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Widely tunable multi-wavelength Tm-doped mode-locked fiber laser

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ABSTRACT

We propose and demonstrate a tunable multi-wavelength Tm-doped mode-locked fiber laser. The mode-locked operation is enabled by nonlinear polarization evolution technique. The tunable operation and multi-wavelength laser emission is achieved by periodical cavity transmission modulation. The tunable range of dual-wavelength mode-locking is 1864 to 1916 nm and tri-wavelength mode-locking is 1863 to 1912 nm, respectively, which is the widest in multi-wavelength Tm-doped mode-locked fiber laser to the best of our knowledge. The system has compact structure and both the multi-wavelength laser emission and tunable operation can be realized by controlling the polarization in the fiber ring cavity.

Keywords: tunable fiber laser, multi-wavelength fiber laser, mode-locked fiber laser, Tm-doped fiber laser.

1. INTRODUCTION

Laser source with multi-wavelength emission and tunable operation is of much significance as it has various applications. For examples, a tunable multi-wavelength laser source used in gas spectroscopy will enable both multi-species detection and the detection at different wavelengths simultaneously for some unstable species[1], in telecommunications this kind of source enables a number of channels over large wavelength span to increase the transmission capacity[2], and in sensor multiplexing it can convey more signals, enlarge the measurement range and help to build a compact system structure[3]. The tunable and fiber-based multi-wavelength laser has many advantages such as low maintenance, minimum alignment requirement, high energy efficiency, low sensitivity and wavelength independent to the temperature. Most tunable multi-wavelength fiber lasers are in the 1 μm and 1.5 μm regime[4–7] and a few in 2 μm regime[8,9], in which Tm- or Ho-doped fiber is used as the gain medium. Since Tm- or Ho- doped fiber lasers operate at the eye-safe regime and have broader emission spectra, they are particular important for medical and communication applications having potentially a widely tunable range and more multiple wavelengths laser emission.

Several methods are adopted to realize the multi-wavelength lasing in mode-locked fiber laser. Pan *et al.* used the nonlinear polarization rotation effect to realize the multi-wavelength laser emission. The emission wavelength is tuned by adjusting the delay line[10]. Li and Chan demonstrated an electrically tunable multi-wavelength fiber laser in an actively mode-locked cavity[11]. Chamorovskiy *et al.* achieved the dual-wavelength soliton pulses by adjusting the polarization controllers in the cavity mode-locked by carbon nanotube saturable absorber[9]. Zhang *et al.* tuned the cavity birefringence strength to enable the multi-wavelength soliton[12]. Zhao *et al.* tuned the intracavity loss by a tunable attenuator to control the number of emission wavelength[13]. Luo *et al.* induced a birefringence comb filter to achieve the tunable multi-wavelength mode-locked fiber laser[14,15]. Jin *et al.* reported a tunable multi-wavelength mode-locked fiber laser by nonlinear amplified loop mirror method[16]. Fiber Bragg grating is also used as a multi-wavelength filter and by

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applying tension to the grating, the wavelength will be tuned[17]. However, the tri-wavelength Tm-doped mode-locked fiber laser has not been reported so far, and the tunable range of the existing lasers is very limited.

In this work, tunable dual- and tri- wavelength Tm-doped mode-locked fiber laser near 2 μm regime is experimentally demonstrated in a compact cavity structure. The laser is constructed in a ring cavity and operated by nonlinear polarization evolution (NPE) technique. The tunable range is 52 nm, from 1864 to 1916 nm for dual-wavelength mode-locking, and 49 nm, from 1863 to 1912 nm for tri-wavelength mode-locking, respectively. The tunable range is the widest in such kind of fiber laser, to the best of our knowledge. The tunable tri-wavelength mode-locking is also firstly reported.

2. EXPERIMENTAL SETUP AND RESULTS

Figure 1 is the experimental setup. A 1.5 m Tm-doped single mode fiber is used as the gain medium. It is bidirectionally pumped by two 793 nm laser diodes (LDs) with maximum output power of 170 and 200 mW, respectively. The pump light from one LD is coupled into the cavity by two wavelength-division multiplexers (WDMs) and one 2×2 40:60 coupler acts as the output port. The 70 m silica SMF is used as the birefringent fiber. The total anomalous dispersion in the laser cavity supports the soliton propagation. With 1 m fiber pigtail in the coupler, WDMs and polarization-dependent isolator (PDI), the total cavity length is around 80 m. Mode-locking of the fiber laser is achieved by NPE formed by two PCs and a PDI. The output is connected to an optical spectrum analyzer and a 33 GHz oscilloscope together with a 7 GHz photodetector to simultaneously measure the spectra and the pulse train using a beam splitter.

