Graphene Q-switched Ho\textsuperscript{3+}-doped ZBLAN fiber laser at 1190 nm

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We report Q-switched pulse operation of holmium (Ho\textsuperscript{3+})-doped ZrF\textsubscript{4}-BaF\textsubscript{2}-LaF\textsubscript{3}-AlF\textsubscript{3}-NaF (ZBLAN) at \textasciitilde1190 nm in an all-fiber ring laser by using a fiber-optic graphene saturable absorber, which was fabricated by depositing graphene onto the flat surface of a side-polished D-shaped fiber. Stable Q-switched operation was established at a pump power of 180 mW with a repetition rate of 24 kHz and pulse width of 5.7 \textmu s. When the pump power was increased to 1125 mW, 0.44 \textmu J Q-switched pulses with a repetition rate of 111 kHz and a pulse width of 0.8 \textmu s were generated. © 2015 Optical Society of America

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Fiber lasers operating in the \textasciitilde1.2 \textmu m range are important to address demands for near-infrared sources for a variety of applications, ranging from molecular spectroscopy, medical treatment, noninvasive medicine, and biomedical diagnostics to pump sources and sensing [1–4]. ZrF\textsubscript{4}-BaF\textsubscript{2}-LaF\textsubscript{3}-AlF\textsubscript{3}-NaF (ZBLAN) is the most stable heavy metal fluoride glass and is an excellent host for efficient and compact ultraviolet, visible, and infrared lasers at 3–4 m [5–8]. Because of its small phonon energy and long radiative lifetimes, rare-earth-doped ZBLAN can support laser emission at a number of wavelengths, which cannot be achieved with silica fibers. Our previous experiments have demonstrated that Ho\textsuperscript{3+}-doped ZBLAN fiber is an efficient gain medium for lasers at 1.2 \textmu m, and single-frequency operation and watt-level continuous-wave (CW) operation have been successfully achieved [5–7]. Pulsed fiber lasers in the \textasciitilde1.2 \textmu m range, however, have not been investigated yet. Pulsed lasers are in high demand for many applications where high energy or high peak power pulses are required. In this Letter, we report a graphene Q-switched Ho\textsuperscript{3+}-doped ZBLAN fiber laser at \textasciitilde1190 nm.

Graphene is a highly promising material for high-performance photonic devices due to its unique properties, featuring its zero-bandgap energy band structure, ultrafast intra- and inter-band carrier excitation and relaxation [9]. Their ultra-broad operating wavelength range and ease of fabrication and integration make graphene-saturable absorbers (SAs) extremely valuable for Q-switching and mode-locking for pulsed laser operation at various wavelengths [10–19]. We have successfully utilized thin-film graphene SAs to obtain Q-switched fiber lasers at 3 \textmu m [10,11]. Efforts to make a compact, stable and all-fiber based laser utilize a variety of techniques to fabricate fiber-optic graphene SAs, such as transferring the atomic-layer graphene onto a fiber [14], depositing graphene on the end of optical fibers using an optically driven deposition method [11], filling hollow optical fiber with graphene [15], and depositing graphene onto the surface of side polished D-shaped fibers [13,16,19], microfibers [17], and tapered fibers [18]. Compared to other techniques, depositing graphene on D-shaped fiber [13,16,19] has several advantages. First, it can entirely avoid optical power-induced thermal damage by adjusting the light interaction length with graphene. Second, the graphene can tightly bond onto the flat surface of a D-shaped fiber. Third, it is robust and convenient for packaging. Moreover, mode-locked and Q-switched fiber lasers at 1, 1.5, and 1.9 \textmu m based on graphene-deposited D-shaped fiber SAs have already been demonstrated [13,16,19]. Therefore, we fabricated graphene-deposited D-shaped fiber SAs and used them to obtain a Q-switched Ho\textsuperscript{3+}-doped ZBLAN fiber laser at 1.19 \textmu m.

A side-polished D-shaped SMF28 fiber (Phenix Photonics Ltd.) with a polished depth of 50.8 \textmu m and polish length of 17 mm was used in our experiment. Figures 1(a) and 1(b) show the side view and top view microscopic images of the D-shaped fiber segment, respectively. A few-layer graphene flake solution was obtained by liquid exfoliation of graphite (Bay Carbon) in 1-methyl-2-pyrrolidinone (NMP). The solution containing the graphene flakes was found to be stable for months, and was used for the preparation of the SA. The D-shaped fiber graphene SA was fabricated by dripping a solution consisting of graphene suspensions onto the flat surface of the D-shaped fiber and air-drying the graphene suspension. The side view and top view microscopic images of the graphene-deposited D-shaped fiber segment are shown in Figs. 1(c) and 1(d), respectively. Graphene has been deposited on the face of the D-shaped fiber with a relatively homogeneous distribution. The transmission spectrum of the fiber-optic graphene SA was measured with a white light source (Yokogawa AQ4305) and optical spectrum analyzer (OSA, ANDO, AQ6317) and is shown in Fig. 1(e). The transmission of the fiber-optic graphene SA is about 20% from 1150 to 1600 nm and decreases slightly with increasing wavelength consistent with the larger mode areas at longer wavelengths. The transmission of the fiber-optic graphene SA becomes 25% for...
the wavelengths below the cutoff wavelength of the SMF28 fiber.

