

Research Article

Self-Q-switched Yb³⁺-doped All-fiber Laser Based on the Saturable Absorption Effect of a Multimode Fiber

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Abstract

A self-Q-switched Yb³⁺-doped all-fiber laser based on the saturable absorption effect in multimode communication fiber was investigated. The laser used an 11m long Yb³⁺-doped double-clad fiber as the gain medium. The high-reflection end of the resonator employed a fiber Bragg grating with a center wavelength of 1083nm, while the output end was the cleaved end-face of the gain fiber. A segment of multimode communication fiber was spliced to the output end of the resonator to act as a saturable absorber, enabling self-Q-switched pulse operation. Under a pump power of 5.3W, the laser achieved stable self-Q-switched pulse operation with a repetition rate of 46kHz, a single pulse energy of 13μJ, and a pulse width of 2.8μs. The influence of the multimode fiber length on the output pulse characteristics was also studied. It was found that optimal Q-switching performance was obtained with a 3.3m long multimode fiber. Meanwhile, the experiment employed custom-built air-cooling and thermo-electric cooler systems to independently control the temperatures of the two diode lasers, with both systems achieving a temperature control precision of ±0.1 °C. Furthermore, a qualitative analysis was conducted to investigate the mechanism of self-Q-switched pulse generation utilizing the saturable absorption effect in multimode fiber. This self-Q-switched all-fiber laser features a simple structure, low cost, and high stability, showing promising application prospects in scientific research, material processing, and lidar.

Keywords

All-fiber Laser, Saturable Absorption, Self-Q-switching, Yb³⁺-doped Fiber, Multimode Fiber

1. Introduction

Q-switched fiber lasers serve as a crucial technology for generating high-pulse-energy laser output, meeting extensive application demands across industrial processing, lidar, medical diagnostics, and scientific research [1-3]. Compared to conventional bulk lasers, all-fiber structured lasers exhibit outstanding advantages such as high efficiency, excellent stability, strong reliability, and compact structure. The ytterbium ion (Yb³⁺), characterized by its broad gain bandwidth,

long upper-level lifetime, high quantum efficiency, and extensive fluorescence spectrum spanning the 1030-1200nm wavelength range, has become one of the most widely used gain ions in high-power fiber lasers [4, 5]. Techniques for achieving Q-switched operation in fiber lasers primarily include active and passive Q-switching. Active Q-switching controls the cavity loss via externally driven modulators (e.g., acousto-optic or electro-optic modulators), enabling precise

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repetition rate control, though the system structure is relatively complex. In contrast, passive Q-switching utilizes the self-saturation characteristics of saturable absorbers (e.g., SESAM, graphene, and carbon nanotubes) to automatically modulate the cavity Q-value, offering advantages such as simple structure, no need for external drive, and the ability to generate narrower pulses. Relevant literature presents both experimental studies and theoretical explanations on pulsed lasers that utilize saturable absorbers as passive Q-switches [6-14]. Traditional saturable absorber materials such as semiconductor saturable absorber mirrors (SESAM), while widely used in Q-switched and mode-locked lasers, suffer from limited operational bandwidth, complexity in integration with fiber systems, and high cost. In recent years, novel low-dimensional materials such as graphene and topological insulators have demonstrated excellent performance as saturable absorbers in Q-switched fiber lasers. For instance, Li Liang from Huaqiao University in China employed a graphene dispersion as a saturable absorber, achieving stable Q-switched pulse output with a pulse width of 33ns and a repetition rate of 38.5kHz in a Yb^{3+} -doped double-clad fiber laser [15]. However, the preparation processes for these materials are complex, their integration with fiber systems still requires precise packaging techniques, and they are prone to performance degradation under high-power conditions. Multimode fiber, as an alternative saturable absorption medium, has attracted research interest in recent years. The fundamental principle is based on the nonlinear coupling effect between different modes within the multimode fiber, which exhibits saturable absorption characteristics under specific conditions. Compared with traditional low-dimensional materials, multimode fiber offers significant advantages such as inherent compatibility with fiber laser systems, low cost, high damage threshold, and ease of integration. Utilizing multimode fiber as a saturable absorber to realize self-Q-switched laser output can further simplify the laser structure and improve system stability and environmental adaptability. This paper proposes and experimentally demonstrates a self-Q-switched Yb^{3+} -doped all-fiber laser based on multimode fiber. The laser adopts an all-fiber linear cavity structure, with Yb^{3+} -doped double-clad fiber as the gain medium and a fiber Bragg grating (FBG) as the cavity mirror. The saturable absorption mechanism is realized through mode-field mismatch and nonlinear effects in the multimode fiber, thereby achieving stable Q-switched pulse output. The influence of multimode fiber length on the laser output characteristics was systematically investigated, and the optimal parameter configuration was obtained. This self-Q-switched all-fiber laser features a compact structure and stable performance. Its design provides a low-cost solution for high-pulse-energy all-fiber lasers, and this research also represents an extension and enhancement of the research group's previous work [16-20].