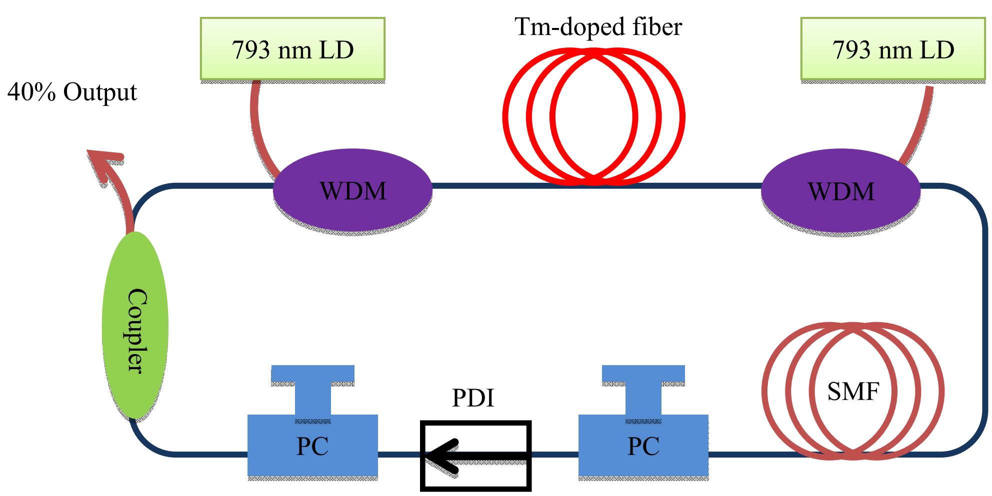

Figure 1. The setup of tunable multi-wavelength mode-locked Tm-doped fiber laser using nonlinear polarization evolution. LD: laser diode. WDM: wavelength-division multiplexer. PC: polarization controller. PDI: polarization-dependent isolator. SMF: single-mode fiber.

By increasing the pump power to 330 mW, the mode-locked laser emission is enabled. The mode-locking usually works in the multi-pulse regime above this threshold, due to the nonlinear effects in a long cavity and the loss perturbation of the optical components. Further increasing the pump power and by either rotating or squeezing the PCs, dual- and tri-wavelength mode-locking appears. The widest tunable range of dual-wavelength mode-locking we can achieve is from 1864 to 1916 nm, and tri-wavelength mode-locking is from 1863 to 1912 nm, as shown in Figure 2. The laser operates at soliton regime with typical Kelly sidebands[18]. The dips in the spectra are due to the water absorption[19]. The separation between the two wavelengths remains around 10 nm, which agrees well with the theoretical calculation in the next section. When decreasing the pump power to 310 mW, the mode-locking can work at single-pulse regime. The pulse train and repetition rate of 2.6 MHz which corresponds to 80-m cavity length are shown in Figure 3. The pulse width is estimated to be several picoseconds as the output power is too low to measure the pulse width accurately [20].