The experimental setup of the graphene Q-switched Ho\(^{3+}\)-doped ZBLAN laser in an all-fiber configuration is presented in Fig. 2. A 12.5-cm-long Ho\(^{3+}\)-doped ZBLAN fiber was used as the gain medium, which was pumped by an 1150-nm Raman fiber laser via an 1150/1190-nm wavelength division multiplexer (WDM). The 3-mol. \% Ho\(^{3+}\)-doped ZBLAN fiber has a core diameter of 5.3 μm, a core numerical aperture (NA) of 0.14, and a cladding diameter of 125 μm. The absorption coefficient of this Ho\(^{3+}\)-doped ZBLAN fiber at 1150 nm, and its propagation losses were measured to be 3.7 and 0.24 dB/m, respectively, by a cutback experiment using a white light source. A polarization-independent isolator was used to force the unidirectional operation of the ring laser, and a second WDM was used to remove the residual 1150-nm pump laser from the fiber ring cavity. The laser output was extracted from the ring cavity via an 80:20 fiber coupler at the 20% output port. The graphene-based SA was spliced to the signal port of the first WDM and the 80% port of the optical coupler. The total length of the all-fiber-integrated laser was about 9 m. The temporal characteristics of the laser output were monitored by using a combination of a photo detector (Thorlabs, DET10C) and a 200-MHz oscilloscope (Tektronix TDS2024B). The optical spectrum was measured with an OSA (ANDO, AQ6317), and the output power was measured with a thermal power meter (Thorlabs, PM320E). The radio-frequency (RF) spectrum of the passively Q-switched laser output was measured by connecting the photo detector to a spectrum analyzer (ADVANTEST, R3131A).

In our experiment, it was found that stable Q-switched pulses were established at a pump power of 180 mW and maintained up to the maximum handling power (~1 W) of the 1150/1190-nm WDM. Figure 3 shows the optical spectrum of the output laser at a pump power of 400 mW. The 3-dB bandwidth is ~0.35 nm, and the central wavelength is 1192.6 nm, which is a typical wavelength of highly Ho\(^{3+}\)-doped ZBLAN fiber lasers. The laser mechanism associated with the 1.2-μm laser emission of Ho\(^{3+}\)-doped ZBLAN fiber has been discussed in detail in [5–7].

As the pump power increased from 180 to 1125 mW, the Q-switched pulse train was very stable, and no significant pulse jitter was observed in the experiment. Three typical Q-switched pulse trains of the graphene Q-switched Ho\(^{3+}\)-doped ZBLAN fiber laser at pump powers of 335, 540, and 900 mW are shown in Fig. 4(a). Figure 4(b) shows the pulse envelopes corresponding to the three pump powers. Clearly, the pulse repetition rate of the graphene Q-switched Ho\(^{3+}\)-doped ZBLAN fiber laser increases while pulse duration decreases with the increased pump power. The repetition rate and pulse duration measured at the different pump powers are shown in Fig. 5. The repetition rate of the Q-switched pulses (black squares) increases from 24 to 111 kHz,
while the pulse duration decreases from 5.73 to 0.8 μs as the pump power increases from 180 to 1125 mW. Figure 4 shows the radio-frequency (RF) spectrum of the graphene Q-switched fiber laser measured at a launched pump power of 900 mW. The fundamental peak is at 88.9 kHz, which corresponds to the repetition rate shown in Fig. 4. Note that the signal-to-noise ratio (SNR) is about 45 dB, which indicates very good stability of this laser during the measurement time. The measured average power (black squares) and the calculated pulse energy (blue dots) as a function of the pump power are shown in Fig. 7. At the maximum pump power of 1125 mW, the average output power is 47.8 mW, and the calculated pulse energy and peak power are 0.44 μJ and 0.56 W, respectively. Note that the average power increases linearly with the increased pump power, whereas the pulse energy shows a saturation property at high pump power.
powers due to the bleaching of the graphene SA. The slope efficiency of this fiber laser is only 4.8%, which is much lower than that of watt-level linear-cavity CW laser using a pair of fiber Bragg gratings [6]. The low efficiency is attributed to the very large cavity loss which includes the ∼7 dB transmission loss of the graphene SA, the 2-dB insertion loss of the isolator, and the 3.4-dB insertion loss of the two 1150/1190-nm WDMs. We expect that the efficiency of this Q-switched laser could be improved by reducing the cavity loss and optimizing the coupling ratio of the fiber coupler. The pulse energy of this fiber laser source is not high enough for practical applications. Much high energy pulses can be achieved by using master oscillator and power amplifiers (MOPAs) [20]. 10-μJ-level and 100-μJ-level pulses are achievable by using current ZBLAN fiber laser technology [8].

In conclusion, we experimentally investigated the Q-switched operation of a 1190-nm Ho$^{3+}/.0135$-doped ZBLAN fiber laser by using a D-shaped fiber graphene SA in the ring cavity. The threshold of stable Q-switched operation is 180 mW. At a pump power of 1125 mW, stable Q-switched pulses with a repetition rate of 111 kHz, pulse energy of 0.44 μJ, and pulse duration of 0.8 μs were obtained. Due to the large cavity loss of the ring cavity, the efficiency of this Q-switched fiber laser is much lower than that of the linear-cavity CW fiber laser. In our experiment, we did not observe mode-locked operation of the Ho$^{3+}$-doped ZBLAN fiber laser. This may due to the large absorption (80%) of the SA. Optimizing the D-shaped fiber SA to achieve a mode-locked fiber laser at 1.2 μm is currently under way.

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