8-HQCdCl$_2$H$_2$O as an organic Q-switcher in erbium laser cavity*

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This paper demonstrated a Q-switched erbium-doped fiber laser (EDFL) using an organic saturable absorber (SA) based on 8-HQCdCl$_2$H$_2$O material. The organic thin film was prepared using the casting process. The proposed Q-switched EDFL has a maximum repetition rate of 143 kHz, minimum pulse duration of 1.85 μs and the highest pulse energy of 167 nJ. The Q-switched peak laser was at a central wavelength of 1 531 nm with a 3 dB bandwidth of 3.52 nm and power intensity of 2.64 dBm.

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Q-switched lasers operate at low repetition rate with high pulse energy and peak power and thus they are widely investigated for various applications, including material processing, remote sensing, skin treatment, medical surgery, etc[1,2]. They can be realized by either active or passive techniques. The active technique used electro- or acousto-optic modulator as Q-switcher, which is costly, bulky, and complex[3]. The passive technique employed a saturable absorber (SA) device to produce Q-switched pulses, which is simpler and better in terms of costing, compactness, and reliability. Therefore, considerable attention has been given to passive SAs, such as graphene[4], carbon-nanotube (CNT)[5], black phosphorus (BP)[6], and transition-metal dichalcogenides (TMDs)[7,8]. This is mainly attributed to their merits, such as low cost, broadband operation, and ease of fabrication, as well as their ability to provide high peak power, excellent beam quality, and short pulses.

Generally, TMDs, BP, and graphene have a short recovery time and a broad spectral range[6,7,9]. However, they have a very small modulation depth and a very narrow bandgap (between 0 and 1.5 eV). Both BP and graphene are susceptible to degradation. CNT has been considered as a promising material that can be used in wide range of electronics and photonics applications[10]. Thanks to its unique features which in turn make it demonstrates superior performance in ultra-short pulse generation applications. Unfortunately, the changing in CNT size affects its operating bandwidth, bandgap, and absorption efficiency. Therefore, many efforts have been devoted in seeking new ideal SAs[11,12].

Recently, organic materials (OMs) have acquired a great attention for nonlinear optical applications. They have been applied in a variety of electrical devices, including solar cells, field-effect transistors (FETs), and organic light-emitting diodes (OLEDs)[13-15]. This is due to their good electrical conductivity, thermal stability, and less costly. In this study, the 8-hydroxyquinolino cadmium chloride hydrate (8-HQCdCl$_2$H$_2$O) is used to fabricate an organic thin film SA. The thin film SA is then applied in an erbium-doped fiber laser (EDFL) as a Q-switcher for generation of pulse train centered at a wavelength of 1 530 nm. Here, polyvinyl alcohol (PVA) is utilized as a host polymer to fabricate a thin film SA due to its high film-forming ability, mechanical flexibility, distinct physical features, and chemical resistance.

In thin film SA fabrication process, 50 mg of 8-hydroxyquinolino powder was dissolved into 5 mL of methanol, while 50 mg of CdCl$_2$H$_2$O powder was dissolved into 2.5 mL of methanol by stirring for about 10 h. Then both solutions were mixed by stirring for about 7 h. Then PVA solution was produced by mixing 1 g of PVA powder with 100 mL of distilled water. The obtained solution was agitated for 1 h. Finally, a 2.5 mL of PVA

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solution was added to the prepared 8-HQ$CdCl_2H_2O$ solution. The thin film of 8-HQ$CdCl_2H_2O$ SA was obtained by spreading the final 8-HQ$CdCl_2H_2O$/PVA solution onto a petri dish and left to dry for about 24 h at room temperature. Fig.1 illustrates the fabrication process of the organic 8-HQ$CdCl_2H_2O$ thin film.

