Mode-locked fiber laser with a manganese-doped cadmium selenide saturable absorber

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We demonstrate the generation of mode-locked pulses in an erbium-doped fiber laser (EDFL) by using a new manganese-doped cadmium selenide quantum-dots-based saturable absorber. The laser produces a soliton pulse train operating at 1561.1 nm with a repetition rate of 1 MHz, as the pump power is varied from 113 to 250 mW. At the maximum pump power, we obtain the pulse duration of 459 ns with a signal-to-noise ratio of 50 dB.

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Pulsed laser generation was started in the 1980s through the development of a dye gain medium, followed by a solid state gain medium a decade later. The research interest moves to a fiber gain medium in the early 2000s, especially on generating pulsed fiber lasers because of their compactness and high reliability. The pulsed fiber lasers, such as a mode-locked erbium-doped fiber laser (EDFL), have offered many applications in various fields, such as telecommunication, bio-sensing, and material processing[1–4]. There are different methods for generating a mode-locked laser; one of the simplest and most effective ways is by using a passive saturable absorber (SA). To date, various mode-locked fiber lasers have used a ytterbium-doped fiber (YDF), an erbium-doped fiber (EDF), or a thulium-doped fiber (TDF) as the gain media[5–7]. On the other hand, various types of SAs have also been reported to produce mode-locked pulse trains, such as a semiconductor SA mirror (SESAM)[8], carbon nanotubes (CNT)[9], and graphene[10]. SESAM is readily available on the market. However, it has limited bandwidth and requires complicated and expensive fabrication. Then, a CNT was regularly used in a mode-locked fiber laser as an SA due to its rapid recovery time and broad absorption spectrum[11], but not for its stability. Later, graphene was reported by Bao *et al.*[12], who showed it as a promising material for an SA. Graphene provides several advantages such as a great saturable absorption modulation depth and fast recovery time[13,14].

Recently, two-dimensional (2D) nanomaterials, such as transition metal dichalcogenides (TMDs)[15] and black phosphorus (BP)[16], have also attracted considerable interest as convincing SA materials for mode-locked fiber laser application. BP has gained more attraction due to its narrow direct band gap, which can fill the gap between graphene and wide band-gap TMDs. However, BP cannot be exposed to oxygen and water molecules due to its hydrophilic properties, which can reduce its performance[17,18]. More recently, a quantum dots (QDs) semiconductor crystal was established as one of nanomaterials groups, which gained attraction for many researchers due to its wide range of applications, including processing a solar cell[19], as a biological device[20], and as a probe for energy filtered transmission electron microscopy (TEM)[21]. One of the promising materials in QDs is cadmium selenide (CdSe), which provides great photoelectrical properties and a direct band gap of 1.74 eV[22,23] for making a photodetector and a photovoltaic system[24]. Moreover, CdSe shows excellent photostability, which maintains its optical properties for ten days under ambient conditions[25]. The CdSe band-gap size can be reduced by increasing the crystal size[26], as well as the impurities and defects in a CdSe crystal[27]. So, the band-gap energy of CdSe depends on the crystal size, and, thus, it is beneficial for biological and chemical sensors.

In this Letter, a mode-locked EDFL operating at 1561.1 nm demonstrates manganese (Mn)-doped CdSe QD as an SA. To the best of our knowledge, this the first demonstration of mode-locking pulse generation by using Mn-doped CdSe as a mode locker.

In this work, the first stage of the process is the fabrication of CdSe powder. The process was similar to previous reports[28,29], where cadmium oxide (CdO), selenium (Se), and Mn acetate powders were used as a precursor. In this process, a mixture of oleic acid and paraffin oil is prepared as a solvent with a ratio 3:5. After that, the CdO and Mn acetate powder is mixed with the prepared solvent under an argon gas flow with a temperature of 160°C by using a three-neck flask. The mixture is then stirred continuously until all of the powders totally dissolve before it is distilled in a vacuum to eliminate any remaining acetone. Later, the Se powder is dissolved in paraffin oil at a 220°C temperature. Lastly, 5 mL of an Mn–Cd solution was promptly added into the Se–paraffin-oil solution so that it allowed for a gradual growth

of the CdSe in the QD atomic structure and exhibited a rapid nucleation of it.