2. Experimental Scheme

Figure 1 shows the schematic diagram of a self-Q-switched Yb^{3+} -doped all-fiber laser based on the saturable absorption effect in multimode communication fiber. The experimental setup was constructed by splicing a segment of multimode communication fiber to the output end of a continuous-wave Yb^{3+} -doped all-fiber laser. The laser cavity is designed with an all-fiber configuration, where a fiber Bragg grating (FBG) serves as the high reflector, and the cleaved facet of the gain fiber acts as the output coupler, utilizing its Fresnel reflectivity. The FBG and the output cleaved facet together form the laser resonator. The FBG has a center wavelength of 1083nm, a reflectivity greater than 98% at 1083nm, a reflection bandwidth of approximately 0.7nm, a core diameter of 7 μm , a core numerical aperture (NA) of 0.22, and a cladding diameter of 125 μm . The fiber loss at 1083nm is less than 0.0015dB/m.

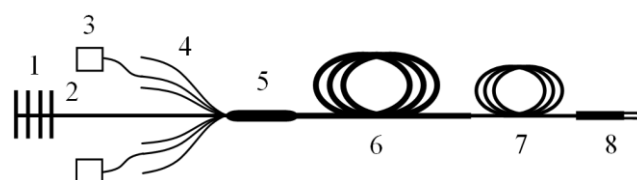


Figure 1. Self-Q-switched Yb^{3+} -Doped all-Fiber Laser Based on the Saturable Absorption Effect: (1) FBG, (2) Signal Port of the Multimode Pump Combiner, (3) LD, (4) Pump Port of the Multimode Pump Combiner, (5) Main Body of the Multimode Pump Combiner, (6) Yb^{3+} -Doped Double-Clad fiber, (7) Multimode Communication Fiber, (8) Output Fiber Tail of the Fiber Laser.

The pump sources used in the experiment were two fiber-coupled semiconductor lasers, both with a center wavelength of 975nm. One was a semiconductor laser with a maximum output power of 25W (hereafter referred to as 25W-LD), coupled to a fiber with a core diameter of 200 μm and an NA of 0.22. A custom air-cooling system was used for temperature control of the 25W-LD, achieving a temperature control accuracy of $\pm 0.1^\circ\text{C}$. The second pump source was a semiconductor laser with a maximum output power of 5W (hereafter referred to as 5W-LD), coupled to a fiber with a core diameter of 200 μm and an NA of 0.22, and employing Thermo-Electric Cooler (TEC) cooling.

The pump light coupling system used in the experiment was a (6+1) $\times$ 1 multimode pump combiner. It features six pump input ports, one signal port, and one output port connected to the double-clad gain fiber (DCF port). The pump input ports of the combiner have a core diameter of 200 μm and an NA of 0.22, with each input port capable of handling a maximum pump power of 25W. The signal port has a core diameter of 20 μm and an NA of 0.06. The DCF port has a double-clad structure with a core diameter of 20 μm and an NA of 0.06, an inner cladding diameter of 400 μm , and an inner cladding NA of 0.46. The maximum insertion loss of the

combiner for the signal light is 0.5dB, and for the pump light is 0.3dB. The pump input ports of the combiner are perfectly matched in size and NA with the tail fibers of the LDs. Transmission tests indicated that the pump light loss within the combiner is less than 5%.

The gain fiber is a D-shaped double-clad Yb^{3+} -doped fiber with a core diameter of $30\mu\text{m}$ and an NA of 0.07. The inner cladding has a diameter of $350/400\mu\text{m}$ (denoting minor/major axis for D-shape) and an NA of 0.49. The absorption coefficient of the gain fiber for the 975nm pump light is 1.2dB/m, and the length of the gain fiber used is 11m. Due to the dimensional mismatch between the gain fiber and the multimode communication fiber (the core diameter of the multimode fiber being larger than that of the gain fiber), direct fusion splicing was challenging. Therefore, a butt-coupling method was adopted in the experiment. Firstly, the end faces of both fibers were ensured to be flat and polished. Then, the two fiber ends were fixed using two five-axis alignment stages, and fine adjustments were made to achieve tight butt-coupling between the central end faces of the two fibers.

