, with a value of 60.18 dB. The inset picture shows the output spectrum of the TDF laser without incorporating the AWG in the cavity, with a peak power of -0.56 dBm and a peak wavelength of 1970.03 nm. The reduction of the peak power in the output laser with the AWG compared to without using the AWG is due to several factors, including higher insertion loss experienced by the cavity with the AWG and the wavelength filtering process that occurs in the AWG.

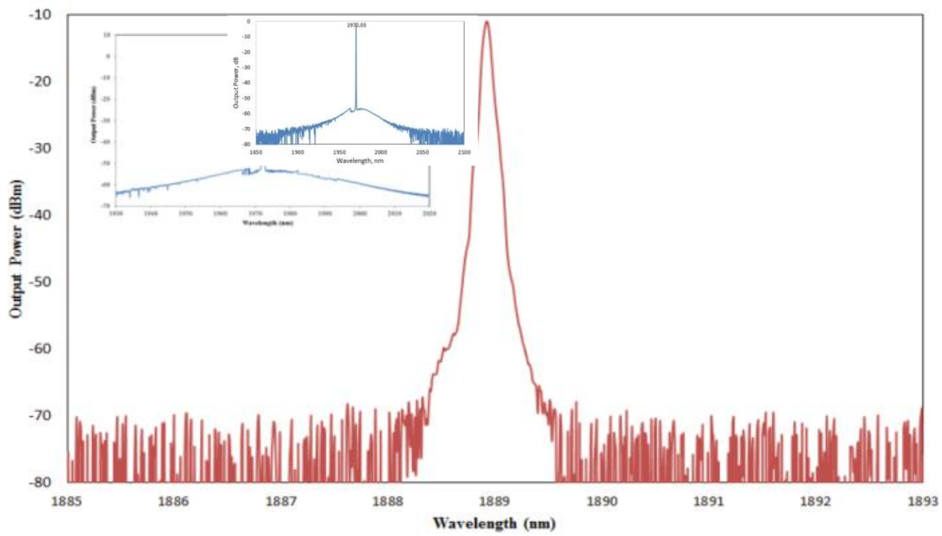

Figure 3: Laser spectrum of single wavelength of 1888.93 nm from the switchable TDFL taken at channel 1 of the AWG. Inset: laser spectrum of the TDFL without the AWG

Figure 4 shows the experimental tunability of the wavelength switchable thulium doped fiber lasers for 16 AWG channels as taken from the OSA (Yokogawa AQ6375) with a spectral resolution of 0.05 nm at a pump power of 220 mW. The indicated tuning range of this fiber laser covers a wavelength range of 14.45 nm, which spans from 1874.47 nm to 1888.92 nm, at a fixed wavelength interval of approximately 0.96 nm, corresponding to the AWG inter-channel spacing of 100 GHz. The tuning range in this work is only limited by the number of channels available in the AWG. From the figure, it can be seen that there is low peak power variation over the entire wavelength range. The maximum peak amplitude of -11.17 dB is observed at the wavelength of 1888.92 nm, corresponding to channel 1 of the AWG, whereas the minimum peak amplitude of -13.11 dBm is observed at the wavelength of 1875.45 nm, corresponding to channel 15 of the AWG, with a peak power difference of about 1.94 dBm. It can also be deduced that the peak power variation across the wavelength follows the pattern of the ASE spectrum of the TDF itself. The average 3-dB bandwidth of the laser spectrum is approximately 0.06 nm, which is quite constant and stable over the wavelength range, locked by the 14.45 nm bandwidth of the AWG.

