All-fiber dual-wavelength fiber laser operating at 1950 nm region based on multimode interference effect

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An all-fiber dual-wavelength fiber laser operating at room temperature in 1950 nm region is reported. It uses a commercial Thulium-doped fiber (TDF) and homemade double-clad Thulium-Ytterbium co-doped fiber (TYDF) as gain media in conjunction with a multimode interferometer (MMI) filter in a ring configuration. The MMI filter consists of a 13.5 cm long MMF axially spliced at both its ends to identical single mode fibers to realize two transmission peaks at 1939.68 and 1959.60 nm with the maximum extinction ratio based on modal interference. By pumping the TDF and TYDF with a fixed 800 nm and 905 nm pumps at 143 mW and 1.5 W, respectively, dual-wavelength output lines are obtained at these two wavelengths with a signal to noise ratio of more than 27 dB, respectively. The dual-wavelength operation was stable for more than two hours and could be tunable since the laser wavelength is only determined by the function of the MMI filter.

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1. Introduction

2 μm laser sources are currently experiencing intense development due to their importance in many scientific applications such as spectroscopy, remote sensing and medicine. The wavelength also overlaps with many absorption lines of several molecules, e.g. carbon dioxide (CO2) or hydrogen bromide (HBr) [1], which creates the possibility of constructing cost-effective trace-gas sensing platforms. Strong water absorption in this range makes the light source extremely desirable in biomedical applications. It has been shown, that 2 μm laser outperform 1μm and 1.55 μm sources in dermatology and surgery, serving as precise and efficient optical scalpels [2-3]. The light source operating in the range of 1.8 to 2.0 μm can be realized using Thulium-doped fiber laser (TDFL).

The lasing near 2 μm is initiated by the transition of thulium ions from $^3H_6$ to $^3F_4$ because of the so-called cross-relaxation energy transfer process between thulium ions. During this process, two ground-level thulium ions are excited to the upper lasing level of $^3F_4$ by absorbing only one pump photon near 790 nm. This suggests that one excited Tm^{3+} ion at the $^3H_4$ level generates two Tm^{3+} ions at the $^3F_4$ upper laser level. However, commercial high power diodes required for the excitation in this wavelength range are difficult to obtain as well as very costly. Pumping Thulium-doped fibres at another pumping wavelength of 1200 nm or 1600 nm is complicated because semiconductor laser diodes with sufficient power are not commercially available. An alternative approach is to co-dope the Thulium fiber with Yb^{3+} so that it can be pumped by a commercial 905−980 nm laser diode. This is due to the $^3H_5$ level of Tm^{3+}, which is (quasi-) resonant with the excited Yb^{3+}level ($^2F_{5/2}$) and thus allows the sensitization of Tm^{3+} doped fibres with Yb^{3+}, similar to the case of Yb^{3+} sensitized Er^{3+}-doped fibres [4]. The up-conversion system has long been proposed based on Tm^{3+}-Yb^{3+} co-doped glass and fibers [5], but only more recently the concept is used for the 2-μm fibre laser application [6]. A cheap and stable low power fiber laser operating near 2 μm region are useful for many potential applications like toxic gas sensing and component characterization.

Recently, many works on all-fiber dual-wavelength fiber lasers have been reported due to interests in their potentials in applications such as optical instrument testing, optical signal processing, fiber sensing systems and microwave photonics [7-9]. Different strategies have been adopted to generate a dual-wavelength lasing for example by using a twin-peak reflection grating and dual-cavity configuration. But, most of the lasers that have been demonstrated operate at 1.00 and 1.55 μm band. For the longer wavelength region of 2 μm, fiber components are not as readily available as those at the shorter wavelengths of 1.00 and 1.55μm. Very recently, 2041.3 nm/2054.6 nm simultaneous dual wavelength Tm, Ho:YVO4 solid state microchip laser was demonstrated [10]. However, 2 µm band all-fiber laser is urgently expected in practical use due to its compact and robust property.