3. Analysis of the Self-Q-switching Mechanism

The self-Q-switching device is realized by butt-coupling a section of multimode communication fiber to the laser output end. The mode-field mismatch at the interface between the multimode fiber and the gain fiber induces mode-selective loss, which, combined with the nonlinear effects in the multimode fiber, collectively forms the saturable absorption mechanism. The self-Q-switching mechanism in the multimode fiber primarily relies on the synergistic effect of two phenomena: (i) coupling loss due to mode-field mismatch at the joint between the multimode fiber and the gain fiber, which is intensity-dependent: higher at low intensities and

reduced at high intensities due to nonlinear effects, exhibiting saturable absorption characteristics; (ii) interference effects between different propagating modes in the multimode fiber, leading to redistribution of optical intensity in both temporal and spatial domains, which further enhances the nonlinear transmission characteristics. When laser light transitions from the gain fiber with a smaller core diameter into the multimode fiber with a larger core diameter, the multiple propagating modes are excited within the multimode fiber. These modes propagate with different propagation constants, creating complex interference patterns within the multimode fiber. Under specific conditions, this interference results in an effective saturable absorption behavior, analogous to the operating principle of a nonlinear optical loop mirror (NOLM), but with a simpler structure.

4. Results and Discussions

4.1. Continuous-wave Operation Characteristics

- 1) In the experiment, simultaneous pumping was performed using both the 5W-LD and the 25W-LD. The drive current of the 5W-LD was first maintained at 5.0A, while the drive current of the 25W-LD was subsequently increased. Throughout this process, the relationship between the output power and the pump power was carefully observed. Figure 2 shows the curve of the output power versus the pump power for the continuous-wave laser. At the maximum total pump power of 12.01W, the laser output power reached 3.426W, corresponding to an optical-to-optical conversion efficiency of 28.5%. The pump threshold was approximately 110mW, which is in good agreement with theoretical calculations [21-23].

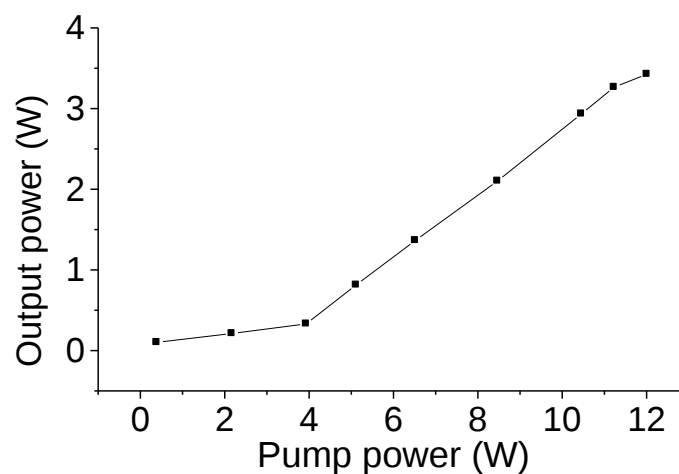


Figure 2. Input-output Characteristic Curve of the Continuous-Wave Yb^{3+} -Doped all-Fiber Laser.

2) Figure 3 shows the corresponding laser output spectrum. The laser operates at a central wavelength of 1083nm with a full width at half maximum (FWHM) of approximately 2nm. The signal observed near 975nm in the figure corresponds to residual pump light. Far-field

observation of the spot profile confirmed that the output laser operates in the fundamental transverse mode. The laser stability was also measured: during continuous monitoring over 30 minutes at an output power of 3W, the output power fluctuation remained below 1%.