The second stage was a filtrating process of the CdSe solution. The aim of this process is to exclude the paraffin oil in the CdSe solution so that the CdSe can be used as SA material. First, we measured about 10 mL of the CdSe solution via a syringe cylinder. The solution was injected into a centrifuge tube. Then, the centrifuge tube was inserted into a centrifuge machine with a rotation speed of 3000 rpm in 10 min. After the sedimentation process, we disposed of the paraffin oil and oleic acid, and then the residue of CdSe was placed onto filter paper. It was to ensure that the paraffin oil and oleic acid filtered entirely out of the CdSe residue. This process was repeated continuously until the paraffin oil was completely removed. The residue of the CdSe solution was finally becoming CdSe powder on filter paper. Later, the CdSe powder was inserted again into a centrifuge tube together with a methanol solution. The centrifuge tube was then immersed in an ultrasonic water bath for about 15 min at a temperature of 25°C. Due to this process, the CdSe powder dispersed into the methanol. The end product of the mixture was an Mn-doped CdSe solution, which was then used to make an SA. In solution form, the CdSe is easy to adhere to fiber ferrule tips compared to the powder form. The Mn-doped CdSe solution was dropped onto a fiber ferrule end surface and left to dry at room temperature for about 10 min. The process was repeated about five times to obtain a sufficient CdSe layer on the fiber ferrule for the mode-locking operation. Figure 1 illustrates the drop and dry process.

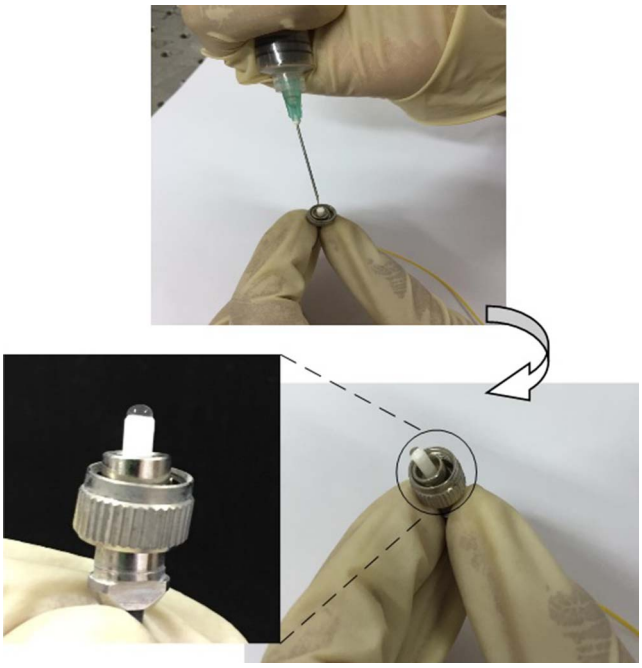

Fig. 1. Preparation of an SA from an Mn-doped CdSe solution (top), dripping the solution onto the fiber ferrule, using a syringe cylinder (bottom) drying process at room temperature.

Figure 2(a) shows the scanning TEM (STEM) image of the Mn-doped CdSe sample solution. The image indicates that the QDs are almost spherical in shape, compact, dense, and clustered together. The diameter of the cluster is about 150–200 nm. We also investigate the nonlinear absorption profile of the Mn-doped CdSe QD-based SA through a balanced twin-detector measurement method, where the external mode-locked fiber laser source for this measurement method has a 1564 nm wavelength, a 1.7 ps pulse width, a 1.1 MHz repetition rate, and a 0.5 nJ/cm^2

