

## Research article

Bo Fu<sup>a</sup>, Pan Wang<sup>a</sup>, Yan Li, Marcello Condorelli, Enza Fazio, Jingxuan Sun, Lijun Xu, Vittorio Scardaci\* and Giuseppe Compagnini

# Passively Q-switched Yb-doped all-fiber laser based on Ag nanoplates as saturable absorber

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**Abstract:** We report on a Q-switched Yb-doped all-fiber laser based on a solution-processed Ag nanoplates saturable absorber. Optical deposition procedure is implemented to transfer the Ag nanoplates onto the fiber core area through the thermal effect. The saturable absorber is sandwiched between two fiber connectors, providing simplicity, flexibility, and easy integration into the laser oscillator. The modulation depth and saturation incident fluence are measured to be ~5.8% and ~106.36  $\mu\text{J}/\text{cm}^2$  at 1- $\mu\text{m}$  region,

<sup>a</sup>**Bo Fu and Pan Wang:** These authors contributed equally to this work.

**\*Corresponding author: Vittorio Scardaci**, Dipartimento di Scienze Chimiche, Università degli Studi di Catania, V.le A. Doria 6, 95125 Catania, Italy, e-mail: vittorio.scardaci@unict.it.

<https://orcid.org/0000-0003-0167-4368>

**Bo Fu:** BUAA-CCMU Advanced Innovation Center for Big Data-Based Precision Medicine, Interdisciplinary Innovation Institute of Medicine and Engineering, Beijing 100191, P.R. China; and Key Laboratory of Big Data-Based Precision Medicine, Ministry of Industry and Information Technology, School of Medicine and Engineering, Beihang University, Beijing 100191, P.R. China. <https://orcid.org/0000-0003-1409-2666>

**Pan Wang:** State key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments, Tsinghua University, Beijing 100084, P.R. China; and Current address: Max Planck Institute for the Science of Light, Staudtstr. 2, 91058, Erlangen, Germany

**Yan Li:** School of Optoelectronic Engineering, Guangdong Polytechnic Normal University, Guangzhou 510665, P.R. China

**Marcello Condorelli and Giuseppe Compagnini:** Dipartimento di Scienze Chimiche, Università degli Studi di Catania, V.le A. Doria 6, 95125 Catania, Italy. <https://orcid.org/0000-0001-8077-9373> (M. Condorelli)

**Enza Fazio:** Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università di Messina, Messina, Italy

**Jingxuan Sun:** School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing 100191, P.R. China

**Lijun Xu:** BUAA-CCMU Advanced Innovation Center for Big Data-Based Precision Medicine, Interdisciplinary Innovation Institute of Medicine and Engineering, Beijing 100191, P.R. China; and School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing 100191, P.R. China

respectively. Self-started stable Q-switched operation is achieved for a threshold pump power of 180 mW. The repetition rates of the pulse trains range from 66.6 to 184.8 kHz when the pump power scales from 210 to 600 mW. The maximum average output power is 10.77 mW, corresponding to the single-pulse energy of 58.3 nJ and minimum pulse duration of ~1.01  $\mu\text{s}$ . To the best of our knowledge, it is the first time that the Ag nanoplates saturable absorbers are utilized in the 1- $\mu\text{m}$  Yb-doped Q-switched fiber laser.

