Q-switched Fiber Laser with Silver Nanoparticles-PVA in an Erbium-based Ring Configuration

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Abstract

This study examines the fabrication and experimental setup of a Q-switched fiber laser using a silver nanoparticle-polyvinyl alcohol (AgNPs-PVA) thin film as a saturable absorber. The thin film was produced by combining 5 mg of silver nanoparticles with 50 mg of polyvinyl alcohol in ionized water, followed by molding and drying. The laser showed a clear peak at 1560 nm, indicating precise output adjustment, with a slope efficiency of 9.69%. Pump power ranged from 49.06 to 81.37 mW, resulting in output power between 4.27 and 7.4 mW and pulse energy increasing from 100 nJ to 136.68 nJ. An optical-signal-to-noise ratio (OSNR) of 75.16 dB and a stable RF spectrum demonstrated strong laser stability. This work's competitive performance, ease of fabrication, and promising results suggest that the AgNPs-PVA thin film is a viable candidate for Q-switched fiber lasers, advancing laser technology.

Keywords

Fiber Laser, Q-switch, Silver Nanoparticles, Saturable Absorber, Ring Configuration

Introduction

The Q-switching serves as a pivotal method utilized in fiber lasers to produce high-intensity, short-duration pulses of laser light, offering precise control over pulse durations and enabling the generation of high peak powers as stated by (Otupiri, 2020). This technique is indispensable across diverse fields including science, technology, and industry. Through the modulation of optical losses within the laser cavity, Q-switching facilitates the gradual accumulation of energy over a defined period, swiftly followed by its rapid release in a concentrated burst. This process yields pulse durations spanning from microseconds to nanoseconds (Guo, Zhang, & He, 2021). In Q-switched fiber lasers, a Q-switch element is introduced into the laser cavity to control the buildup

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of energy and the timing of pulse release. Common Q-switching mechanisms include acousto-optic, electro-optic, and saturable absorber devices (Chizhikov et al., 2022). These elements selectively block or allow the passage of light within the cavity, effectively controlling the population inversion necessary for laser emission. Consequently, Q-switched fiber lasers can achieve high peak powers and pulse energies, making them ideal for applications such as laser material processing, telecommunications, lidar systems, medical diagnostics, and nonlinear optics (Li et al., 2023).

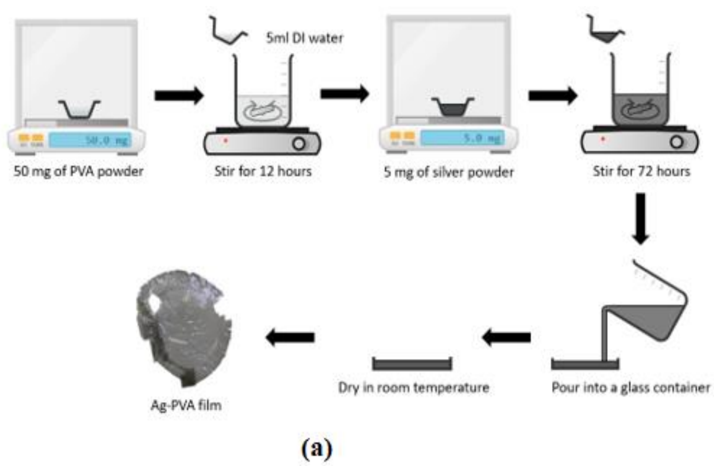
However, despite its effectiveness in generating short and intense pulses, Q-switching in fiber lasers presents challenges (Wang et al., 2020). These include achieving stable and reliable pulse generation, optimizing pulse parameters, and minimizing detrimental effects such as mode instabilities and spectral broadening. Therefore, researchers are actively engaged in addressing the challenges of Q-switching in fiber lasers through innovative approaches and advanced technologies. This includes exploring novel materials for saturable absorbers, gain mediums, refining laser configuration designs, and optimizing laser parameters for improved stability and performance (Markom et al., 2022).

