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High-energy, tunable-wavelengths, Q-switched pulse laser

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ABSTRACT

An all fiber, wavelength tunable, Q-switched erbium-doped fiber laser (EDFL) based on a graphene saturable absorber (SA) and an unbalanced Mach–Zehnder interferometer (UMZI) has been demonstrated. The wavelengths of the Q-switched laser can be accurately tuned over a range of ~35 nm by inserting into the cavity an UMZI with a variable optical delay line (OVDL) in one arm, which acts as an optical beam filter into the cavity. The Q-switched pulse duration and the pulse energy have all been characterized. The maximum pulse energy of 36.9 nJ was obtained.

1. Introduction

Tunable Q-switched fiber lasers have attracted significant attention because of their wide fields applications, such as in materials processing, fiber optical sensing and wavelength division multiplexing (WDM) for communications. In addition, in many cases one tunable light source can be used to replace several sources with different wavelengths. In the early days, researchers typically used a volume diffraction grating [1], a bulk tunable filter [2–4] or an F–P filter [5,6] as a wavelength selection device. Fan et al. have demonstrated a hybrid Q-switched laser with a tunable wavelength range from 1080.8 to 1142.7 nm by using a Yb-doped double-clad fiber as the gain material and a volume diffraction grating to realize wavelength tuning [1]. Popa et al. have used a bulk tunable filter to obtain a Q-switched fiber laser with a pulse tunable between 1522 and 1555 nm [2]. Cao et al. have used a narrow bandwidth tunable filter to get a wide-band tunable passively Q-switched fiber laser with a tunable range from 1519.3 to 1569.9 nm [3]. Dong et al. have achieved a low threshold of 12.8 mW, tunable Q-switched laser based on two F–P filters working in C- and L-band respectively [5]. These Q-switched fiber lasers have realized a wide wavelength tunable range; however, they usually have large coupling losses, stringent alignment requirements or high cost since they used non-fiber tunable instrument in the laser cavity. In 1996, an all fiber, wavelength tunable Q-switched fiber laser with fiber Bragg grating mirrors has been demonstrated for the first time [7]. Though this laser had lower coupling losses, its tunable range was very narrow, and the central wavelength could not easily be placed at a specific position by applying only axial strain or lateral stress to the FBG [8]. In many practical applications, the requirements for wavelength tuning in lasers are very rigorous, so it is very desirable to enhance the flexibility of tunable fiber lasers. Unfortunately, the filters above-mentioned cannot meet these need. An unbalanced Mach–Zehnder interferometer (UMZI) is also a fiber-based component, which is relatively simple to implement and has been used in several studies to provide flexibly broadband tunable filtering [9–11]. Recently, Tan et al. have demonstrated a switchable Q-switched erbium-doped fiber laser (EDFL) by using the nonlinear polarization rotation (NPR) to realize mode locking and using an UMZI to realize wavelength switching operation [12]. Since the NPR Q-switched laser was unstable against environmental perturbations, only slightly above 10 dB signal-to-noise ratio was observed in their experiment. Q-switched fiber lasers incorporating a real passive saturable absorber (SA), such as a semiconductor saturable absorber mirror (SESAM) [13,14] or carbon nanotubes (CNTs) [8,15,16] have been proposed. A 1.53 μm all-fiber passively Q-switched laser with 0.1 mJ pulse energy based on a SESAM has been reported in [13]. Dong et al. have demonstrated an all-fiber Q-switched linear cavity tunable EDFL based on CNTs as SA [15]. Liu et al. have reported a Q-switched EDFL with a central wavelength tunable range of 26 nm [16]. A SESAM, however, has a narrow wavelength tuning range for a tunable laser and requires complex fabrication and packaging. CNTs are confronted with the problem of high non-saturated losses [17]. Besides, its operation wavelength is related to the diameter and chirality of CNTs [18]. Compared with SESAM and CNTs, graphene, a single layer atom of carbon [19], has its desirable optical characteristics,

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such as ultrafast recovery time, low cost, a higher damage threshold, wider tunable range and easy of fabrication, so it has been widely accepted to replace the usage of SESAM and CNTs as a broadband SA within the laser cavity to realize laser tunable over a wide wavelength range [20–22]. Zhang et al. have demonstrated a 30 nm broadband tunable graphene mode-locked fiber laser with single pulse energy of 2.3 nJ [20]. Sun et al. have reported a tunable graphene mode locked ultrafast fiber laser with wavelength tunable range from 1525 to 1559 nm [21]. Recently, our research group has produced the graphene SA and has experimentally observed multiple-solitons dynamic patterns in the graphene mode-locked EDFL [23,24]. However, to the best our knowledge, up to now, there have been no reports of broadband tunable Q-switched EDFLs based on the combined effect of graphene SA and an UMZI.

In this paper, we report the demonstration of a wavelength tunable Q-switched EDFL. By combining graphene as SA and an UMZI as an optical beam filter, we have obtained Q-switched fiber lasers with tunable central wavelength from 1523.03 nm to 1558.65 nm, a range of ~35 nm. Furthermore, by using an optical variable delay line (OVDL) to change the path difference between the two interferometer arms of the UMZI, the tunable wavelength spacing of the Q-switched laser can be precisely controlled. The maximum pulse energy can reach 36.9 nJ. That is to say, an all fiber, precise broadband tunable Q-switched EDFL with higher pulse energy has been obtained.

