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基于马来酸掺杂聚苯胺被动调Q的掺铒光纤激光器(特邀)

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摘 要:使用一种新型有机材料马来酸掺杂聚苯胺作为可饱和吸收体,在掺铒全光纤激光振荡器中实现稳定的调Q运转。实验中,采用双臂探测法测得该材料的调制深度和可饱和吸收强度分别为13.9%和0.336 MW/cm^2,将其以薄膜三明治形式插入到光纤谐振腔中,最终获得了重复频率从33.78 kHz到87.01 kHz的范围内可调,最窄脉冲宽度为2.29 μs,最大单脉冲能量为54.64 nJ的稳定调Q脉冲输出。马来酸掺杂聚苯胺可以被认为是脉冲光纤激光器应用及其它光电器件的良好候选者。

关键词:可饱和吸收体;调Q激光;光纤激光器;有机材料
中图分类号:TN248 **文献标识码**:A **doi**:10.3788/gzxb20215010.1014004

Passively Q-switched Erbium-doped Fiber Laser with Maleic Acid-doped Polyaniline Saturable Absorber (Invited)

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Abstract: Based on an organic nonlinear optical material, Maleic Acid-Doped Polyaniline (MADP) Saturable Absorber (SA), a stable Q-switched pulse operation was realized in an erbium-doped all-fiber laser for the first time. In this experiment, the modulation depth and saturable absorption intensity of the MADP-SA were measured at 13.9% and 0.336 MW/cm^2 using the twin detector technique, respectively. The MADP-SA is inserted into the fiber resonator in the form of a thin film sandwich. The stable Q-switched pulse operation are achieved with the repetition rate range from 33.78 kHz to 87.01 kHz, the narrowest pulse width of 2.29 μs and the maximum single pulse energy of 54.64 nJ. MADP can be considered as a good candidate for pulsed fiber laser applications and other optoelectronic devices.

Key words: Saturable absorbers; Q-switched laser; Fiber laser; Organic material
OCIS Codes: 140.3510; 140.3540; 060.2410

0 Introduction

In recent years, passively Q-switched fiber laser are widely used in material processing, optical communications, biomedicine and laser spectroscope [1-3], due to its high peak power, narrow pulse width and good beam quality. Meanwhile, as one of the important devices for short pulse generation, various types of

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Saturable Absorber (SA), such as graphene[4-5], Carbon Nanotubes (CNTs)[6-7], Black Phosphorus (BP)[8-9], Transition Metal Dichalcogenides (TMDs)[10-12] and Topological Insulators (TIs)[13-14] have been found and studied successfully. These SAs with fast recovery time, unique optical properties have some limitation in fiber laser for generating short pulses. For example, graphene exhibits obvious broadband saturation absorption characteristics under the light irradiation, but the low modulation depth caused by its lacking of the band gap cannot meet application requirements at certain wavelengths, making it difficult to obtain ultrashort pulses. TMDs have a tunable band gap structure that can be achieved by increasing or decreasing the number of atomic layers, but have the disadvantages of low damage threshold and complicated preparation process. In addition, BP is extremely unstable and easily reacts with oxygen when exposed to the air, which is also a very challenging issue about the storage of BP. Therefore, looking for a SA with excellent optical properties and exploring its application in fiber lasers has gradually become the direction of the researchers.

Organic nonlinear optical materials have the advantages of mechanical flexibility and low cost[15], so they are widely used in light-emitting diodes, field-effect transistors and solar cells[16-18]. In addition, organic materials have great application potential in generating short pulses due to their ultra-fast nonlinear optical response and wide-spectrum tunability. There have been some related reports on the application of new organic materials in fiber lasers. In 2019, SALAM S, et al.[19] achieved Q-switched pulse output in an Erbium-Doped Fiber Laser (EDFL) based on Firpic saturable absorber, which generated pulse with the shortest pulse width of 3.4 μs. Furthermore, SAMSAMNUN F S M, et al.[20] reported a EDFL using Alq_3 as the SA. The maximum pulse energy of 139 nJ and the shortest pulse width of 6.03 μs are realized.