**Keywords:** Ag nanoplates; saturable absorber; fiber laser; Q-switched.

## 1 Introduction

Q-switched laser sources have attracted considerable attention during the past decades due to the versatile applications in widespread industry and scientific research areas, such as laser materials processing, remote sensing, range finding, medicine, telecommunications, and nonlinear optics [1–5]. In Q-switched mechanism, the Q-factor of the cavity is modulated to iteratively induce excited population buildup and abrupt photon emission [6]. The Q-switched laser sources are mainly generating short pulses with pulse duration of micro-second or nano-second level and low repetition rate of kHz. In contrast with the active Q-switched lasers, where costly, complex, and bulky external devices like acoustic- or electro-optic modulators are utilized in the cavity, passively Q-switched lasers with saturable absorbers (SAs) possess the attractive advantages of compactness, simplicity, and flexibility of implementation [7]. In recent years, the investigation of novel high-performance SAs for pulsed laser systems has been a rich and fascinating subject in the field of fiber laser physics, leading to an outburst of publications realized with Q-switched and mode-locked fiber lasers. To date, numerous nanomaterials have been demonstrated as efficient saturable absorption materials for SAs in Q-switched fiber lasers, such as carbon nanotubes [8–10], graphene [11–14], transition-metal dichalcogenides [15–18], topological insulators [19–21], black phosphorus

[22–24], quantum dots [25, 26], MXenes [27], filled skutterudites [28], and transition metal oxides [29–31].

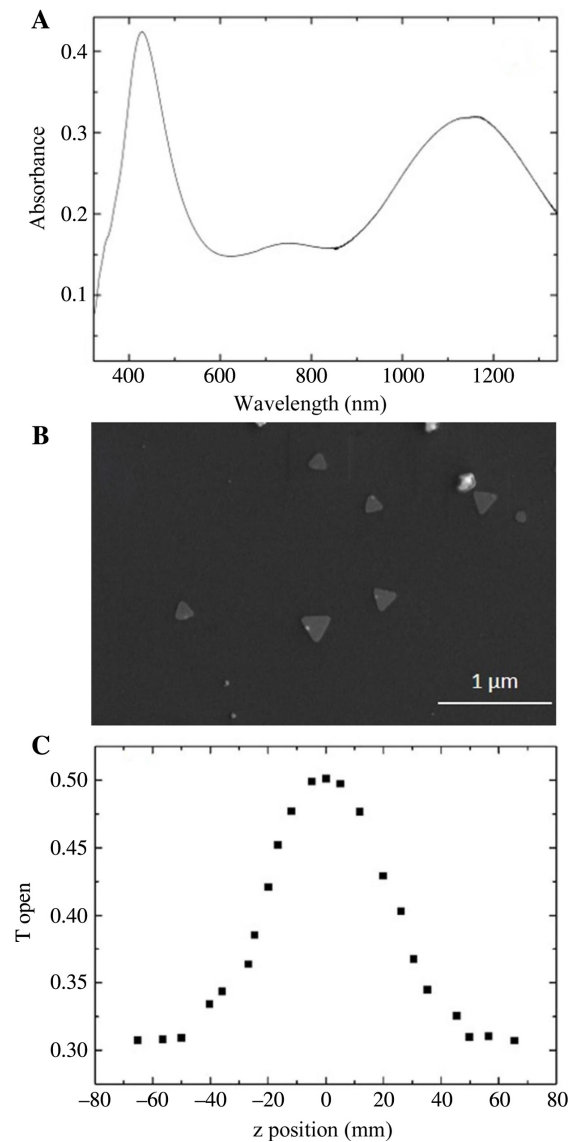
Most recently, metal nanoparticles, e.g. gold (Au), silver (Ag), and copper (Cu), have attracted increasing attention due to their distinctively optical and physical properties such as broadband surface plasmon resonance, ultrafast response time, and large third-order nonlinearity [32–35]. The outstanding properties of the metal nanoparticles have been promoting the interesting applications in the areas of optics, medicine, and spectroscopy [36–41]. It is worthy to note that metal nanoparticles have exhibited great potential in the application of ultrafast fiber lasers as SAs for Q-switched and mode-locked pulse generation [42–50]. Up to now, most metal nanoparticles-based SAs researches focus on Au nanoparticles as SAs for achieving Q-switching or mode-locking, implemented in the major fiber lasers (i.e. Yb-, Er-, and Tm-doped fiber lasers) [42–46]. On the other hand, the Ag nanoparticles possess the properties of the highest electrical and thermal conductivities among metal materials, as well as large and ultrafast third-order optical nonlinearities [34, 35, 41], indicating the high potential as SAs in pulsed fiber lasers. Moreover, compared to other materials used as SAs [51–60], Ag nanoparticles are easy to fabricate with no need of purification, and particle size can be controlled. However, despite a few works reported on Ag nanoparticles as SAs for Q-switched pulses generation at 1.5- and 2- $\mu\text{m}$  bands [48–50], the investigation of Ag nanoparticles is still insufficient to date, with no experimental report of Q-switched operation at the 1- $\mu\text{m}$  Yb-doped fiber laser (YDFL). It would be interesting to give more insight into the application of Ag nanoparticles material for SA in the field of ultrafast fiber laser. Plasmon resonance in metal nanoparticles depends on their shape and size. Spherical Ag nanoparticles have their plasmon resonance around 400 nm [61]. Because saturable absorption is a resonant phenomenon, a shape change is needed to red-shift the plasmon resonance to the near infrared (IR) [61].