Additionally, advancements in nanotechnology offer promising avenues for developing more efficient and reliable Q-switched fiber lasers. 2D nano-based saturable absorbers harness the unique properties of two-dimensional materials, such as graphene, transition metal dichalcogenides, transition metal carbides, black phosphorus, hexagonal boron nitride, and MXenes to control laser pulses in ultrafast laser systems (Ghafar et al., 2023). These atomically thin materials offer exceptional nonlinear optical properties, enabling precise modulation of intra-cavity losses for passive Q-switching and mode-locking operations. Moreover, silver nanoparticles (AgNPs) are garnering increasing attention as versatile components in fiber laser systems. AgNPs have distinctive optical characteristics such as localized surface plasmon resonance (LSPR) and powerful nonlinear effects, making them highly promising for improving laser performance (Mahmudin, 2024; Mohamed, 2022). When integrated into fiber laser cavities, AgNPs can modulate the optical properties, allowing for precise control over pulse generation, dispersion management, and mode-locking mechanisms.

Methodology

The AgNPs-PVA thin film Sa using the sol-gel method depicted in figure 1(a), precisely measure 50 mg of PVA powder using a digital weighing device and place it in a beaker. The beaker was positioned on a hot plate and the mixture was stirred gently for 12 hours at room temperature with a stirring rate of 650 rpm using a CORNING PC400D hot plate. While stirring, 5 mL of deionized (DI) water was slowly introduced to the PVA powder. Subsequently, 5 mg of silver nanoparticle powder was accurately measured and introduced into the PVA solution in the beaker. The liquid was agitated for 72 hours at 350 rpm employing a magnetic stirrer until full dissolution occurred. A thin film of AgNPs-PVA composite was created by mixing 2.5 mL of the silver solution with 2.5 mL of the PVA solution. The mixture was mixed completely until it was uniform. The solution-filled mold was allowed to air dry for over 48 hours at room temperature.

To evaluate the effectiveness of the AgNPs-PVA film in a fiber laser, an all-fiber ring setup was assembled, as depicted in Figure 1(b). Central to this setup was the placement of the AgNPs-PVA film between two fiber ferrules with a diameter of 1mmx1mm for the thin film. An erbium-doped fiber (EDF) measuring 1.8 meters served as the active laser medium. The EDF has a numerical apertura of 0.23 at the pumping wavelength of 980 nm, with a core/cladding diameter of 4 µm/125 µm. Connection between the EDF and the pump input of a 980 nm diode laser was established using a 980/1550 nm wavelength-division multiplexer (WDM). At the opposite end of the EDF, an optical isolator is connected to ensure the unidirectional propagation of laser oscillation within the ring laser setup. To separate 20% of the q-switching pulses from the laser setup, an 80:20 optical coupler was employed, allowing the remaining 80% to continue oscillating within the ring resonator. A combination of an electrical spectrum analyzer, digital oscilloscope, and rapid photodetector (PD) facilitated the study of the q-switching signal's properties in both the frequency and temporal domains. The laser's optical spectrum was analyzed using an optical spectrum analyzer (OSA) with a resolution of 0.02 nm. Pulse width assessment was conducted using an autocorrelator connected to a photodetector. The total length of the configuration measures approximately 9.8 meters.



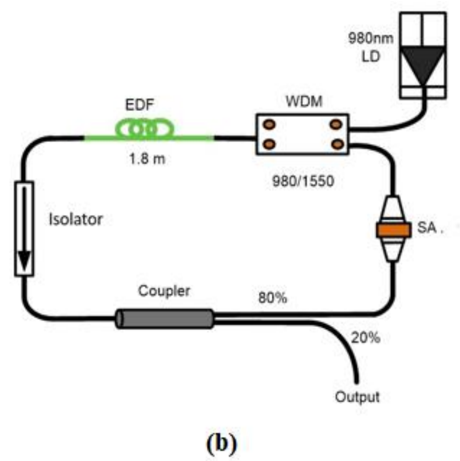


Figure 1. (a) Fabrication of the AgNPs-PVA SA (b) Experiment configuration.