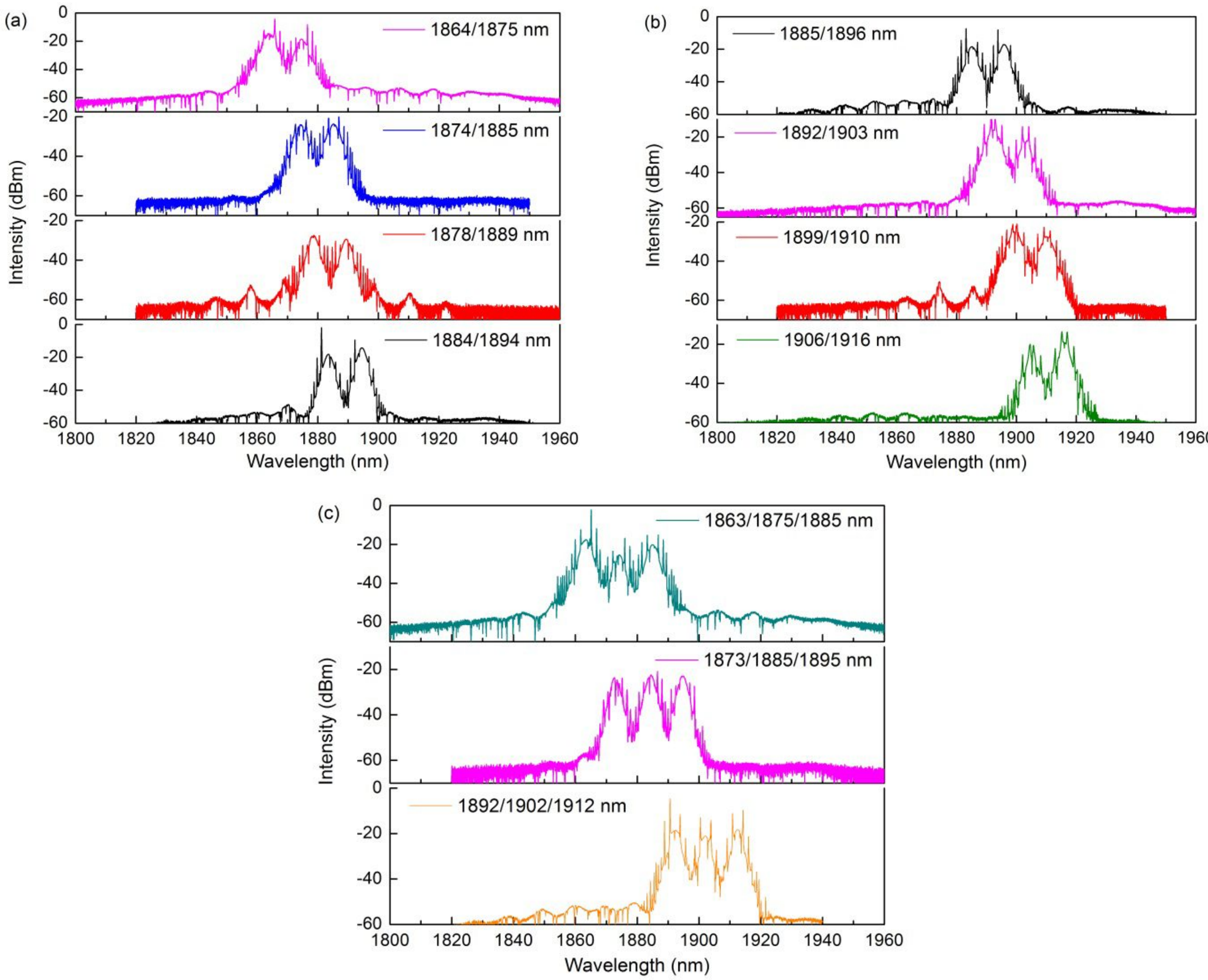

Figure 2. The spectra of tunable Tm-doped mode-locked fiber laser with (a) dual-wavelength from 1864 to 1894 nm, (b) dual-wavelength from 1885 to 1916 nm, and (c) tri-wavelength from 1863 to 1912 nm.

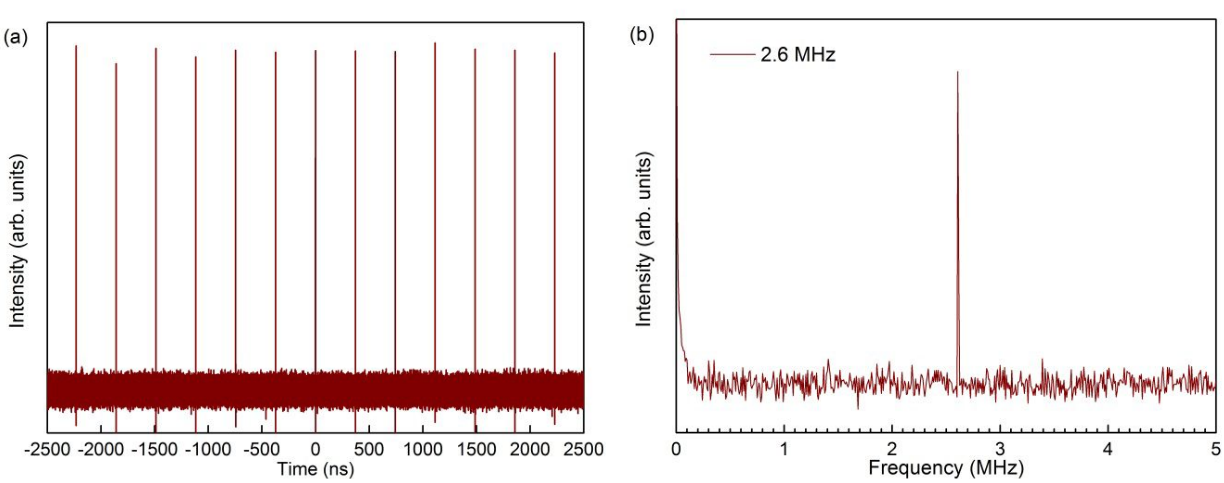

Figure 3. (a) The pulse train and (b) the corresponding RF spectrum.