In this paper, we report on the optical characterization of solution-processed Ag nanoplates and demonstrate their use as SA in YDFL operating at 1- $\mu\text{m}$  band. Stable Q-switched operation is realized, generating the pulse trains with repetition rates ranging from 66.6 to 184.8 kHz when the pump power scales from 210 to 600 mW. To the best of our knowledge, it is the first time that the Ag nanoparticles SA is utilized in the 1- $\mu\text{m}$  Yb-doped Q-switched fiber laser.

## 2 Fabrication and characterization of Ag nanoplates SA

The Ag nanoplates are fabricated in two steps. Spherical Ag nanoparticles are firstly obtained by chemical reduction

of  $\text{AgNO}_3$  by  $\text{NaBH}_4$ , in the presence of trisodium citrate as stabilizing agent, and secondly converted into flat triangular nanoplates by hydrazine and citrate. The Ag nanoplates feature a plasmon resonance that can be widely tuned across the visible and near-IR range, by simply varying the amount of spherical Ag nanoparticles subjected to transformation into the nanoplates [61]. Figure 1 shows characterization of our Ag nanoplate solution by absorption spectroscopy, scanning electron microscopy (SEM), and open aperture z-scan. Such solution shows a broad plasmon resonance in the 1100–1200 nm region and nanoplate size around 150 nm. Z-scan experiments show transmittance increase from 30% to 50% thus confirming a strong saturable absorption effect. All reagents were sourced from Sigma-Aldrich, Milan, Italy.

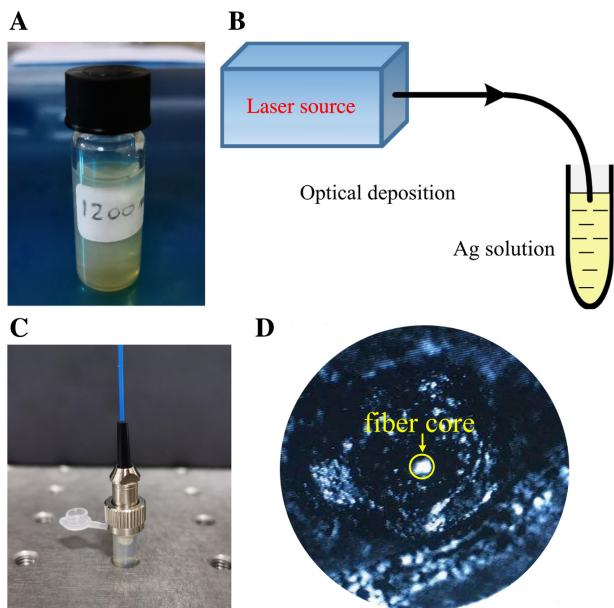


**Figure 1:** Characterization of the Ag nanoplates solution. (A) Absorption spectrum; (B) SEM image of nanoplates deposited on Si substrate; (C) open aperture Z-scan data.