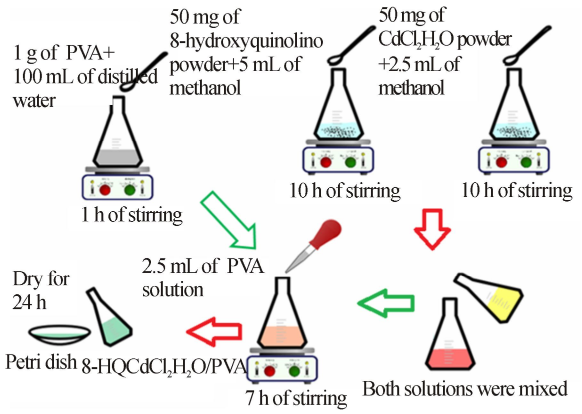


Fig.1 Fabrication process of the organic 8-HQ$CdCl_2H_2O$ thin film

By using the scanning electron microscope (SEM), the structure of organic 8-HQ$CdCl_2H_2O$ thin film was verified. Fig.2(a) shows the SEM image that demonstrates the consistent distribution of organic molecules inside PVA polymer. The chemical elements of the organic 8-HQ$CdCl_2H_2O$ thin film were determined by using the energy-dispersive X-ray (EDX), as shown in Fig.2(b). The 8-HQ$CdCl_2H_2O$ thin film mainly consisted of carbon (C), oxygen (O), cadmium (Cd), chloride (Cl), and silicon (Si) elements.

The linear absorption of the organic 8-HQ$CdCl_2H_2O$ thin film was determined by transmitting a broadband light from a white light source (WLS) through the film. The output spectrum was recorded by using an optical spectrum analyzer (OSA) as shown in Fig.3(a). At 1 540 nm, a linear absorption of about 4 dB was found. The nonlinear absorption of the organic 8-HQ$CdCl_2H_2O$ thin film was also determined by using a balanced twin-detector setup as shown in Fig.3(b). In the experiment, a homemade mode-locked laser pulse source was used. It operated at a repetition rate of 3.6 MHz, a pulse width of 1.02 ps, and a wavelength of 1 562 nm. The nonlinear absorption curve obtained is shown in Fig.3(c). It reveals that the organic 8-HQ$CdCl_2H_2O$ thin film has a saturable absorption of 18%, a non-saturable absorption of 70%, and a saturable intensity of 0.1 MW/cm^2.

The setup of the proposed Q-switched EDFL with 8-HQ$CdCl_2H_2O$ SA is based on a ring cavity as shown in Fig.4. A 980 nm laser diode (LD) was used to produce amplified spontaneous emission in the laser cavity, which is then oscillated to generate laser at 1.5 μm region. A 980/1 550 nm wavelength division multiplexer

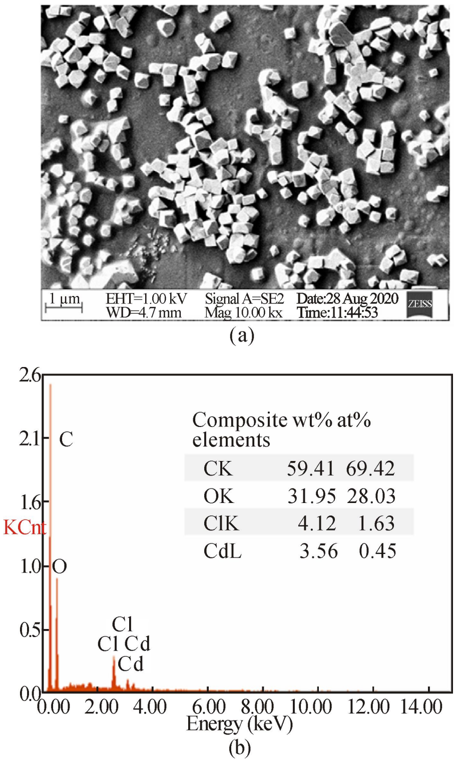
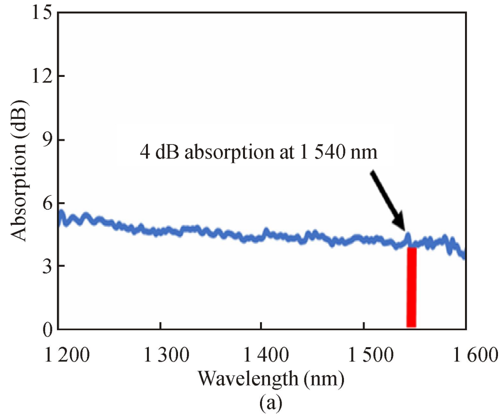