Results and Discussion

The spectrum for the q-switching fiber laser acquired by using an OSA after integrating the AgNPs-PVA SA into the core of fiber ferrules is displayed in Figure 2 (a). The analysis was performed in ideal conditions, using a maximum pump power of 220 mA generated by a laser diode that provided 81.37 mW. The spectral graph displays a clear peak in the pulse, which is recorded at an output power of 0 dBm. This peak is specifically detected at a wavelength of 1560 nm. The analysis presented in Figure 2(b) illustrates an investigation into the correlation between pump power and output characteristics concerning the AgNPs-PVA SA within the laser system. The experimental setup involved varying the pump power within the range of 49.06 to 81.37 mW, resulting in an output power ranging from 4.27 to 7.4 mW. The optical damage threshold depends on the maximum pump power of 81.37 mW used in the study. Beyond this power level, the pulse disappears. Concurrently, pulse energy increased from 100 nJ to a maximum of 136.68 nJ across this pump power range, demonstrating a direct relationship between input pump power and resulting output power and pulse energy. The calculated slope efficiency, obtained from the linear relationship between input and output powers, was determined to be 9.69%.

Figure 2(c) illustrates the correlation between pump power and the repetition rate and pulse width of the laser system. As the pump power rises, both the repetition rate and pulse width of the generated pulses increase accordingly. Within this range, an escalation in pump power results in an improved repetition rate, ranging from 40.65 to 54.14 kHz. Simultaneously, the pulse width expands from 3.6 to 4.7 µs across the same range of pump powers. This interdependence highlights how the pump power directly affects the temporal characteristics of the laser output. Meanwhile figure 2(d) shows the radio frequency (RF) spectrum obtained from RF analyzer with 1 MHz span of frequency. The optical-signal-to-noise (OSNR) is 75.16 dB, displayed a very strong stability in the laser setup. Finally, figure 3 displays the pulse train of the q-switching process under different conditions: (a) when the pump power is 49.06 mW with a pulse interval of 24.8 microseconds, and (b) when the pump power is 81.37 mW with a pulse interval of 118.5 microseconds. The repetition rate ranges from 40.65 kHz to 54.14 kHz, while the pulse width ranges from 4.66 microseconds to 3.63 microseconds.