The Ag nanoplates are deposited on the facet of an optical fiber connector by the extensively reported laser-induced deposition method [48, 62]. As depicted in Figure 2B, the optical deposition procedure is implemented by dipping the distal end of the standard single-mode fiber connector into the solution, under the irradiation of 60 mW continuous wave laser for 30 min, which is generated by a 1550 nm laser source (Santec MLS-8100). As shown in Figure 2D, the Ag nanoplates are deposited by thermal effect and attached to the fiber core area, enabling the interaction with the light propagating in the fiber. Finally, the Ag nanoplates SA is self-assembled by fixation of the two fiber connectors, as illustrated in Figure 3.

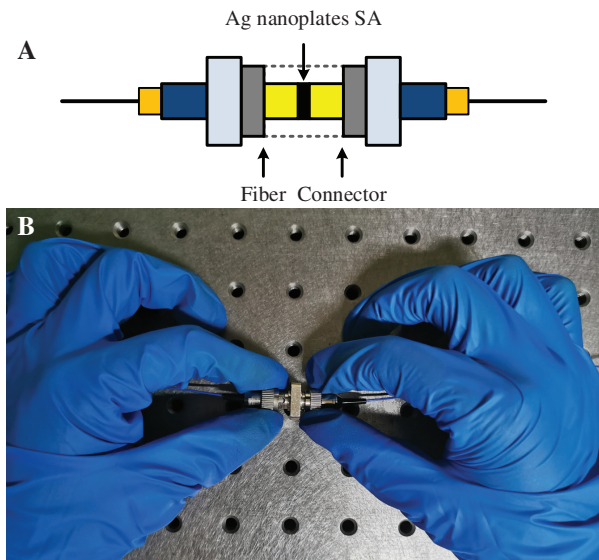
The nonlinear saturable absorption property of the Ag nanoplates SA is investigated by measuring the power-dependent transmission based on a twin-detector measurement technique [63].

The experiment is implemented with a home-made 1- $\mu\text{m}$  mode-locked fiber laser source, depicted in Figure 4. An Yb-doped dissipative soliton oscillator serves as the seed laser, and the nonlinear polarization rotation technique is utilized for mode-locking, generating pulse train with repetition rate of 64.2 MHz and pulse duration of  $\sim 4.2$  ps. After amplification by a two-stage Yb-doped fiber amplifier (YDFA) and compression by a pair of gratings

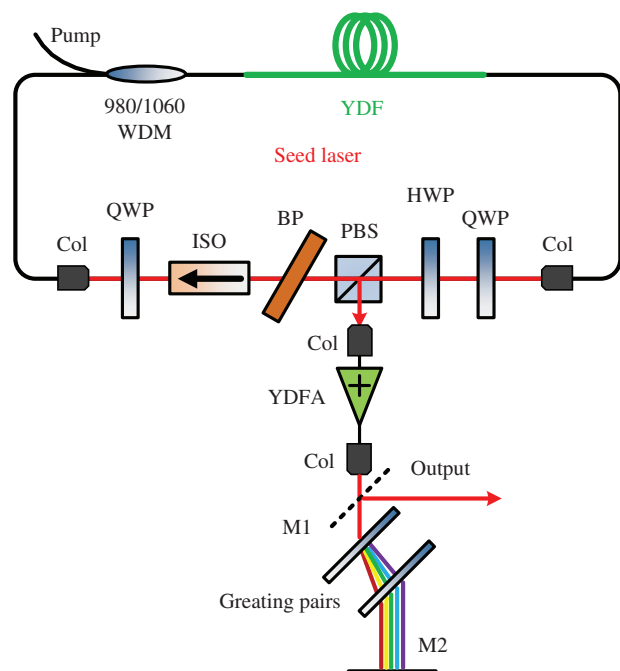


**Figure 2:** Optical deposition of Ag nanoplates.

(A) The solution with  $\sim 150$  nm wide Ag nanoplates prepared, resulting in a plasmon resonance at  $\sim 1200$  nm; (B) scheme of laser-induced deposition method; (C) image of optical deposition to induce the Ag nanoplates to fiber facet; (D) fiber facet with Ag nanoplates after optical deposition.