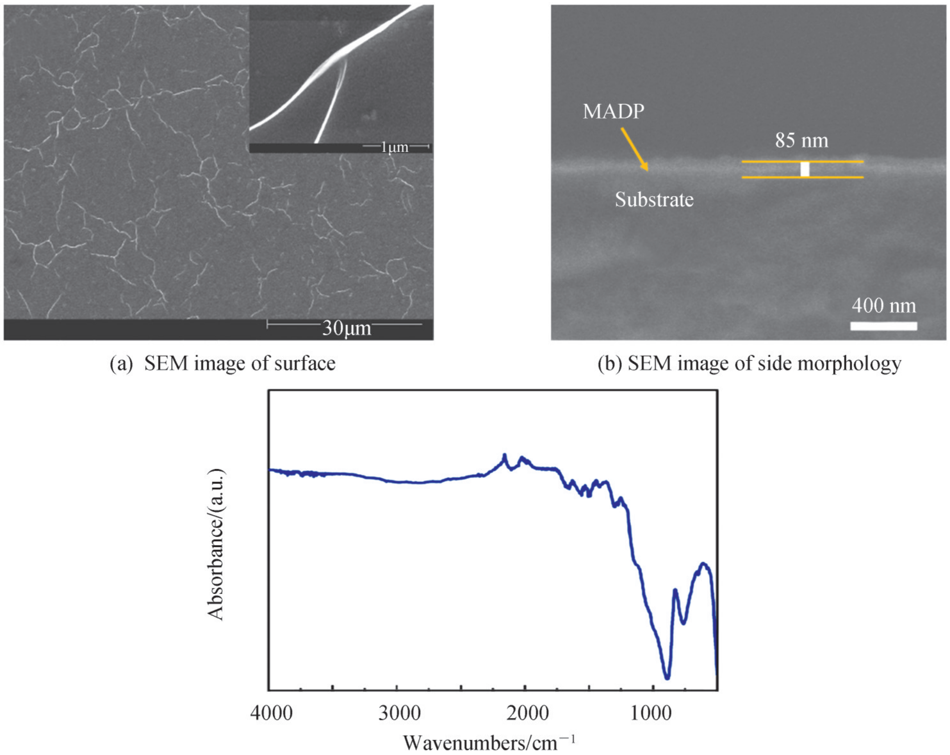
MADP is an organic conductive compound formed after chemical doping with acid. It exhibits excellent electrical conductivity and environmental stability. In addition, after strong light irradiation, MADP shows short response time and high nonlinear optical properties. Therefore it can be used as a SA in the laser for short pulse generation. This kind of short-pulse fiber laser is widely used in industrial cutting, material processing, laser spectroscopy and biomedicine[22, 23].

In this work, we demonstrated a Q-switched fiber laser at 1 560 nm based on MADP-SA at the first time. By inserting MADP into laser cavity, a stable Q-switched pulse with maximum output power of 3.6 mW and a minimum pulse width of 2.29 μs can be achieved, which corresponding to the maximum pulse energy of 54.64 nJ. The experimental results depicted that MADP can be considered as a good candidate for pulse laser generation in optoelectronic devices.

1 Preparation and characterization of MADP

MADP is an organic conductive compound formed by chemically doping acid, which exhibits excellent electrical conductivity, optical properties and environmental stability. Therefore, it is considered to be the most promising polymer material. The MADP film used in this experiment was prepared by chemical oxidation polymerization. The production method is relatively simple. At a constant temperature, the analysis of pure aniline is added to a certain amount of water. The acid was added while stirring to form aniline salt, and then poured into the acid solution of the oxidant. After the reaction lasted for half an hour, it is filtered, washed and dried several times to obtain a powdered eigenstate polyaniline. A certain amount of N-Methyl Pyrucketone (NMP) is then added to the powdered eigenstate polyaniline, dripping the formed dark blue ink liquid on the cover glass and spin coating at a speed of 5 000 r/min. Then the glass slides loaded with materials are stored in the vacuum drying box and exposed to malic acid vapor. Over time, the color of the film changes from dark blue to green and then transferred to deionized water to remove the MADP film from the cover glass. In this way, a MADP film is formed.

In order to understand the basic properties of the material, a corresponding characterization study was carried out. In this experiment, surface and side features of MADP films were obtained using Scanning Electron Microscopy (SEM). Therefore, the surface and side morphology details of the sample can be carefully observed. Fig.1 (a) and illustration have shown SEM images at different focusing multiples, respectively. From the figure, it can be observed that the MADP surface has lots of microscale folds, which represent irregularly shaped discrete particles uniformly distributed throughout the sample. Fig.1 (b) shows the side SEM image of the MADP, and the measured thickness of the film is about 85nm. Meanwhile, we further identify functional groups of the material membrane surface using Fourier Infrared Spectrum (FTIR), with the FTIR spectrum as shown in Fig.1 (c).