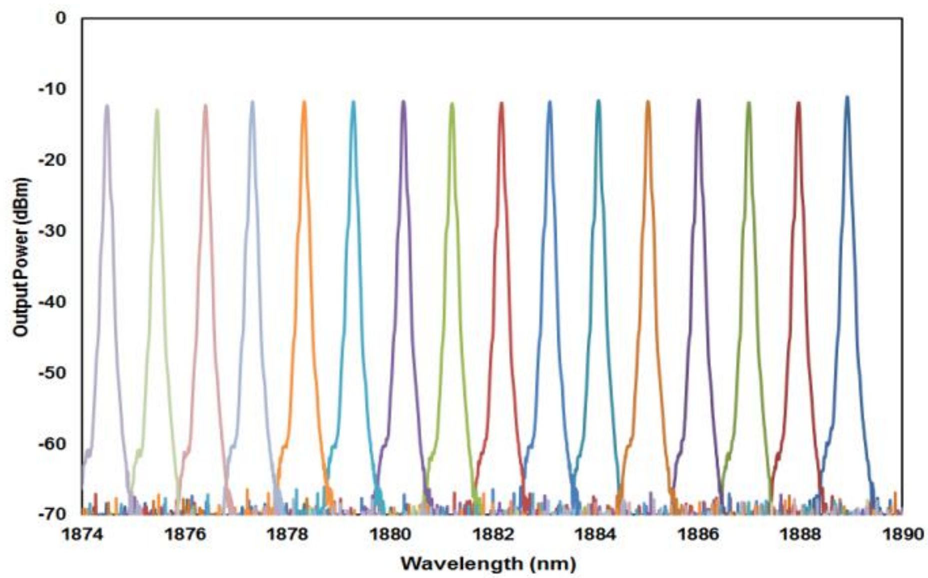

Figure 4: Output spectra of the wavelength switchable thulium doped fiber lasers for 16 different wavelengths, corresponding to 16 different channels of the AWG

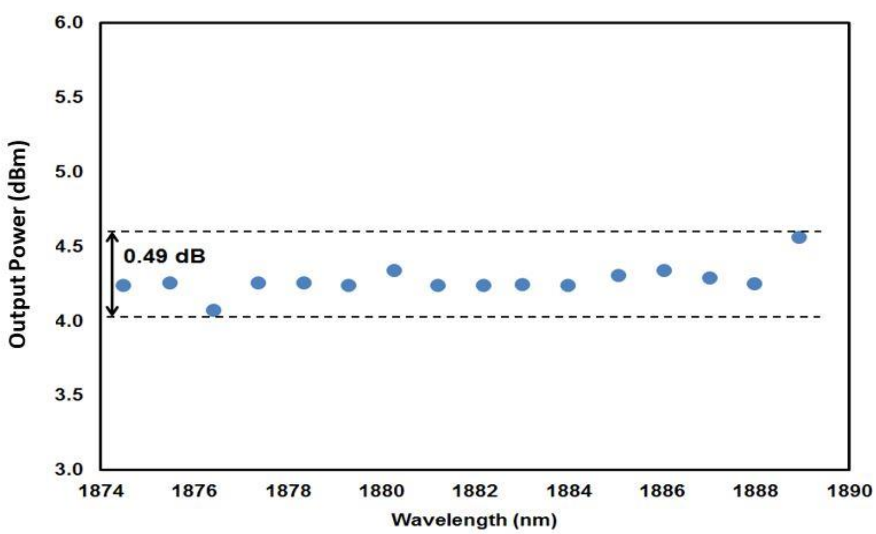

Figure 5: Output power profile measured using an optical power meter.

Figure 5 shows the output power profile with respect to 16 different wavelengths measured from the OPM. The output power fluctuates slightly across the wavelength, ranging from 4.56 to 4.07 dBm, with a maximum difference of 0.49 dB. Similar to peak power variation pattern, the highest and lowest output power are also measured at 1888.92 nm and 1875.46 nm respectively. It can be deduced that the output power measured from the OPM is slightly higher than the peak power measured from the OSA due to different measurement techniques between both devices. Unlike OPM, the measurement using OSA is influenced by its span and resolution, thus making it less accurate compared to the one from OPM.

CONCLUSION

An all-fiber wavelength switchable thulium-doped fiber laser incorporating AWG as the tuning element has been proposed and demonstrated. The AWG consists of 16 switchable channels with approximately 0.96 nm inter-channel wavelength spacing. By switching the AWG channels using an OSC, the laser wavelength can be switched over 14.45 nm, which consists of 16 different wavelengths generated from 1874.47 to 1888.92 nm in a short period of time. The average peak power of the laser output is -12.85 dB as measured from the OSA, whereas the average output power as measured by the OPM is about 4.56 dBm. Measurement of the SMSR gives a value of between 57.32 dB and 60.18 dB, with a low variation of only 2.86 dB across the wavelength range, indicating a good stability and high quality of the laser output. The laser spectrum also has a narrow 3 dB bandwidth, with an average value of approximately 0.06 nm, which is quite constant and stable over the wavelength range. This is suitable for application in the 0.8 nm inter channel spacing of DWDM systems.

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