In an earlier work, Zhou et. al. [11] demonstrated an all-fiber dual-wavelength TDFL operating at room temperature using a cascaded fiber Bragg grating array. In this paper, a new all-fiber dual-wavelength fiber laser operating in 1950 nm region is proposed using a simpler approach based on an incorporation of a short length of multimode fiber (MMF) in the laser cavity to act as a multimode interference (MMI) filter. The proposed laser uses a commercial Thulium-doped fiber (TDF) and homemade double-clad Thulium-Ytterbium co-doped fiber (TYDF), which are forward pumped by a single-mode 800 nm and a multimode 905 nm pumps respectively as a cascaded gain medium.

2. Configuration

The schematic diagram of the proposed dual-wavelength fiber laser based on cascaded gain medium is shown in Fig. 1. The fiber laser uses a ring cavity consisting of a 2 m long commercial TDF and 15 long homemade TYDF are used for the active medium. The TDF is pumped by 800 nm laser diode via an 800/2000 nm wavelength division multiplexer (WDM) while the TYDF is pumped by 905 nm multimode laser diode via a multimode combiner (MMC). The TDF has a core and cladding diameters of 9 µm and 125 µm respectively, a loss of less than 0.2 dB/km at 1900 nm and Tm ion absorption of 27 dB/m at 793 nm. The homemade TYDF has an octagonal shaped double-clad structure, which was drawn from a lithium-alumino-germano-silicate (LAGS) core glass optical preform. The preform was made using the MCVD process, in conjunction with solution doping technique. The preform consists of an Al_2O_3, Y_2O_3, Tm_2O_3 and Yb_2O_3 dopants with average weight percentage of 5.5, 3.30, 0.70 and 4.0, respectively. Such octagonal geometry of the cladding improves the pump absorption efficiency. The doping levels of Tm^{3+} and Yb^{3+} ions of the TYDF are 4.85 ions/cc and 27.3 ions/cc, respectively as measured using an electron probe micro-analyser (EPMA). The NA and core diameter of the fabricated TYDF are 0.23, and 5.96 µm, respectively.

The operating wavelength of the proposed TDFL is determined by the MMI filter, which is obtained by splicing a 13.5 cm long MMF between two single-mode fibers (SMFs) inside the laser. A polarization controller (PC) is used to control the polarization state of light in the laser cavity. The 10dB output coupler is used to tap 10% of the laser out while the optical spectrum analyzer (OSA) is used to measure the output spectrum and the power of the laser.

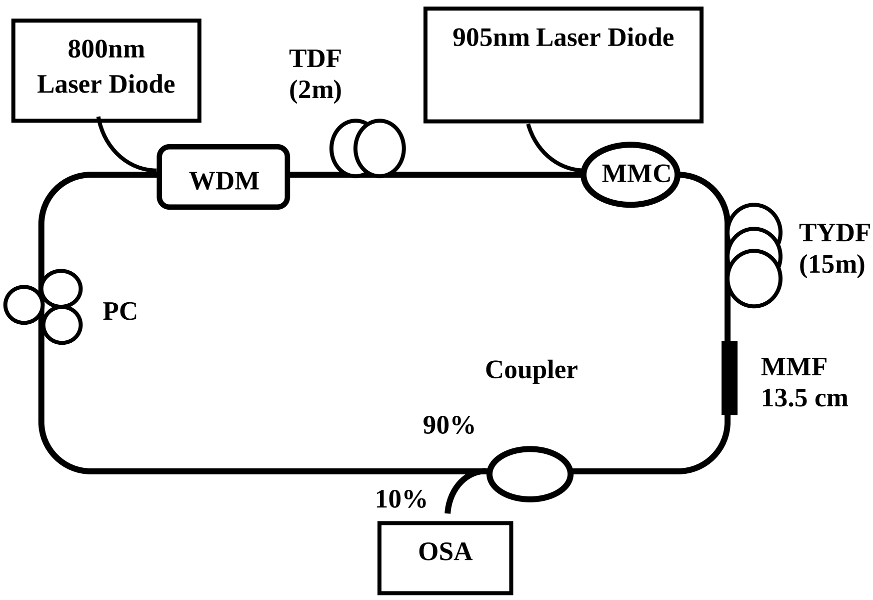

Fig. 1. Schematic diagram of the setup for the proposed dual wavelength fiber laser using a cascaded TDF and double-clad TYDF as the gain medium and an inline MMI as a wavelength selective filter.