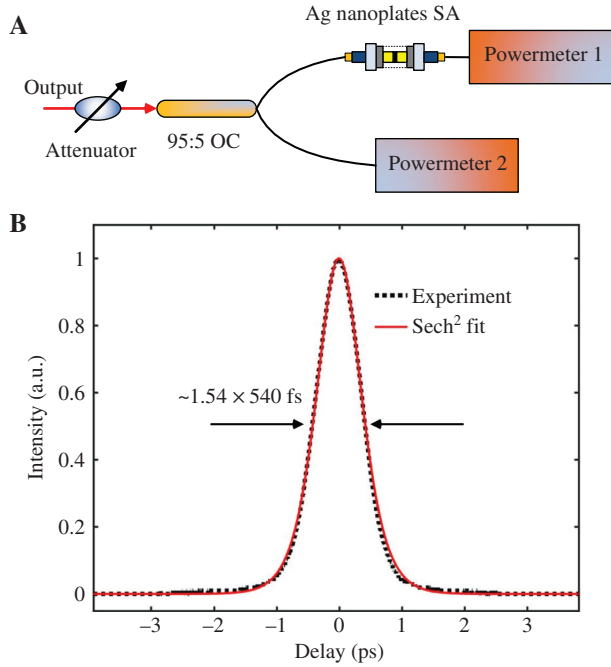
**Figure 3:** Self-assembly conducted Ag nanoplates SA.



**Figure 4:** Home-made 1- $\mu\text{m}$  mode-locked fiber laser for the measurement of nonlinear saturable absorption property of the Ag nanoplates SA.

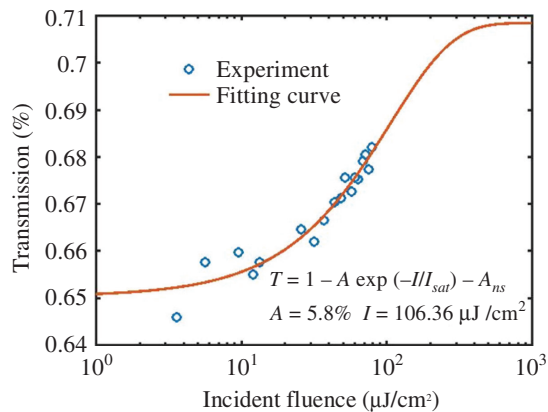
Col, collimator; WDM, wavelength division multiplexer; YDF, Yb-doped fiber; HWP, half wave plate; QWP, quarter wave plate; PBS, polarization beam splitter; BP, birefringent plate; YDFA, Yb-doped fiber amplifier; ISO, isolator; M, mirror.

with 1000 lines/mm, the average output power of the pulse train is scaled beyond 300 mW, with pulse duration of  $\sim 540$  fs, shown in Figure 5B.



**Figure 5:** Experimental setup for the measurement of nonlinear saturable absorption property. (A) Schematic experimental setup for measurement of the nonlinear saturable absorption property of the Ag nanoplates SA. (B) Optical autocorrelation trace of the pulse train for the measurement.

The configuration to characterize the nonlinear saturable absorption property is schematically shown in Figure 5A. The output of the home-made 1- $\mu\text{m}$  mode-locked fiber laser source is modulated by a variable optical attenuator and divided by a 95:5 optical coupler. Ninety-five percent of the power passes through the Ag nanoplates SA and is measured by a power meter, while the other 5% is monitored by another reference power meter. The nonlinear transmittance of the Ag nanoplates SA is shown in Figure 6, as a function of the incident fluence. Fitted with



**Figure 6:** Nonlinear transmittance as a function of incident fluence.

the saturable absorption formula [27], the saturation incident fluence and the modulation depth are estimated to be  $\sim 106.36 \mu\text{J}/\text{cm}^2$  and  $\sim 5.8\%$ , respectively.