Fig.2 Characterization of the organic 8-HQ$CdCl_2H_2O$ thin film: (a) SEM image; (b) EDX profile

(WDM) was utilized to merge the LD pump source and laser feedback into the cavity. The fiber of WDM has a group velocity dispersion (GVD) of about 48.5 ps^2/km. An erbium-doped fiber (EDF) was used as an active gain medium with a length of 1 m. The EDF has an ion absorption, numerical aperture, core diameter, and GVD of 23 dB/m at 980 nm, 0.16, 4 μm, and 27.6 ps^2/km, respectively. A 50: 50 optical coupler (OC) was used in the EDFL ring cavity to allow 50% of the laser beam to oscillate inside the ring cavity and extract the other 50% outside the cavity for measurements. An optical isolator was used to direct the laser power in one direction and prevented any back-reflected laser. The ring cavity has a total length of 3 m and a complete cavity dispersion of 0.029 2 ps^2. Two FC/PC ferrules were used to sandwich the organic 8-HQ$CdCl_2H_2O$ thin film to form a compatible SA device.



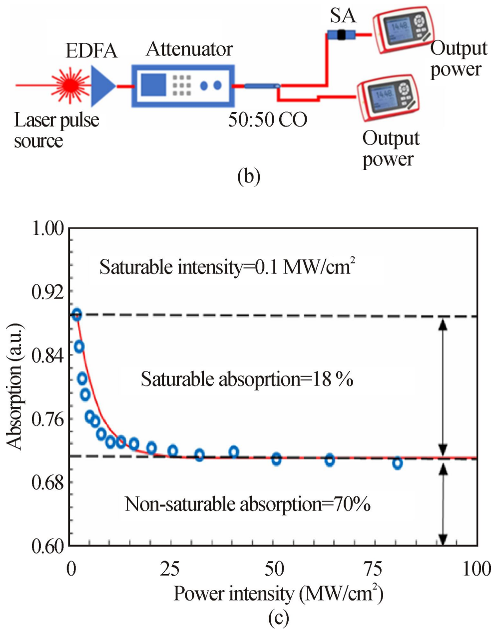


Fig.3 (a) Linear absorption spectrum; (b) Balanced twin detector setup; (c) Nonlinear absorption spectrum

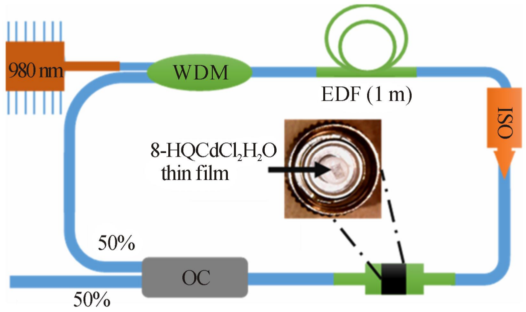


Fig.4 The proposed Q-switched EDFL with 8-HQCdCl$_2$H$_2$O SA

The prepared organic SA was placed in the EDFL cavity to operate as a Q-switcher for modulating the intra-cavity loss. The organic SA saturates before the saturation of the EDF and thus allows the energy of the gain medium to reach a sufficient level to emit laser pulses. A photodetector (Thorlabs: DET01CFC) was used to monitor and quantify the real-time dynamics in the cavity. An oscilloscope (OSC) (GWINSTEK: GDS-3352) and a radio frequency spectrum analyzer (RFSA) (Anritsu: MS2683A) were utilized to record the output. The photodetector, OSC, and RFSA have bandwidths of 1.2 GHz, 350 MHz, and 7.8 GHz, respectively. The output power of the Q-switched laser was measured by using an optical power meter (OPM) (Thorlabs: PM100D), while the output spectra were traced by using OSA (MS9710C).