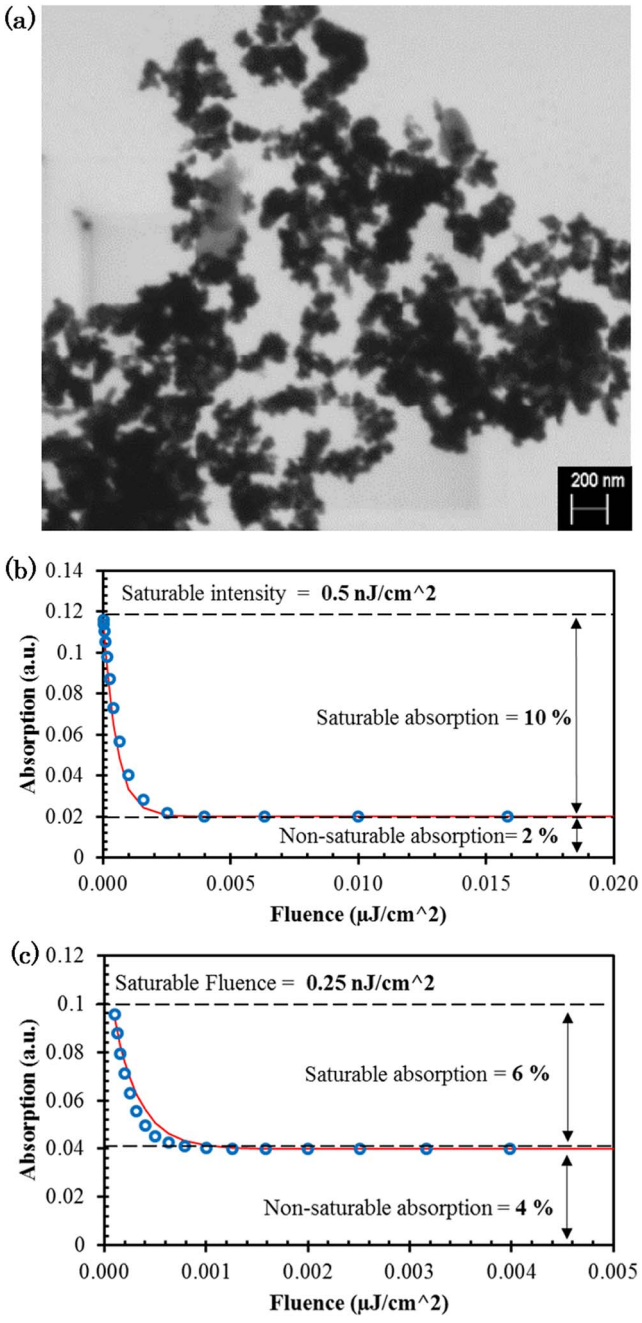

Fig. 2. Characteristic of Mn-doped CdSe, (a) STEM image in the nanometer scale, (b) the nonlinear absorption properties for five droplets, and (c) the nonlinear absorption properties for three droplets.

maximum intensity before the sample. While varying the input power of the laser source, the transmitted power that passes through the QD CdSe was recorded as a function of incident intensity. The result is plotted in Fig. 2(b), where the QD transmission increases with the input intensity before it saturates at a high input intensity. From the analysis, the modulation depth measured was 10%, which is significantly higher than other SA materials that have been previously reported[30,31]. The nonsaturable absorption and saturation intensity were measured to be 2% and 0.5 nJ/cm^2, respectively. This result shows that the QD CdSe QD has met the requirement to be a good SA for pulsed laser generation. However, for three CdSe droplets, the obtained saturable absorption is 6%, as shown in Fig. 2(c). As we increase the number of droplets to five, the pulse train of the mode-locking operation becomes unstable and easy to eliminate.

Figure 3 shows the schematic diagram of the proposed mode-locked EDFL with an Mn-doped CdSe QD-based SA. The SA device obtained by connecting the prepared ferrule with another ferrule via a fiber connector is then integrated into the ring cavity as a mode locker. The net cavity length of the mode-locked EDFL is measured to be 202 m long and comprised of 2.4 m of EDF as a gain medium, 6.6 m of a standard single mode fiber (SMF), and an additional 193 m of SMF to gain sufficient nonlinearity effects for the mode-locking generation. The mode-locking operation formation on the spectrum is in soliton regime. With the integration of CdSe in the cavity, the addition of the single SMF is used to ensure that the cavity operates in the anomalous dispersion region[32]. Moreover, this additional SMF can be used to balance the value of the anomalous dispersion and nonlinearity in the cavity. Therefore, the soliton mode-locked EDFL can be generated at this appropriate cavity length (with an additional 193 m of SMF). The group dispersion velocities (GVDs) of the EDF and standard SMF-28 were 27.6 and -21.7 ps^2/km, respectively. Therefore, the mode-locked EDFL operates in the anomalous fiber dispersion regime of -4.265 ps^2, and it could be classified as a soliton fiber laser. The EDF has core and cladding diameters of 4 and 125 μm, respectively, a numerical aperture (NA) of 0.16, and also an erbium ion absorption of 23 dB/m at 980 nm. It was pumped by a 980 nm laser diode via a wavelength division multiplexer (WDM). An isolator is used in this setup to force the propagation of light in only a clockwise direction and avoid backward reflection. The mode-locked laser delivers the output performances through a 10 dB optical coupler and keeps another 90% of light to retain oscillation in the cavity. The output spectrum is observed through 0.02 nm of spectral resolution of the optical spectrum analyzer (OSA, Yokogawa AQ 6370B). For output power measurement, we use an optical power meter. A 350 MHz oscilloscope with a time resolution of 2.9 ns (OSC, GW Instek GDS-3352) is used to analyze the output pulse train via a 1.2 GHz bandwidth photodetector and confirmed by a 7.8 GHz radio frequency spectrum analyzer (RFSA, Anritsu MS2683A) coupled with an InGaAs photodetector (1.2 GHz Thorlabs DET01CFC).