3. DISCUSSIONS

The multi-wavelength emission is due to the periodic transmission modulation of the effective gain (net gain minus cavity loss) induced by PCs and the polarizer inside the PDI[21]. The periodic transmission modulation changes the effective gain profile to have multiple peaks. By controlling the PCs the polarization states inside the cavity is changed. Light with different polarization states experiences different loss when passing through the PDI. Under certain polarization states the power will distribute almost equally over these multiple peaks to enable multi-wavelength emission. The separation between the adjacent peaks is determined by the modulation period of cavity transmission function (Eq. 1).

$$T = \cos^2\theta_1\cos^2\theta_2 + \sin^2\theta_1\sin^2\theta_2 + \frac{1}{2}\sin(2\theta_1)\sin(2\theta_2)\cos(\Delta\varphi_L + \Delta\varphi_{NL}) \qquad (1)$$

where $\Delta\varphi_L = 2\pi L(\mathrm{n}_x - \mathrm{n}_y)/\lambda$ and $\Delta\varphi_{NL} = 2\pi n_2 PL\cos(2\theta_1)/\lambda \mathrm{A}_{eff}$ are the linear and nonlinear cavity phase delay, respectively, θ_1 / θ_2 is the angle between polarization direction of the light and fast axis of the fiber/polarizer inside PDI, respectively, L is the length of birefringent fiber, $|\mathrm{n}_x - \mathrm{n}_y| = B_m$ is the strength of modal birefringence, P is the instantaneous power of input signal, n_2 is the nonlinear refractive index, λ is the operating wavelength, and A_{eff} is the effective mode area. In this setup, $L = 80\ m$, $P = 0.003W$, $n_2 = 2.7\times10^{-20}\ m^2/W$, mode-field diameter is $12.4\,\mu m$. By choosing $\theta_1 = 3\pi/4$, $B_m = 4.9\times10^{-6}$, the $\Delta\lambda$ is calculated to be around 10 nm as shown in Figure 4, which agrees well with the experimental results.

The tunable operation is due to the peak-shifting in the transmission function. This can be done by changing some parameters in Eq. 1, such as the polarization angle θ_1 and modal birefringence B_m. Experimentally by tuning PCs, the polarization angle θ_1 is changed, and the fiber inside the PCs will be squeezed or twisted thus B_m is changed. Figure 4 is the simulation results with different peak positions by setting different values of θ_1 and B_m.

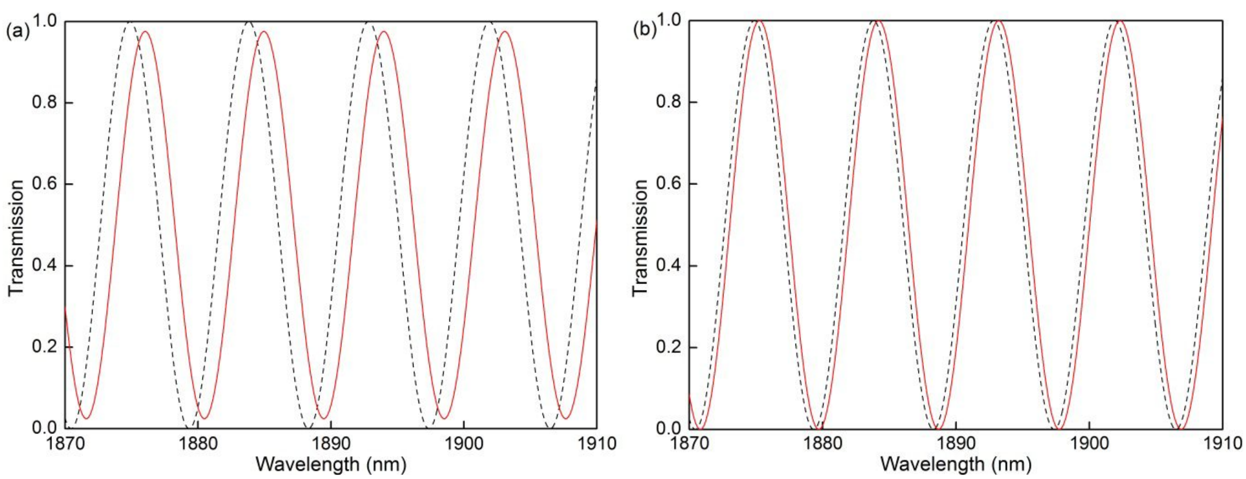

Figure 4. Simulation results of cavity transmission function. The dash line and the solid line is by different value of (a) θ_1, $\Delta\theta_1 = \pi/20$, (b) B_m, $\Delta B_m = 10^{-9}$.

4. CONCLUSION

We have demonstrated tunable dual- and tri-wavelength mode-locking in an ultrafast Tm-doped fiber laser by the NPE technique. The multi-wavelength emission and tunable operation results from the periodical modulation of the effective gain, and it is experimentally realized by simply rotating or squeezing the PCs. The wavelength tuning range is 1864 to 1916 nm for dual-wavelength mode-locking and 1863 to 1912 nm for tri-wavelength mode-locking, respectively, which is the widest in multi-wavelength Tm-doped mode-locked fiber laser as far as we know. This provides a simple and compact solution to tunable multi-wavelength mode-locked fiber lasers. This fiber laser will find spreading applications in spectroscopy, optical communications, optical signal processing and optical sensor multiplexing.

5. ACKNOWLEDGMENTS

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