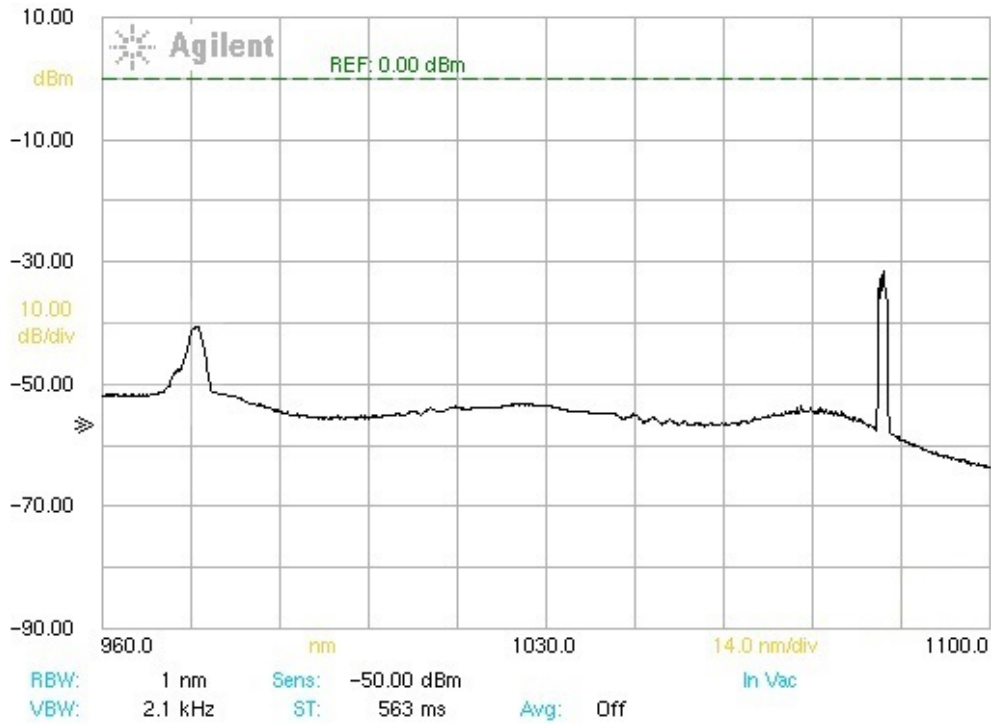


Figure 3. Output Spectrum of the Continuous-Wave Yb^{3+} -Doped all-Fiber Laser.

4.2. Q-switched Operation Characteristics

In the experiment, only the 25W-LD was used for pumping, with a multimode communication fiber length of 3.3m. When the pump power was increased to 3.35W, the saturable absorption effect in the multimode communication fiber began to initiate self-Q-switching, and a pulse train with microsecond-scale duration was observed at the output, though the pulse amplitude showed slight instability. As the pump power was further increased, the pulse amplitude gradually stabilized. At a pump power of 5.30W, the pulse train shown in Figure 4 was obtained (oscilloscope horizontal scale: 10 μ s/division). The pulse width was 2.8 μ s, the average pulse interval was approximately 21.7 μ s, corresponding to a repetition rate of 46kHz, and the pulse energy was 13 μ J. The stability of the laser's pulsed output was measured over a two-hour period. The measurements revealed that the pulse energy fluctuation remained within $\pm 3\%$, and the pulse width demonstrated good long-term stability with variations of less than $\pm 0.2\mu$ s. Furthermore, no significant distortion in the pulse profile was observed.

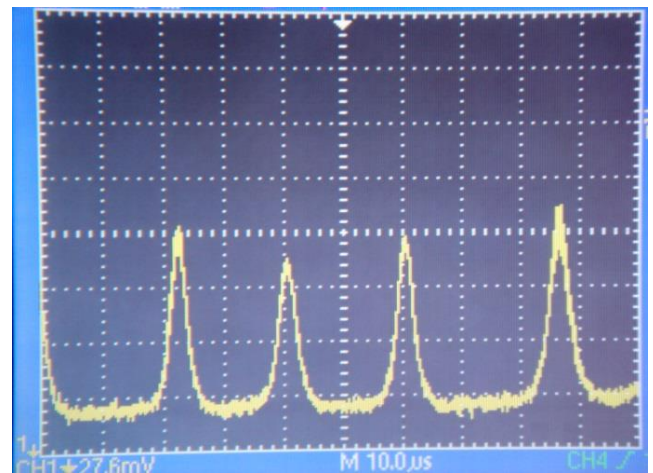


Figure 4. Pulse Train 1 of the Self-Q-Switched Yb^{3+} -Doped all-Fiber Laser.

When the length of the multimode communication fiber was increased to 5m and only the 5W-LD was used for pumping, the pulse train shown in Figure 5 was obtained at a pump power of 4.16 W (oscilloscope horizontal scale:

5 μ s/division). The pulse duration ranged between 3-5 μ s, with a repetition frequency below 50kHz. The full width at half maximum (FWHM) of adjacent single pulses showed slight variations, and the pulse width increased compared to previous results, indicating a less optimal performance under this configuration.