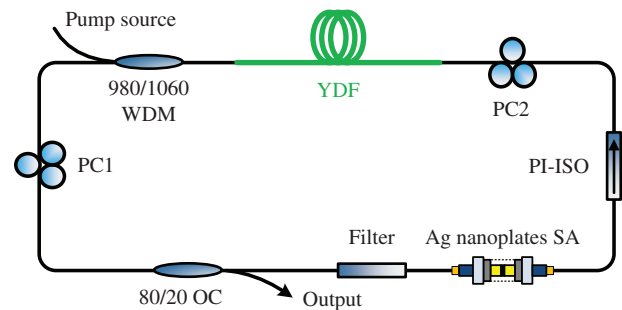
### 3 Experimental setup and results

The schematic construction of the Q-switched YDFL is illustrated in Figure 7. A piece of  $\sim 1.8 \text{ m}$  moderately Yb-doped fiber (YDF, Nufern SM-YSF-LO, 80 dB/km core absorption at 980 nm, the dispersion is  $-37 \text{ ps}/\text{nm}/\text{km}$  at 1060 nm) serves as the gain medium and is backward pumped by a 980 nm laser diode through a 980/1060 nm wavelength division multiplexer (WDM). A polarization-insensitive isolator (PI-ISO) is utilized to provide unidirectional operation. Two polarization controllers (PCs), as well as an 8-nm band pass filter centered at 1030 nm, are employed to optimize the Q-switching pulse operation. The rest of the cavity is composed of  $\sim 17.7 \text{ m}$  standard single-mode fibers, yielding a total cavity length of  $\sim 19.5 \text{ m}$ . A 20/80 optical coupler is used to extract 20% of the generated laser for measurement.

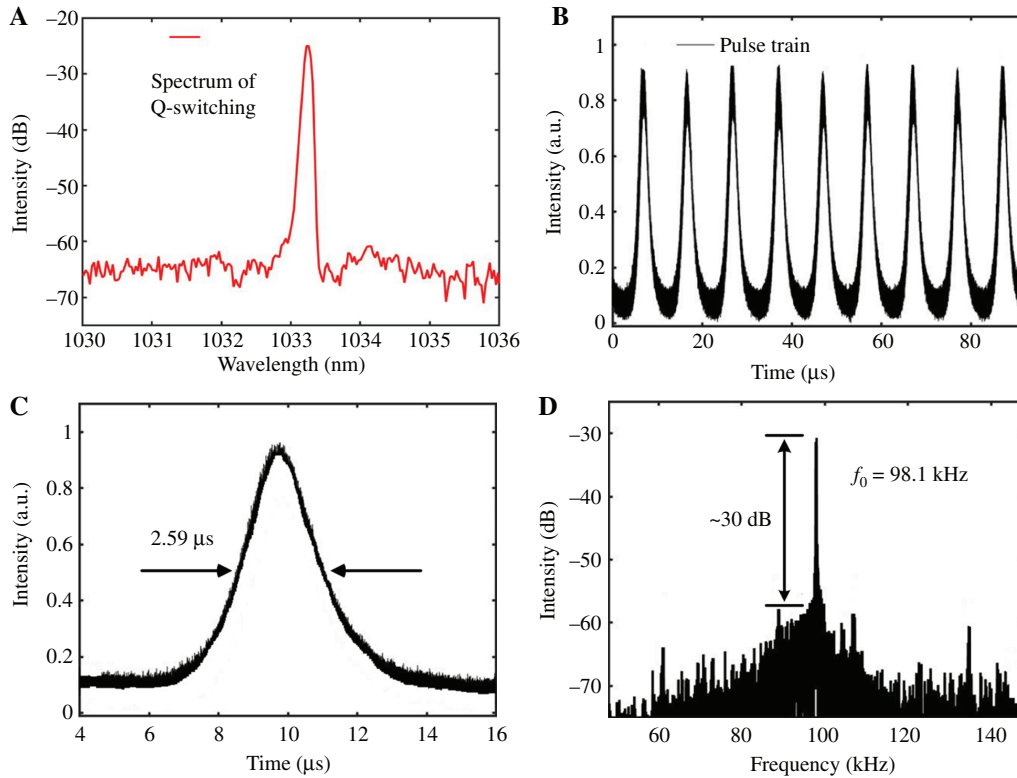
The output is monitored by an optical spectrum analyzer (Agilent 86142B) with 0.06-nm resolution, a 1-GHz photodetector recorded by a 2-GHz oscilloscope (Agilent Infiniium DSO80204B), and a radio frequency (RF) signal analyzer (Agilent N9020A).