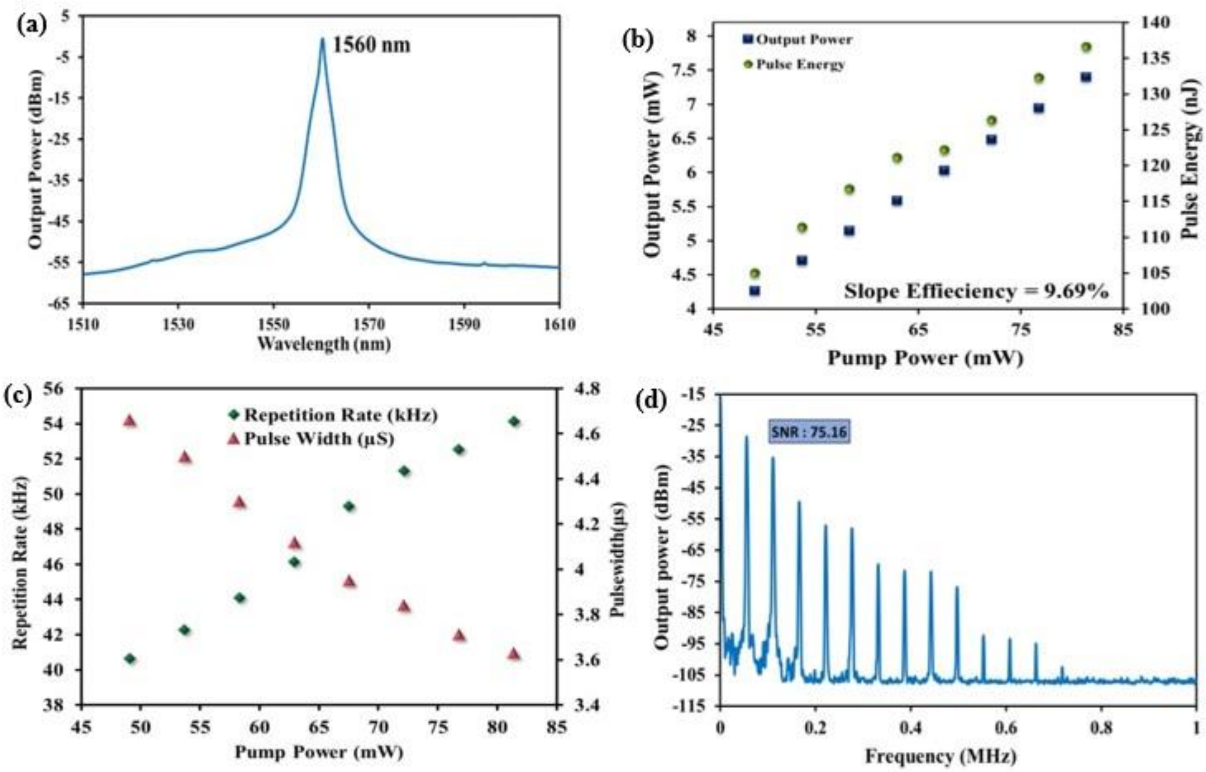


Figure 2. The output. (a) Optical spectrum (b) Pump power against to output power and pulse energy (c) Repetition rate with pulse width (d) RF spectrum.

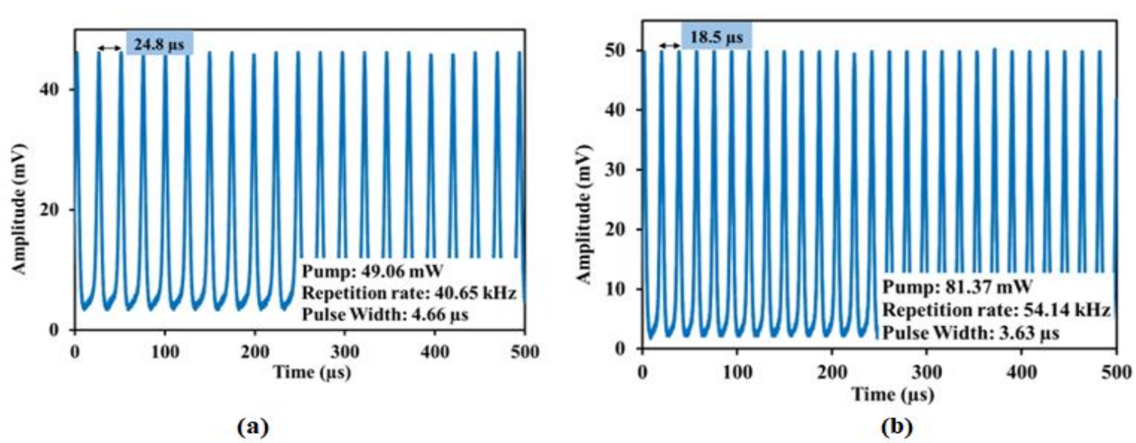


Figure 3. Oscilloscope pulse train at pump power of (a) 49.06 mW (b) 81.37 mW.

In conclusion, this study successfully fabricated and implemented a Q-switched fiber laser using an AgNPs-PVA thin film as a saturable absorber in a ring configuration. The laser's output characteristics, including maximum pump power, pulse energy, repetition rate, and pulse width, demonstrated competitive performance. The erbium-doped fiber in the ring configuration facilitated efficient energy transfer and amplification, enhancing overall laser performance.

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