At the threshold LD power of 10 mW, the EDFL ring cavity generates continuous wave laser. However, the Q-switched laser pulses were observed when the LD power was increased to the threshold of 71 mW. Fig.5(a) shows that the Q-switched laser operation remained with increasing gradually the LD power from 71 mW to 167 mW. The optical efficiency of the EDFL ring setup was reported at 14%. Fig.5(b) illustrates the spectral characteristic of the EDFL with CW and Q-switched operation. The CW laser peaks at 1 561 nm wavelength with a 3 dB bandwidth of 1.51 nm. The power intensity was 9.58 dBm at the maximum LD power of 167 mW. However, the peak spectrum of the Q-switched laser was observed at 1 531 nm with a 3 dB bandwidth of 3.52 nm. The spectral broadening was observed due to the self-phase modulation. At 167 mW pump power, the power intensity reduced to 2.64 dBm and the spectrum shifted to a shorter wavelength region due to the insertion loss of the organic SA.

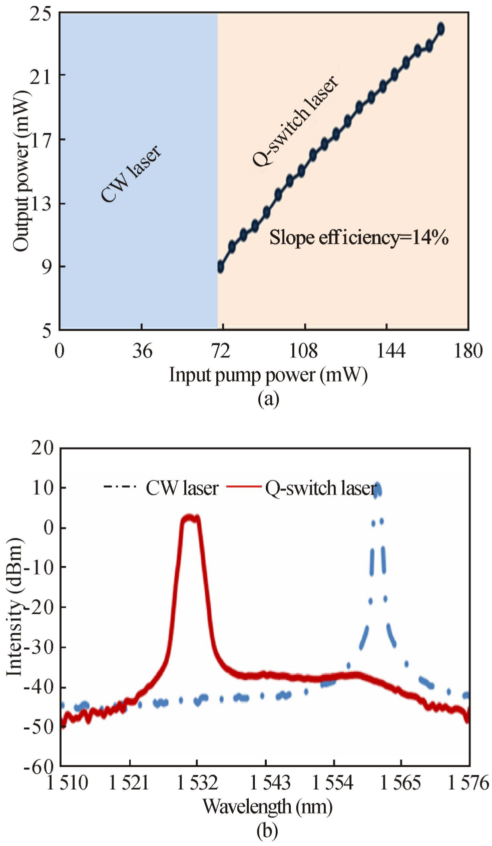


Fig.5 EDFL ring cavity performance: (a) Optical efficiency; (b) Peak laser spectra

The repetition rate and pulse width of the proposed Q-switched EDFL were recorded with varying the LD power from 71 mW to 167 mW, as illustrated in Fig.6(a). The repetition rate increases from 111 kHz to 143 kHz, while the pulse duration reduces from 3.67 μs to 1.85 μs. At the same range of LD power, the output power and pulse energy increase from 9 mW to 23.9 mW and from 81 nJ to 167 nJ, respectively, as shown in Fig.6(b). The linear increasing trend of the output power and pulse energy are due to the increasing of the gain as LD power was increased. It is worthy to note that no mode-locked pulse is obtained in the current EDFL's setup. However, the mode-locked operation could be realized by modifying the laser cavity so that it has a lower loss and optimum length of cavity. Also, the extending of cavity length enables a balance between nonlinearity and dispersion into the laser cavity which may allow the generation of mode-locked laser.

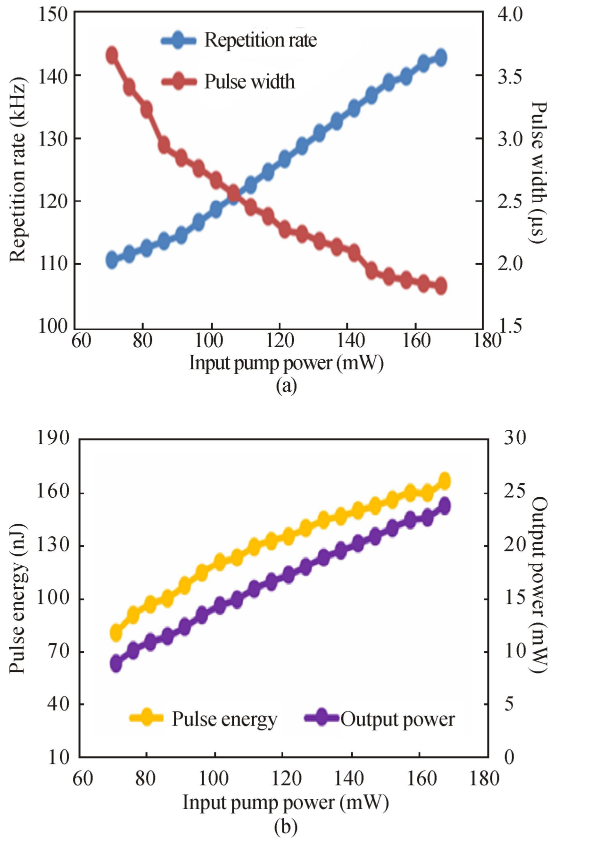


Fig.6 The proposed Q-switched EDFL performance: (a) Pulse repetition rate and pulse width; (b) Pulse energy and output power

