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Stable multiwavelength thulium fiber laser assisted by four wave mixing effect

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ABSTRACT

In this work, stable multiwavelength thulium laser (TDFL) using interleaving filter and assisted by four wave mixing (FWM) effect in 0.5 km long highly nonlinear fiber (HNLF) is experimentally demonstrated. The impacts of altering the thulium pump power and wavelength on several laser characteristics such as threshold, laser count, output power and optical signal to noise ratio are investigated. Up to 19 output wavelengths within a 10 dB bandwidth with optical signal-to-noise ratio of more than 35 dB were generated from 1875 nm to 1897 nm. The laser has a threshold pump power of 0.3 W and a maximum peak power and wavelength fluctuations within 60 min of 1 dB and 0.2 nm respectively, which indicates the good stability of the proposed fiber laser. The laser performance without HNLF emphasizes the significant role of FWM in the performance of TDFL in terms of stability and number of wavelengths.

1. Introduction

The rapid growth of information traffic in telecommunication networks demands a wavelength-division multiplexing (WDM) system with a much higher transmission capacity. An attractive method for improving the transmission capacity is to increase the number of channels in the WDM system by expanding the gain bandwidth of amplifiers [1–5]. Nowadays, thulium-doped fiber (TDF) has emerged as a provider of ultra-broadband amplification essential to increase transmission capacity of the optical fiber system. TDF has approximately 400 nm (1700–2100 nm) emission bandwidth, which is much wider than that of Erbium-doped fiber [6–11]. In addition to expanding the telecommunications window, multiwavelength TDFL around 2 μm also has potential applications in remote sensing and laser radar [12,13]. The main concern in TDFL is realizing stable multiwavelength lasing with narrow wavelength spacing at room temperature because of the homogeneous gain-broadening effect. To suppress mode competition in the homogeneously broadened gain medium, nonlinear effect is typically used. Some approaches employed a long standard single mode fiber (SMF) to enhance nonlinearity such as FWM, and suppress gain mode competition [14]. In other approaches, several km of SMF were replaced by a short length of highly nonlinear fiber (HNLF) [15–17]. In these approaches, the performances of multiwavelength laser in terms of stability and channel count were improved. A phase modulator and a nonlinear polarization rotation were also added to TDFL cavity to suppress gain competition among the various narrow-wavelength spacing lasing modes, which results in stable multiwavelength output [15,18]. In the aforementioned schemes, nonlinear effects and self-phase modulation are the main mechanisms to tackle gain competition.

In many applications, achieving simultaneous multiwavelength lasing in 2 μm band can be realized by incorporating a comb filter to the laser cavity. In this regard, different types of filters have been employed: fiber-based beating filter [2], a nonlinear amplifier loop mirror (NALM) loop mirror [19–21], Fabry-Perot filter [22], Lyot filter [23], Mach-Zehnder interferometer [24] and a hybrid interference filter [18,25]. Although these methods successfully generate multiple wavelengths [11], their structures require high pump power to generate stable lasing lines.

In this article, multiwavelength TDFL based on an interleaving comb filter integrated in a ring cavity is demonstrated. The comb filter provides definite spacing between adjacent wavelengths and enhances the intensity-dependent gain in the laser cavity. In addition, the gain competition between the generated wavelengths is significantly improved by inducing FWM process in the HNLF and therefore self-stable multiwavelength output is achieved. The performances with and without the HNLF are compared, which demonstrate the important role that HNLF plays for the broadband multiwavelength generation and stability of the lasing. With pumping of 1.13 W at wavelength of 1560 nm, multiwavelength

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lasing are generated over wavelength range of 22 nm with wavelength spacing of 1.2 nm. At this pump power, up to 19 channels within 10 dB bandwidth are obtained, which is better than past studies using higher excitation power and more complex configuration [14–16,18,23–25].

2. Experimental setup and initial characterization

Fig. 1 represents the schematic diagram of the multiwavelength TDFL. The laser ring structure consists of optical components operating in the 1.9 μm wavelength region. The linear gain medium is a 5-m long Tm-doped fiber with peak absorption of 200 dB/m at 790 nm and numerical aperture (NA) of 0.26.

The configuration is forward pumped by a tunable laser source (TLS), which can be tuned from 1535 nm to 1565 nm with output power of 8 dBm and is utilized as a thulium pump (TP). The produced TP signal is amplified by employing an erbium doped fiber amplifier (EDFA) module that can drive the output power of the TP signal up to 5 W. The amplified TP signal is coupled into the laser cavity through a C-L band wavelength division multiplexer (WDM) coupler. An isolator was included to enforce unidirectional operation.

An Oplink 50 GHz interleaver is used as a comb filter to produce the multi-wavelength seeds. The wavelength spacing between adjacent wavelengths is well defined by the interleaver, which is 1.2 nm at 2 μm wavelength region. A section of HNLF with 0.5 km length is positioned in the laser cavity to provide intensity dependent gain. The HNLF is pre-spliced to single mode fiber by the manufacturer and its parameters are: nonlinear coefficient = 11.5 $(W\,km)^{-1}$, dispersion slope = 0.016 ps/(nm^2·km), zero dispersion wavelength (ZDW) = 1557.6 nm and effective area = 11 μm^2. 5% portion of the signal is siphoned out by a 95/5 coupler and monitored by a long wavelength optical spectrum analyzer (OSA) with bandwidth resolution of 0.1 nm, while the rest propagated in the ring cavity for further amplification. This repeated oscillation eventually leads to the formation of multiple lasing lines once the lasing threshold condition is fulfilled.