(a) SEM image of surface

(b) SEM image of side morphology

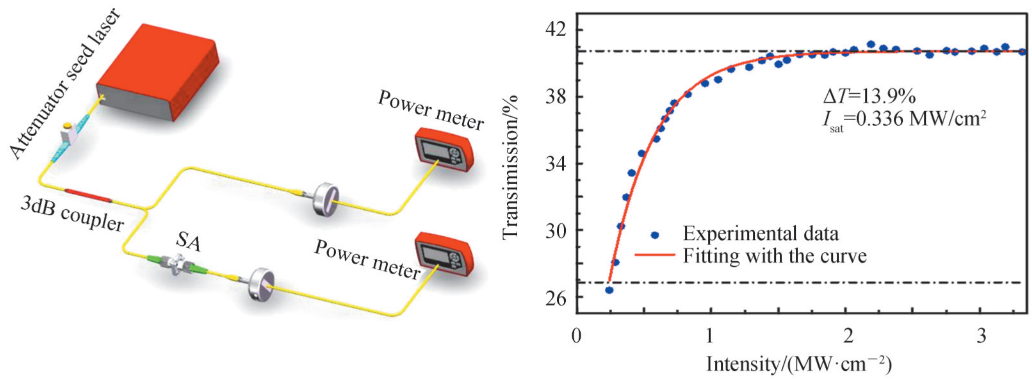
(c) FTIR spectra

Fig.1 SEM image and FTIR spectra of the MADP film

The saturable absorption properties, which indispensable characterize the optical properties of materials, is an important parameter for evaluating a SA[21]. As shown in Fig.2(a), based on the balanced twin-detector technique, we measure nonlinear transmission of SA. In the system, a stable homemade Er-doped Nonlinear Polarization Evolution (NPE) mode-locked fiber laser (repetition rate of 38 MHz, pulse duration of 3.6 ps, and center wavelength of 1 550 nm) worked as a pump source. The output pulse laser of the mode-locked laser was attenuated by Variable Optical Attenuator (VOA) and then was split by a 3 dB fiber coupler. One port of the coupler was a reference port and the other was a signal port. The output power was measured with two power meters. The measured experimental data and fitted result with the following formula

$$T(I) = 1 - \Delta T \times \exp\left(-I/I_{sat}\right) - A_{ns}$$

where T is transmission, ΔT is modulation depth, I is input intensity of the laser, I_{sat} is saturable power



(a) Experimental setup

(b) The transmission curve

Fig. 2 Experimental setup for measuring nonlinear absorption characteristics and the transmission curve of MADP-SA intensity and A_{ns} is non-saturable absorbance. Fig. 2(b) shows the result of the nonlinear saturable absorption characteristics of MADP-SA. the MADP-SA has the saturation intensity and modulation depth of 0.336 MW/cm^2 and 13.9%, corresponding to a non-saturable absorption loss of 58.7%, which were obtained by fitting the experimemtal results.

2 Experiment setup and results

2.1 Expriment setup

Taking advantage of the saturable absorption properties of MADP, we further constructed a passively Q-switched all-fiber Er-doped laser with the MADP as a SA. The experimental setup of the compact MADP SA based EDF fiber laser is depicted in Fig.3. As is shown, a 976 nm Laser Diode (LD) with the maximum output power of 600 mW was used as a pump source. The pump energy was injected into the oscillator via a 980/1550 Wave Division Multiplexer (WDM). A piece of 38 cm highly doped Er-doped fiber (Liekki Er-110-4/125) with a dispersion parameter of 12 ps^2/km was employed as the laser gain medium. A Polarization Controller (PC) was used to adjust the birefringence of fiber and change the polarization states of light for optimizing the Q-switched operation. A Polarization-Independent Isolator (PI-ISO) was used to guarantee unidirectional transmission in the ring cavity. And a Optical Coupler (OC) with output ratio of 10% was utilized to output the laser. The Maleic acid SA is deposited directly into two standard FC/PC fiber end face, and inserted into the EDFL cavity to generate short pulses. The total length of the cavity was about 6.4 m.