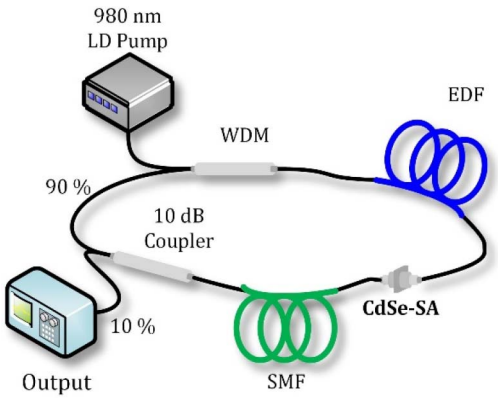

Fig. 3. Configuration of the mode-locked EDFL with Mn-doped CdSe QD-based SA.

In this experiment, the obtained continuous wave (CW) was at a pump power of 22 mW. Continuously increasing the pump power lead to the stable mode-locking operation, while no Q-switching operation took place in our experiment. Beyond the 113 mW pump power, the presence of the mode-locking operation suppresses the CW regime. The operation maintains as the pump power increases to the maximum level of 249 mW. Figure 4(a) shows the typical soliton-operation spectrum together with small Kelly sidebands $(+1, -1, +2, -2)$, owing to the net negative GVD in the cavity[33]. The central wavelength locates at 1561.1 nm with a 3 dB bandwidth of 0.7 nm. In agreement with the total cavity length, the pulse train of a mode-locking operation dominated with a repetition rate of 1 MHz is depicted in Fig. 4(b). The single envelope of the pulse trains in the inset exhibits the pulse duration of 480 ns. We have measured our pulsed duration using an auto-correlator (Alnair Lab, HAC-200), and it has result no pulse formation on the auto-correlator due to the pulse duration being more than 100 ps. The evidence of pulse duration can also be confirmed by the presence of number harmonics in the radio frequency (RF) spectrum, which indicates the number of modes that has been locked, but only up to six modes. Therefore, the fewer number of modes locked in the cavity will produce a large pulse duration. The RF spectrum of the pulse train in Fig. 4(c) shows that the obtained mode-locked laser has a signal-to-noise ratio (SNR) of 50 dB, which certifies its stability. Also, the number harmonics presence is up to six harmonics. At the third harmonic, the SNR is 20 dB and drops to less than 5 dB at the sixth harmonic.

Figure 5 maps the evolution of the average output power and pulse energy versus the input power. The optical-to-optical slope efficiency is 2.37%, which is relatively low due to the insertion loss from the SA and SMF. We cannot observe the optical damage of the Mn-doped CdSe SA since the maximum pump power in the experiment is restricted to 249 mW. The maximum average output power is 6.24 mW. The pulse energy is also directly

