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Dual-wavelength mode-locked Tm^{3+}-doped fiber laser at 2 μm region with controllable soliton pulse number by employing graphene on microfiber

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ABSTRACT

We demonstrate the generation of dual-wavelength ultrafast Tm^{3+}-doped fiber laser at 2 μm region based on graphene saturable absorber. A section of graphene film is transferred on a microfiber, which allows light-graphene interaction via evanescent field. Due to the cavity birefringence-induced comb filter, dual-wavelength mode-locking at 1932/1981 nm region is obtained. The number of soliton pulses at 1932 nm region can be controlled by adjusting the pump power and the pulse trains at 1981 nm region remain the soliton state at fundamental repetition frequency 20.65 MHz. By tuning the polarization controller (PC) under proper pump power, dual-wavelength soliton/four-soliton operation centered at 1927.04/1977.94 nm is also experimentally investigated.

1. Introduction

Tm^{3+}-doped mode-locked fiber lasers (TDFL) in 2 μm region have gained intense interests due to their various scientific applications in free space optical communication, remote sensing, mid-infrared spectrum generation and medical treatment [1,2]. There are many methods to realize mode-locked lasing in 2 μm region such as nonlinear polarization evolution (NPE) [3], nonlinear optical loop mirror (NOLM) [4], graphene saturable absorber (GSA) [5], semiconductor saturable absorber mirror (SESAM) [6], carbon nanotube (CNT) [7]. However, those lasers are mode-locked at single wavelength. Compared with mode-locked lasers at single wavelength, multi-wavelength mode-locked lasers can be further used in next generation wavelength division multiplexing communication systems, pump-probe measurements, optical signal processing and optical wave synthesis. The main challenge of the multi-wavelength mode-locked laser is the strong homogeneous line broadening of Tm^{3+}-doped fiber at room temperature. In order to achieve multi-wavelength operation at 2 μm, there are two major categories to overcome homogeneous gain-broadening of Tm^{3+}. For the first category, additional components are used as filter in the cavity, such as Bragg grating [8], Mach–Zehnder interferometer [9]. Recently, Wang et al. demonstrate a fiber taper based dual-wavelength mode-locked TDFL, in which the comb filter was formed by multimode interference in the taper's waist region [10]. However, such additional components increase the cavity loss and make the laser system more complex. The second category is the nonlinear switching technique, in which the transmission is dependent on the nonlinear phase shift induced by nonlinear polarization evolution (NPE) or nonlinear amplifying loop mirror (NALM). Yan et al. realized a wavelength tunable and switchable dual-wavelength mode-locking Tm^{3+}-doped fiber laser over a range from 1852 to 1886 nm based on NPE [11]. Jin et al. demonstrate a tunable multi-wavelength mode-locked Tm/Ho-doped fiber laser based on a NALM [12]. However, those lasers always need long single mode fiber or high nonlinear fiber to increase phase shift because of the small fiber nonlinearity at 2 μm. The additional fiber extends the cavity length and makes the cavity complex.

Recently, graphene saturable absorber draws much attention as its ultrafast nonlinear optical responses [13]. Moreover, compared with SESAM and CNT, it does not require bandgap or diameter control to achieve broadband saturable absorption. Thus, graphene is an excellent candidate for multi-wavelength mode-locking fiber laser. To integrate GSAs in fiber laser cavities, microfiber provides a promising method, which allows light-graphene interaction via evanescent field. Most interestingly, the GSA based on microfiber can generate a polarizing effect [14–16]. The polarization mechanism of the graphene based on microfiber is attributed to the dif-

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ferential attenuation of two polarization modes. Thus, this device not only acts as an excellent saturable absorber for mode-locking, but also induces a weak polarizing effect to form an artificial birefringent filter. It can alleviate the mode competition at different wavelengths and enables the dual-wavelength mode-locking lasing.

As we all know, under strong pumping strength, multi-soliton pulses caused by a peak-power-limiting effect are always generated in the laser cavity [17]. In the 2 μm region, Wang et al. demonstrate pulse bundles and passive harmonic mode-locked pulses in Tm^{3+}-doped fiber laser based on NPR [18]. Pulse number varies with pump power. Yin et al. realized bunched solitons with soliton number up to 15 and harmonically mode-locked solitons with harmonic order up to 10 in a Tm^{3+}-doped fiber laser based on Bi_2Te_3 [19]. However, those lasers operate at single wavelength. The multiple-soliton pulses with controllable number in the dual-wavelength thulium-doped mode-locked fiber laser have not been reported before.

In this paper, for the first time to our best knowledge, we experimentally demonstrate a dual-wavelength mode-locked Tm^{3+}-doped fiber lasers by using graphene on microfiber. The fiber is mode-locked by the graphene. The artificial birefringent filter formed by the polarizing effect is responsible for the dual-wavelength operation. Furthermore, under dual-wavelength operation at 1932/1981 nm region, the number of pulses at 1932 nm region can be controlled by tuning the pump power and the pulse trains at 1981 nm region remain the soliton state at fundamental repetition frequency 20.65 MHz. By tuning the pump power and the PC, the multi-soliton state can operate at the longer wavelength and the single soliton corresponds to the shorter wavelength. The dual-wavelength soliton/four-soliton operation at 1927.04/1977.94 nm is also investigated.