In our experiment, continuous wave lasing is obtained at the pump power of 130 mW. With appropriate PC settings, stable passive Q-switching is self-started by further increasing the pump power to a certain threshold value of 180 mW.

Figure 8 shows the typical Q-switching characteristics of the YDFL at the pump power of 300 mW. As shown in Figure 8A, the central wavelength of the Q-switched



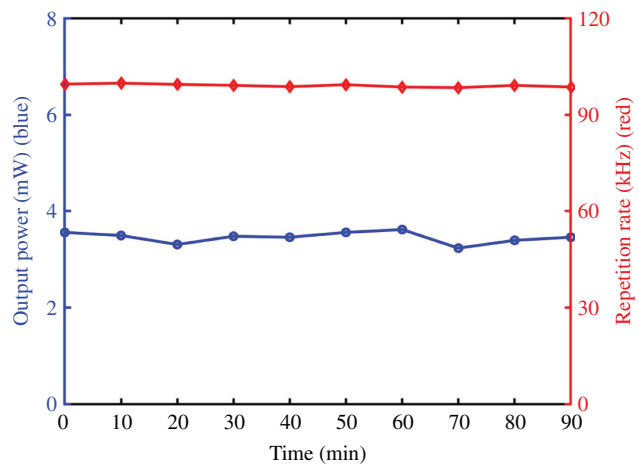
**Figure 7:** Scheme of the Q-switched Yb-doped fiber laser. WDM, wavelength division multiplexer; YDF, Yb-doped fiber; PC, polarization controller; PI-ISO, polarization-insensitive isolator; Filter, 1- $\mu\text{m}$  band pass filter; OC, optical coupler.



**Figure 8:** Stable Q-switched operation at the pump power of 300 mW. (A) Optical spectrum; (B) temporal sequences of output pulse recordings; (C) single-pulse profile of the Q-switched pulse train; (D) RF spectrum over a 100 kHz span with resolution bandwidth of 10 Hz.

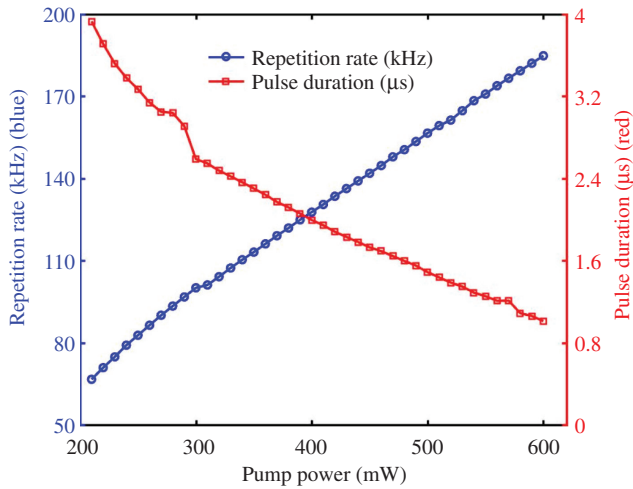
operation locates around 1033.3 nm with 3-dB spectral bandwidth of 0.24 nm. Figure 8B shows the temporal waveform of the pulse train on the oscillator, with a 10.19- $\mu$ s period. The single-pulse profile of the Q-switched pulse train is presented in Figure 8C in a symmetrical Gaussian-like shape. The full width at half-maximum of the pulse profile is measured to be  $\sim 2.59$   $\mu$ s, which is the typical time scale of Q-switched operation. The RF spectrum is also measured (Figure 8D) with a repetition rate of 98.1 kHz and more than 30-dB signal-to-noise ratio, confirming relatively stable operation. The long-term stability is also investigated by measuring the output power as well as the repetition rate as a function of time for hours as shown in Figure 9, indicating the stable operation of the laser.