3. Result and discussion

At first, we investigate the transmission spectrum of the MMI filter, which consists of a 13.5 cm long MMF axially spliced at both its ends to identical SMFs. In the experiment, broadband amplified spontaneous emission (ASE) light centred at 1950 nm is launched into the MMF section through the lead-in SMF at the first splice. Generally, the spot size of the fundamental mode of the MMF is different than that of the SMF. This leads to the excitation of a number of guided modes in the MMF at the input splice. Due to their different propagation constants, the guided modes of the MMF develop a certain phase difference as they propagate along the MMF length. At the lead-out splice the MMF modal fields are then coupled to the fundamental mode of the lead-out SMF. This forms a comb-type structure at the output as a result of the transmission function of the MMI filter, as shown as a dashed line in Fig. 2. It can be seen that the maximum transmission dip is obtained at 1951.0 nm. Two peaks at 1939.68 and 1959.60 nm have the maximum extinction ratio with the transmission losses of around 4 and 5 dB, respectively.

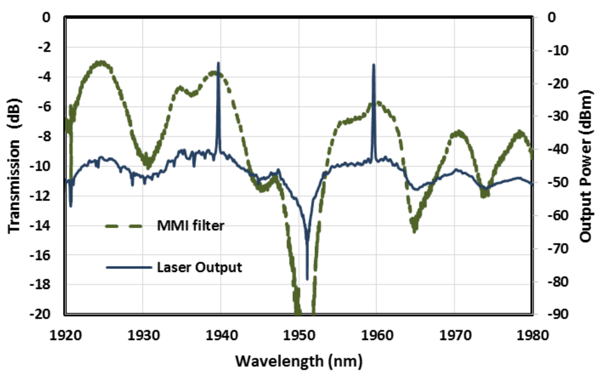

Fig. 2. Comparison between the transmission spectrum of the MMI filter and the laser output spectrum.

As the TDF is pumped, an ASE is generated at 1900 nm region in both directions via spontaneous and stimulated emission processes. The Thulium ions absorb the pump photons and are excited to $^3F_4$ level to create a population inversion between $^3H_6$ and this energy level. Then they drop to the ground state ($^3H_6$) while emitting ASE at 1.9 µm which is then amplified by the forward pumped double-clad TYDF. The amplified ASE centered at relatively longer wavelength region of 1951 nm due to the use of Thulium Ytterbium co-doped fiber, which provides a higher gain at longer wavelength due to energy transfer from Ytterbium to Thulium ions. The ASE oscillates in the ring cavity to produce laser for which the operating wavelength is determined by the transmission characteristic of the MMI filter. Due to transmission characteristic of the filter, it is possible to have the oscillation of two wavelengths in the cavity if the difference of cavity loss between them can be reduced to suppress the mode competition. By adjusting the polarization state of the oscillating light in the ring cavity, the cavity loss of the two wavelengths can be tuned to seek dual-wavelength oscillation with the help of both TDF and TYDF, whose gain broadening behaves inhomogeneously.

The output spectrum of the laser is depicted as a solid line in Fig. 2 when the single mode 800 nm and multimode 905 nm pump is fixed at 143 mW and 1.5 W, respectively. As shown in the figure, a dual-wavelength output lines are located at 1939.68 and 1959.60 nm, which coincide to two of the transmission peaks of the MMI filter. The 1939.68 and 1959.60 nm lasers peak at -13.8 and -15.2 dBm with a signal to noise ratio of about 27 and 28 dB, respectively. The 3 dB bandwidth of both laser lines is measured to be less than 0.2 nm.