2. Experiment setup

Firstly, we transferred a monolayer graphene with size 1×1 cm^2 from the substrate to polydimethylsiloxane (PDMS) film. Then, the fabricated polymer-supported graphene film is transferred onto the upper surface of the microfiber with a diameter down to 5 μm, a length up to 3 cm and an insertion loss of 0.3 dB. The microfiber is drawn from standard single mode fibers (SMF28) by use of the flame brushing method. We then measured the insertion loss of this structure by using a 1960 nm continuous wave (CW) laser source with polarization control. The maximum insertion loss is 7.9 dB and the minimum insertion loss is 3.3 dB. Thus the polarization-dependent loss (PDL) is 4.6 dB. The PDL level of ~4.6 dB is not high enough to induce mode-locking based on NPE [5]. The transmittance curves of GSA as the function of peak power intensity is shown in Fig. 1(b). An amplified mode-locked laser operated at central wavelength 1960 nm with 19.2 MHz repetition rate, 3 ps temporal duration was used as the probe. The transmission of the black and red curves corresponding to two different polarization states increase by 8.3% and 5.8% respectively due to absorption saturation.

The proposed fiber laser is schematically showed in Fig. 1(a). A 3 m Thulium-doped fiber (nufern, SM-TSF-9/125) is used as the gain medium at a pump wavelength of 1559 nm. The pump light is coupled into the cavity by a wavelength-division multiplexer (WDM). A polarization controller (PC) is used to tune the polarization states while a polarization independent isolator (PI-ISO) is used to force the unidirectional operation. A 10:90 fiber optical coupler (OC) is utilized as the output port of the fiber laser. The total length of the laser is 9.7 m. The anomalous dispersion values of the Tm^{3+}-doped fiber and the SMF-28e fiber are about -73 ps^2 km^{-1} and -71 ps^2 km^{-1} at 1920 nm. The total anomalous dispersion supports the soliton propagation in the laser cavity. An optical spectrum analyzer (OSA) (Yokogawa AQ6375) with a resolution of 0.05 nm is utilized to measure the spectrum of the laser. The pulse train is monitored by a photodetector (Newport 818-BB) of 12.5 GHz and a digital oscilloscope with a bandwidth of 2 GHz. The pulse duration is measured by an autocorrelator (FR-103X L).

3. Results and discussion

Under proper polarization control and pump power, dual-wavelength operation at 1932/1981 nm region was obtained. Fig. 2(a) and (b) respectively shows the evolution in spectral and temporal domain with pump power. At the low pump power of 217 mW, the laser exhibits CW/soliton centered at 1928.93/1980.87 nm. This is because lower pump power can't simultaneously support two wavelengths operating at soliton mode-locking. The oscilloscope trace shows that there is only one pulse train propagating in the cavity. The pulse train corresponds to the wavelength of 1980.87 nm, which is the typical spectrum of soliton mode-locking with Kelly sidebands. The repetition of the pulse is 20.65 MHz, which corresponds to the cavity round-trip frequency. Under fixed polarization and by increasing the pump power to 225 mW, dual-wavelength soliton operation centered at 1932.24/1981.14 nm wavelengths could be achieved. The existence of continuous wave centered at 1929.24 nm induces that the pulse is not mode-locked completely. However, the oscilloscope trace shows that there are two soliton pulses propagating in the cavity. When triggered with one soliton, the other soliton then moved on the oscilloscope screen, indicating that the two solitons have different group velocities in the cavity. At a higher pump power of 235 mW, dual-soliton/soliton operation was obtained. The continuous wave at 1929.24 nm disappeared and the soliton number at 1932.24 nm increases to two. The 3 dB spectral bandwidths are 3.3 and 3.7 nm respectively. The total output power of the two wavelengths is 4.5 mW. By carefully increasing the pump power, new solitons could be generated one by one at 1932 nm region. At the pump power of 324 mW, the soliton number reaches to nine. However, the pulse at 1981 nm region still remained operating at the fundamental repetition frequency.

As mentioned above, the graphene interacting with optical evanescent light can generate a polarizing effect as a weak polarizer. The graphene-induced polarizing effect combined with the cavity birefringence constructs an artificial birefringent filter. The free spectral range of the filter can be expressed as $FSR = \lambda^2/(\Delta n \cdot L)$ [20]. In our laser, L = 9.7 m, $\Delta n = 3 \times 10^{-5}$, the calculated separation of filter peaks is around 13 nm. The oscillating wavelength spacing in our laser is 48.9 nm, which is nearly four times than the wavelength spacing with filtering effect. As the pump power increasing, the transmission property of the artificial birefringent filter is slightly changed. Thus, the center wavelength of the two soliton trains has a slight shift in the spectrum. However, the oscillating wavelength spacing is not changed. The artificial birefringent filter also effectively changes the inversion condition of the TDF, and most of the increasing pump power transformed into the energy at 1932 nm region. Therefore, in the spectral domain, the intensity of the 1932 nm region increases with the pump power and the intensity of the 1981 nm region remain unchanged. In the temporal domain, operation state at 1932 nm region is changed from CW to nine-soliton with pump power increasing and the pulse at 1981 nm region remains the single soliton state.

The artificial birefringent filter together with the thulium-doped fiber determines the effective laser gain. By tuning the pump power and the PC, the transmission of the artificial birefringent filter can be effectively changed. Thus, the multi-soliton state can also operate at the longer wavelength. At pump power of 315