The pulse repetition rate, pulse duration, output power, and pulse energy versus the pump power are further measured, as shown in Figures 10 and 11. In contrast with the repetition rate of mode-locked operation, which is determined by the cavity length, the repetition rate of Q-switched pulses is dependent on the pump power. Attributed to the dependence of Q-switched pulse generation on the saturation of the SA, higher pump

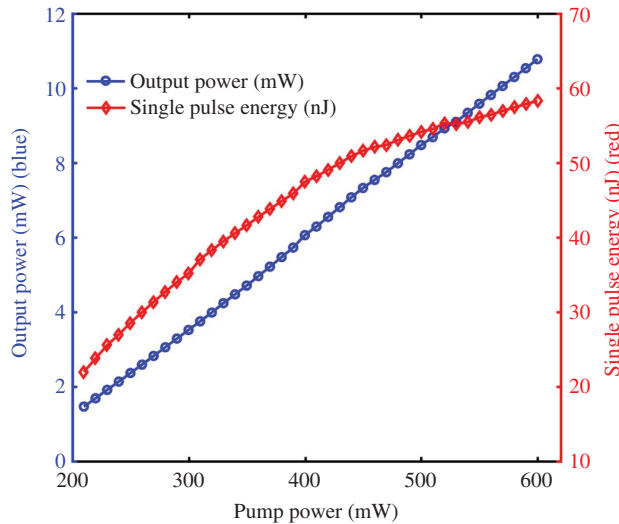


**Figure 9:** Measurements of output power and pulse repetition rate for long-term stability.

power provides much more gain to saturate the SA within a shorter time, which leads to faster bleaching of the Ag nanoplates SA, resulting in the increase of the repetition rate. As shown in Figure 10, in our experiment, the pulse repetition rate of the Q-switched operation increases



**Figure 10:** Pulse repetition rate and pulse duration versus the pump power.



**Figure 11:** Output power and single-pulse energy vary with the increasing pump power.

monotonically with the increase of the pump power. The pulse repetition rate changes from 66.6 to 184.8 kHz, and the pulse duration decreases from  $\sim 3.93$  to  $\sim 1.01$   $\mu\text{s}$ , when the pump power scales from 210 to 600 mW.

The output power and single-pulse energy as a function of pump power are presented in Figure 11. By increasing the pump power from 210 to 600 mW, the output power varies from 1.46 to 10.77 mW, and the single-pulse energy changes from 21.9 to 58.3 nJ. At the pump power of 600 mW, the maximum average output power is 10.77 mW for 184.8 kHz repetition rate, corresponding to the single-pulse energy of 58.3 nJ. The maximum average output power of the pulse train is limited by the pump source in our experiments. The stability of the laser and the

maximum pulse energy can be further improved by optimizing the design of the Ag nanoplates SA as well as the structure of the laser cavity.

## 4 Conclusions

We experimentally investigate Ag nanoplates as SA for Q-switched pulse generation in YDFL. The stable self-started Q-switched operation is achieved for a threshold pump power of 180 mW. The pulse train repetition rate increases with the increase of the pump power. At the maximum pump power of 600 mW, the maximum repetition rate and average output power are 184.8 kHz and 10.77 mW, respectively, corresponding to single-pulse energy of 58.3 nJ. To the best of our knowledge, it is the first demonstration of the passively Q-switched fiber laser by using Ag nanoparticles at the wavelength of 1- $\mu\text{m}$  region. Our results demonstrate the flexibility of the solution-processed Ag nanoplates as SAs, making it a promising candidate for achieving a variety of stable and low-cost ultrafast lasers.

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