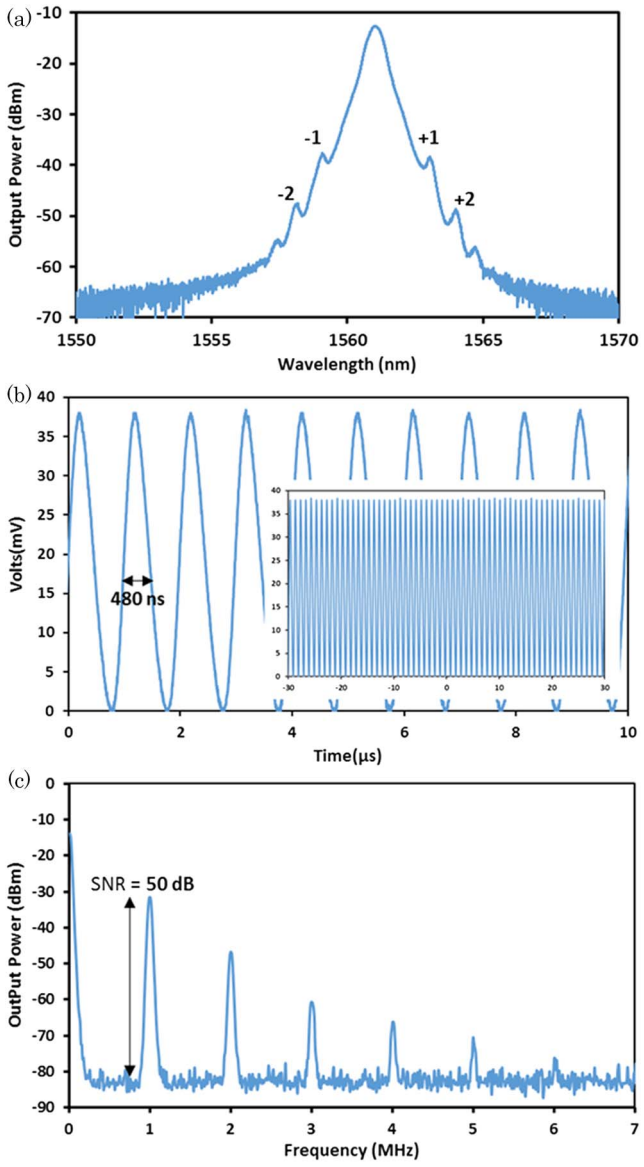

Fig. 4. Mode-locked EDFL performances. (a) Output spectrum. (b) Pulse train. (c) RF spectrum with a 7 MHz span.

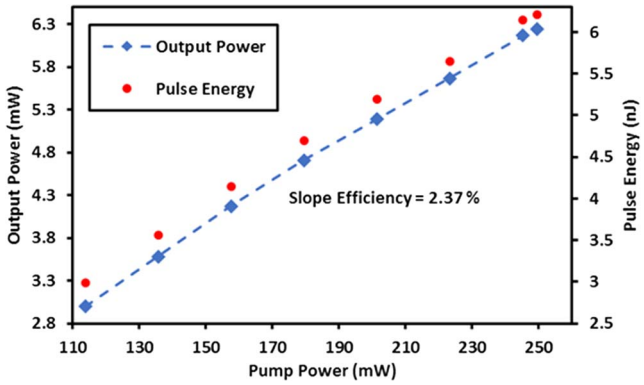

Fig. 5. Output power and single pulse energy as a function of pump power.

proportional to the pump power, which is the maximum pulse energy of 6.2 nJ that is recorded at 249 mW of pump power.

To verify that the mode-locking operation is purely contributed by the CdSe SA, we purposely replace both ferrules with a clean ferrule without CdSe coating. No mode locking was observed no matter what the conditions of the pump power were, unambiguously meaning that the CdSe SA could operate as an effective passive mode locker in mode-locked EDFLs.

We demonstrate a new SA based on Mn-doped CdSe for a self-starting mode-locked EDFL, operating at 1561.1 nm. The CdSe SA has a nonlinear modulation depth of 10%. The mode-locked fiber laser can produce 480 ns pulses with a 1 MHz repetition rate in a 202 m long laser cavity with an anomalous fiber dispersion of -4.265 ps^2. The pump power threshold for the mode-locking operation was 113 mW, while the maximum pulse energy was 6.2 nJ at the maximum pump power of 249 mW. The Mn-doped CdSe is a cost-effective SA in generating mode-locked fiber lasers, where a possible benefit in the saturable absorption property can be optimized to meet the requirements. Better performance of mode-locked fiber lasers using the CdSe SA is supposed to be implemented by optimizing the dispersion of the laser cavity.

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