Fig.7(a) illustrates the pulse train of the proposed Q-switched EDFL at 167 mW. The larger image depicts two pulses with a full-width half-maximum (*FWHM*) of 1.85 μs, and a peak-to-peak distance of 6.9 μs. Fig.7(b) shows the electrical spectrum of the proposed Q-switched EDFL. The signal-to-noise ratio (*SNR*) was 82 dB at 2 000 kHz. The frequency of initial peak was 143 kHz, which matches the oscilloscope trace perfectly. Tab.1 shows the comparison of the proposed Q-switched EDFL to the previous works using other materials. Our Q-switched laser has demonstrated a comparable performance compared to other SAs. Also, the proposed laser obtained the highest pulse energy. The proposed Q-switched pulses were stable in the laboratory for more than 3 h without any obvious deterioration in the system performance.

In conclusion, a Q-switched EDFL was successfully produced using an organic 8-HQCdCl_2H_2O based SA. The organic thin film was prepared using the casting process. The proposed Q-switched EDFL has a maximum

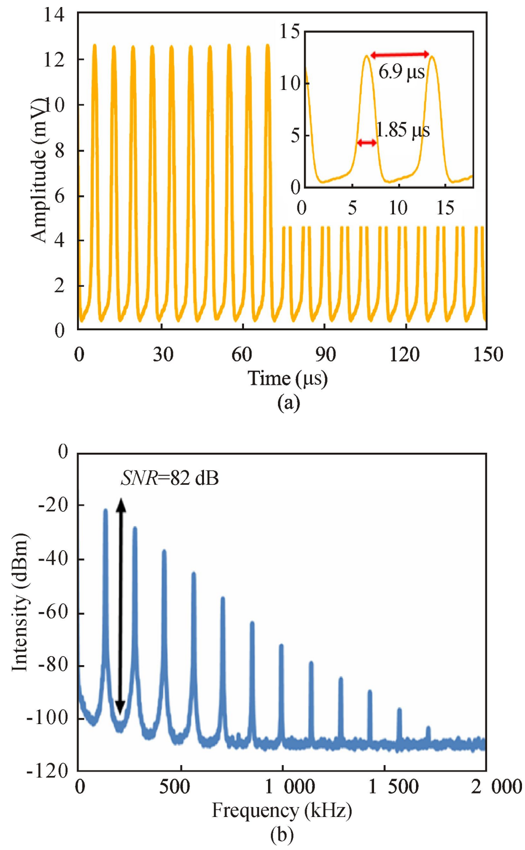


Fig.7 The proposed Q-switched EDFL performance: (a) Pulse train; (b) Radio frequency

Tab.1 Q-switched fiber lasers with various SAs

Material	Wavelength (nm)	Min pulse width (μs)	Max repetition rate (kHz)	Pulse energy (nJ)	Modulation depth (%)	Reference
Ti_2AlC	1 560.4	4.88	27.5	22.6	6.3	[16]
WTe_2	1 560.5	1.77	55.6	18.9	21.4	[17]
P_3HT	1 562.0	3.79	78.6	15	11	[18]
Eu_2O_3	1 568.0	3.6	68.6	162	20	[19]
WO_3	1 562.8	1.85	56.7	142.9	20	[20]
8-HQCd Cl_2H_2O	1 531.0	1.85	143	167	18	This work

repetition rate of 143 kHz, a minimum pulse duration of 1.85 μs and highest pulse energy of 167 nJ. The Q-switched peak laser was at central wavelength of 1 531 nm with a 3 dB bandwidth of 3.52 nm and power intensity of 2.64 dBm.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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