To highlight the contribution of HNLF on the multiwavelength generation, the output spectrum of the proposed laser was compared for three cases; without HNLF and comb filter, comb filter alone and a combination of HNLF and comb filter. The TP power was fixed at 1.3 W in all cases. From Fig. 2, it is observed that the self-lasing cavity modes of the TDFL without HNLF and comb filter emerges around 1970 nm region with lasing bandwidth of about 25 nm. The self lasing spectrum exhibits unstable multiwavelength operation with stochastic wavelengths due to mode competition in the TDF, which possesses homogeneous broadening gain characteristic.

With the addition of comb filter in the laser cavity, the multiple-wavelength operation is shifted to shorter wavelengths due to increasing cavity loss [26]. To validate this finding, the comb filter

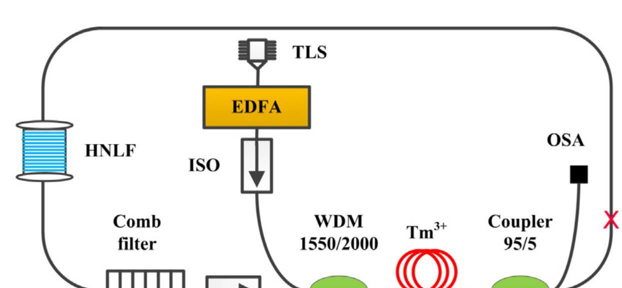

Fig. 1. Schematic configuration of multiwavelength thulium fiber laser.

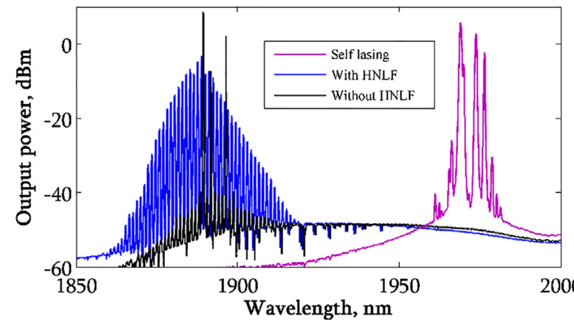

Fig. 2. Tm fiber laser spectra at 1560 nm pump power of 1 W for three cases; without comb filter and HNLF, with comb filter only and a combination of comb filter and HNLF.

loss measurement at 2 μm region is investigated. In this experiment, the TP wavelength was fixed at 1560 nm with power of 0.7 W. Fig. 3(a) shows the transmission loss spectrum, which is obtained by comparing the spectrum of TDF backward ASE with and without comb filter. The comb filter is found to have dependent wavelength loss, with more than 30 dB loss noted at the initial free lasing wavelength. This leads to a change in the net gain profile and explains the shift of the multiwavelength generation region from free lasing operation of TDFL at about 1.97 μm to around 1.88 μm region. Such finding also suggests that tuning of the center of TDFL spectrum generally could be achieved by changing the overall cavity loss through addition of a spectral filter or a wavelength selective tuning element.

Fig. 3(b) exhibits a magnified view of the transmission loss around the eventual lasing wavelength of 1880 nm, which demonstrates wavelength spacing of 1.2 nm defined by the optical interleaver. Supposedly, gain competition between lasing modes of the comb filter-integrated TDFL is reduced due to the definite spacing between adjacent wavelengths thus resulting in enhanced stabil-

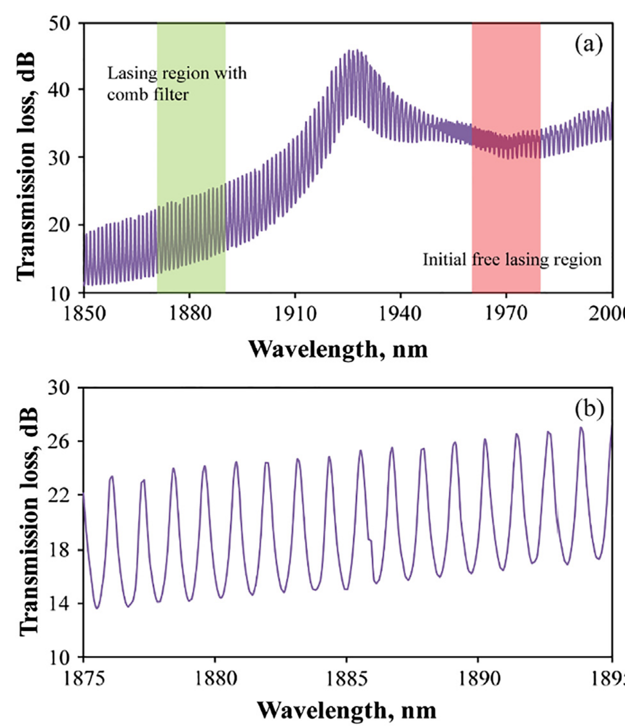

Fig. 3. (a) Measured transmission loss of comb filter and (b) magnified view of the wavelength spacing.