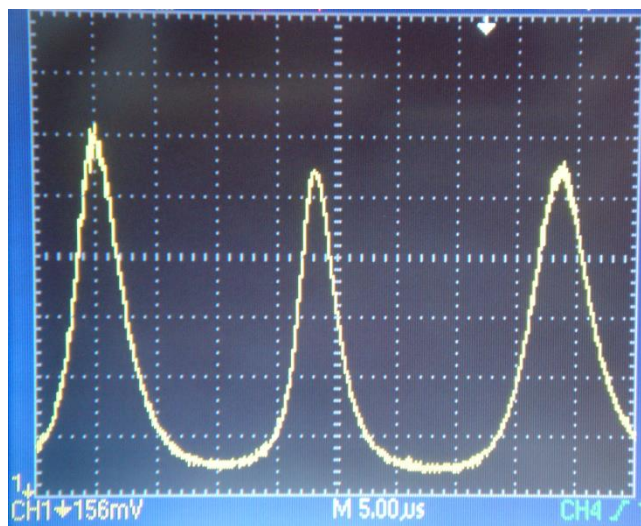


Figure 5. Pulse Train 2 of the Self-Q-Switched Yb³⁺-Doped all-Fiber Laser.

4.3. Influence of Multimode Fiber Length on Pulse Characteristics

The length of the multimode fiber significantly impacts the Q-switching performance. An experimental study was conducted to investigate the Q-switched pulse characteristics with different multimode fiber lengths (e.g., 1m, 2m, 3m, 3.3m, 3.6m, 4m, 5m, and 6m). The results indicate that when the multimode fiber length was 1m, the saturable absorption effect was relatively weak, leading to quasi-continuous-wave laser operation with a broad pulse width (7 μ s). As the fiber length increased to 3.3m, optimal Q-switching performance was achieved, yielding the narrowest pulse width (2.8 μ s) and the highest pulse stability. However, when the fiber length was extended to 5m, the Q-switching performance degraded. Further increasing the length to 6m resulted in unstable pulse output, exhibiting multiple-pulsing behavior due to excessive insertion loss and overly strong nonlinear effects. Analysis suggests that the multimode fiber length directly influences two key parameters: (i) the accumulation of nonlinear phase shift, which determines the modulation depth of the saturable absorber; and (ii) the transmission loss, which affects the overall conversion efficiency of the laser. In summary, shorter multimode fibers provide insufficient nonlinearity, resulting in shallow modulation depth, while excessively long fibers introduce substantial loss, reducing laser efficiency and causing unstable operation. In essence, the optimal length represents the ideal convergence point among mode inter-

ference contrast, nonlinear strength, and transmission loss within the multimode fiber. Therefore, an optimal multimode fiber length exists in this experiment, 3.3m at which the Q-switching performance is maximized.

5. Conclusions

This study successfully developed a self-Q-switched Yb³⁺-doped all-fiber laser based on the saturable absorption effect in multimode fiber. The laser employs a high-reflection FBG to realize an all-fiber structure, and utilizes mode-field mismatch and nonlinear effects in the multimode fiber to achieve a saturable absorption mechanism, enabling stable self-Q-switched pulsed output. Under a pump power of 5.3W, the laser produced output at a central wavelength of 1083nm with a repetition rate of 46kHz, a pulse width of 2.8 μ s, and a single pulse energy of 13 μ J. Experimental investigation demonstrated that the multimode fiber length significantly influences the self-Q-switching performance, with an optimal length of 3.3m identified in this work for obtaining the best pulse characteristics. Compared to traditional saturable absorbers based on low-dimensional materials, the multimode fiber-based self-Q-switching device offers advantages including simple structure, low cost, high damage threshold, and inherent compatibility with fiber systems. Future work will focus on further optimizing multimode fiber parameters (such as core diameter and numerical aperture) to enhance Q-switching performance, investigating pulse stability, nonlinear effects, and the fiber damage threshold at higher power levels, and exploring practical applications of this laser in fields such as material processing and lidar.

Abbreviations

SESAM	Semiconductor Saturable Absorber Mirror
FBG	Fiber Bragg Grating
NA	Numerical Aperture
TEC	Thermo-electric Cooler
LD	Diode Laser
DCF	Double-clad Fiber
NOLM	Nonlinear Optical Loop Mirror
FWHM	Full Width at Half Maximum

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Conflicts of Interest

The authors declare no conflicts of interest.

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