The relation between the peak power of the dual-wavelength output lines of 1939.68 and 1959.60 nm against the pump power is shown in Fig. 3. In the experiment, the 800 nm pump power is fixed at 143 mW while the 905 nm multimode pump power is varied from 0 to 2.0 W. The dual-wavelength laser starts to lase at threshold power of 1.5 W before both output peaks power increases linearly with the increment of multimode pump power. At the maximum multimode pump power of 2.0 W, the 1939.68 and 1959.60 nm laser lines produces the maximum output powers of 0.21 and 0.20 mW, respectively.

The output spectrum of the dual-wavelength laser is scanned every 20 minute interval as shown in Fig. 4. In this experiment, the dual-wavelength operation is observed to be stable for more than two hours provided that the temperature variation and mechanical vibration are reasonably small (i.e., in a laboratory). The stability of the output is indicated by the small difference in each laser wavelength which is less than 0.2 dB. As expected, no other lasing modes are observed in the thulium gain band. Since the laser wavelength is only determined by the function of the MMI filter, the operating wavelength could be tuned by controlling the number of guided modes inside the core and their phase difference.

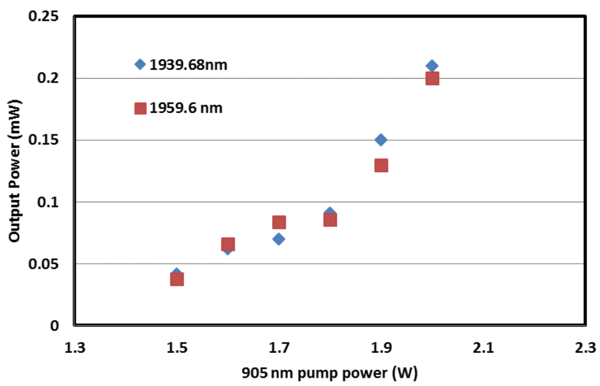

Fig. 3. The peak power of the dual-wavelength laser lines against the input 905 nm pump power when the 800 nm pump is fixed at 143 mW.

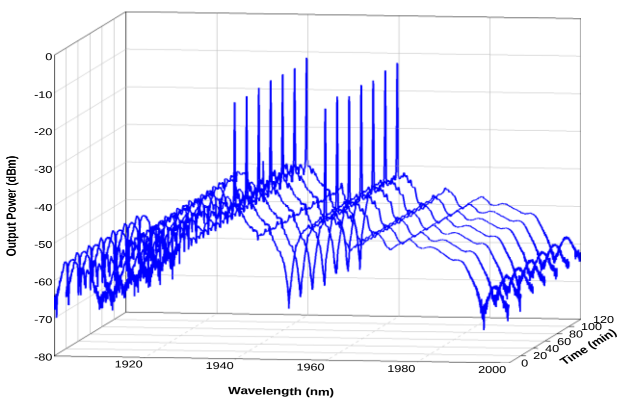

Fig. 4. The stability graph of the proposed dual-wavelength laser with 20 minute's period for each frame.

4. Conclusion

All-fiber dual-wavelength TDFL operating in 1950 nm region is successfully demonstrated at room temperature using a MMI filter in conjunction with a cascaded gain medium, which consists 2 m long TDF and 15 m long homemade double-clad TYDF. The MMI filter is designed by splicing a 13.5 cm long MMF inside a ring cavity so that two transmission peaks at 1939.68 and 1959.60 nm with the maximum extinction ratio can be realized based on modal interference. The proposed laser generates dual-wavelength output lines at 1939.68 and 1959.60 nm with the corresponding optical signal to noise ratio of 27 dB and 28 dB, respectively. Both lines start to laser at threshold pump powers of 143 mW and 1.5 W for 800 nm and 905 nm pumps, respectively and the output lasers power increases with the pump power. The laser was stable for more than two hours and the dual wavelength operation could be tuned by adjusting the parameters of the MMI filter. The proposed fiber laser is expected to have potential applications in many areas such as for sensing toxic gases due to their specific IR absorption.

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