To measure the output states of laser in the intra-cavity. A real-time sampling oscilloscope (Tektronix DPO3052, 500 MHz, 2.5 GS/S, Shanghai, China) and a photodetector (Harmoniclaser UltraPD-1550, Yancheng, China) was employed to monitor the temporal evolution and output power of the output pulse train. Meanwhile, an optical spectrum analyser (HORIBA IHR550, Shanghai, China) with a resolution of 0.02 nm was utilized to record the optical spectrum.

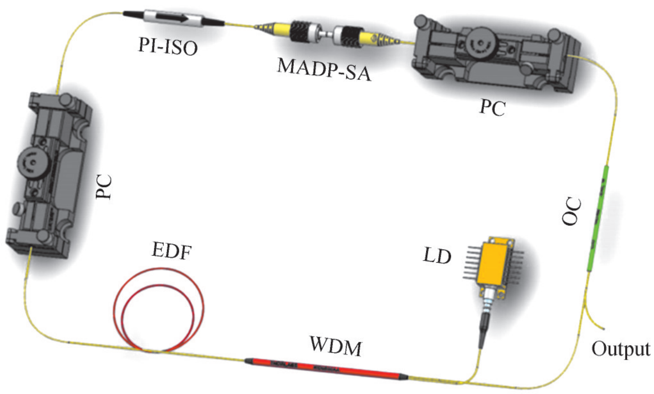


Fig. 3　Schematic of the all-fiber Q-switched EDF laser cavity

2.2 Results

In our experiment, through adjusting the PC cautiously, a stable Q-switched phenomenon emerges when pump power is increased to 160 mW. Fig. 4 shows a series of typically Q-switched pulse trains based on MADP SA at different pump power of 180 mW, 260 mW, 340 mW and 420 mW. It can been seen that as the pump power increases, the number of pulses in the laser cavity gradually increases and the pulse interval keeps getting smaller, which is a typical characteristic of the Q-switched fiber laser.

Fig. 5(a) presents the output power and single pulse energy change with the increase of pump power. When the pump power is adjusted from 160 mW to 440 mW, the output power increases from 0.95 mW to 3.6 mW and pulse energy from 28.12 nJ to 54.64 nJ. As the input pump power is further increased higher than 440 mW, the stability of Q-switched operation gradually deteriorates, which may be due to the oversaturation of the SA. However, a stable Q-switched operation can be still obtained by decreasing the pump power. Meanwhile, Fig. 5(b) shows the repetition rate and pulse width of the Q-switched EDFL are varied by increasing the pump power. As depicted, the repetition rate increases from 33.78 kHz to 87.01 kHz, while the corresponding single pulse width decreases from 4.19 μs to 2.29 μs. However, the output pulse width curve fluctuates when the pump power is higher than 400 mW. This phenomenon attributed to the uneven distribution of the material at the fiber core, which leads to thermal effects at higher powers. Therefore, to a certain extent, it has an impact on Q-switched operation.