2. Experiment setup

Fig. 1 shows the experimental schematic of the laser discussed in this paper. A 2 m-long high doping concentration erbium doped fiber (HDCEDF) with an Er-doping concentration of 2280 ppm and a group velocity dispersion (GVD) of −52 (ps/nm)/km at the wavelength of 1550 nm was used as the gain medium. The HDCEDF had a core diameter of ~6.5 μm and an absorption of 20 dB/m at 1530 nm. The pump source was a laser diode with a maximum output power of 258 mW at 980 nm. A 980/1550 nm WDM was used to couple the pump light into the gain medium. An UMZI, which was constructed of two 3 dB couplers, and with a optical variable delay line (OVDL) in one arm, was used as an optical beam filter. As mentioned above, we chose a graphene SA to obtain the Q-switched pulse. The modulation depth of graphene is 3.41%. The polarization independent isolator (PI-ISO) in the cavity ensured that the light was unidirectional during operation. A fiber polarization controller (PC) was also inserted into the cavity to change the polarization state of the circulating light in the laser cavity. The total cavity length was ~14.9 m, including a 12.9 m length of standard single mode fiber (SMF) with a dispersion of −22 ps^2/km. The net dispersion of the laser cavity was −0.15 ps^2/km. A 90/10 coupler (OC1) was used to output the light signal. An optical spectrum analyzer (AQ6317C) with a maximum resolution of 0.01 nm and a 1-GHz digital sampling oscilloscope (DL9140) with a 1 GHz bandwidth photodetector were used to observe the optical spectrum and temporal pulse shape simultaneously.

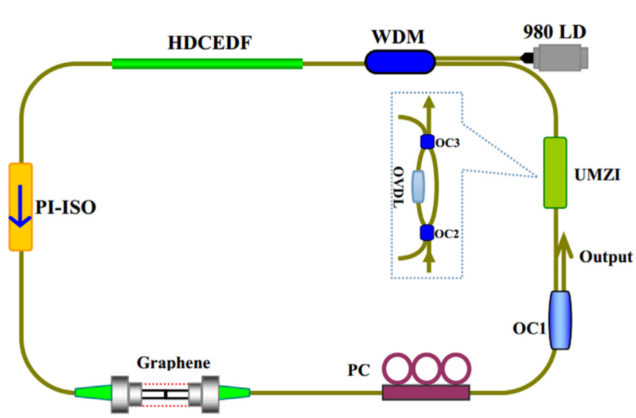

Fig. 1. Experimental setup of an all fiber wavelength tunable graphene Q-switched EDFL. WDM: wavelength division multiplexer, HDCEDF: high doping concentration erbium-doped fiber, PI-ISO: polarization independent isolator, PC: polarization controller, OC1: fused fiber 90/10 coupler, OC2 and OC3: fused fiber 50/50 couplers, OVDL: optical variable delay line, UMZI: unbalanced Mach–Zehnder interferometer.

3. Experimental results and discussion

3.1. Q-switched pulse trains

The threshold pumping power of the laser for CW operation was ~8.51 mW. When the pump power was increased to 15.9 mW, with careful adjustment of the PC, the EDFL started lasing in the passive Q-switching mode, but the pulse was not stable. The Q-switched pulse trains were stabilized, with a further increase in the pump power to 17.9 mW. The spectrum of the output pulse train at a pump power of 60.4 mW is shown in Fig. 2 (a). The central wavelength was 1559.2 nm. Fig. 2(b) shows the temporal trace of this pulse. The repetition rate was 24.14 kHz. It is worthy to note that in the absence of graphene, the Q-switched pulses disappeared which indicates that the Q-switching was due to graphene SA rather than to self-Q-switching.

We found that there was a CW component in the spectrum, which resulted from the graphene film. With a small number of layers less than 8–15 layers, graphene would lead to “weaker” mode locking [25]. There was also some modulation on both sides of the central wavelength of the spectrum, which was caused by reflection at the fiber-end surface in the laser cavity. There were three mechanical connections in the cavity, at the both ends of the PI-ISO and the location of the graphene saturable absorber. At higher pump power, the multiple F–P cavities formed by several ends of fiber could play a role in filtering to some extent, with the result that modulation could appear in the spectrum.

The pulse width and repetition rate as functions of the pump power are shown in Fig. 3(a) and (b), respectively. The pulse repetition rate increased monotonically with increasing pump power from 11.95 to 49.29 kHz while the pulse width changed from 17.25 μs to 1.70 μs in the opposite direction. The pulse energy also grew monotonically with increasing pump power. At a pump power of 210.8 mW, we obtained a Q-switched pulse with a average output power of 1.82 mW, a repetition rate of 49.29 kHz, a pulse width of 1.70 μs and the maximum pulse energy of 36.9 nJ.

3.2. Tunable center wavelength

The output wavelength could be tuned if an UMZI, which acts as a comb filter, was inserted into the cavity. The optical path difference of the UMZI is expressed by $\Delta L = \lambda^2/(n\Delta\lambda)$, where ΔL is the optical path difference between the two arms of UMZI, λ is the operating wavelength, and n is the refractive index of the fiber. ΔL can be tuned by, for instance, adjusting an OVDL in one arm of the UMZI. So in order to precisely control tunable wavelength spacing of the Q-switched laser, an OVDL were incorporated to change the path difference between the two interferometer arms of the UMZI [26, 27]. Fig. 4(a) shows the optical transmission spectrum of the UMZI with a 93.1 μm optical path difference between the two arms. As expected, there are three intensity transmission peaks in the spectral response of the UMZI. With the UMZI acting as a comb filter, lasing could occur only at these peaks.