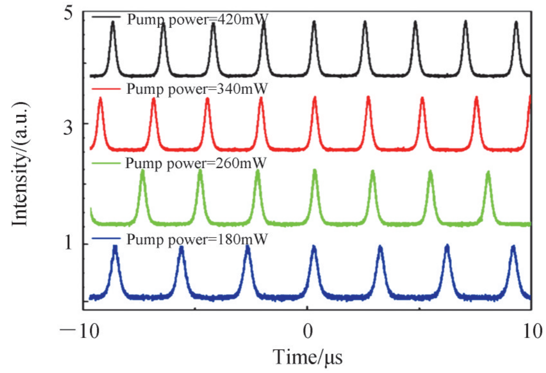


Fig. 4 Q-switched pulse trains under different pump power

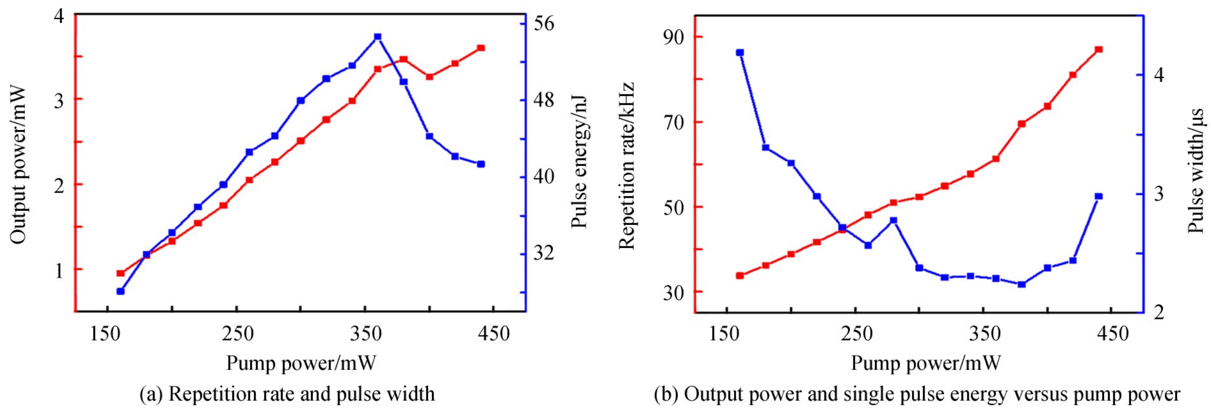


Fig. 5 Repetition rate and pulse width and output power and single pulse energy versus pump power of the Q-switched operation

Fig. 6(a) illustrates the minimum pulse width of 2.29 μs at the pump power of 380 mW. Fig. 6(b) depicted the measured optical spectrum of the laser output, whereas the center wavelength is 1 560.65 nm with a Full Width at Half-Maximum (FWHM) bandwidth of 5 nm.

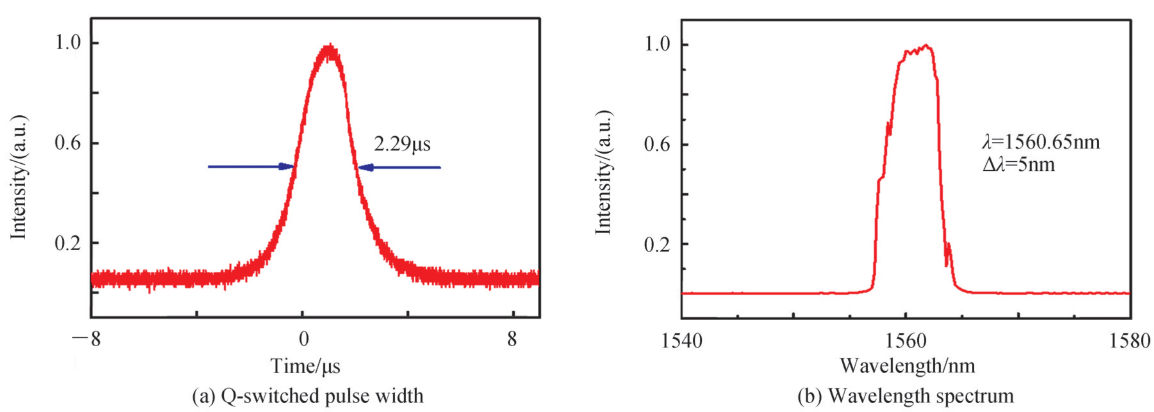


Fig. 6 The Q-switched pulse width and the wavelength spectrum of the Q-switched EDF laser at the pump power of 380 mW

We compare previously reported results with our work about Er-doped Q-switching fiber laser based on different organic materials. As Table 1 shows, our work have the shortest pulse width of 2.29 μs, but the pulse energy is lower than that of other results, which may be due to the thicker SA film.

Table 1 Comparison of this work with other reports using different organic materials

Year	WSA	Repetition rate/kHz	Min. pulse width/μs	Max. pulse energy/nJ	Wavelength/nm	Ref.
2019	FIrpic	33.22~87.4	3.4	122.6	1 560.4	[19]
2019	Alq_3	45.87~68.3	6.03	139	1 564.1	[20]
2020	MADP	33.78~87.01	2.29	54.64	1 560	This Work

3 Conclusion

In summary, a stable passively Q-switched Er-doped all-fiber laser has been demonstrated using the organic material as SA. The modulation depth and saturable intensity of the MADP-SA are 13.9% and 0.336 MW/cm^2. Based on the MADP-SA, Q-switched pulse exhibited the maximum pulse energy of 54.64 nJ and minimum pulse width of 2.29 μs at the pump power of 380 mW. To our best knowledge, this is the first report on a Q-switched Er-doped fiber laser based on MADP SA. We believe that it will have excellent application prospects in ultrafast photonics.

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