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Stable C-Band Q-Switched EDFL Using a D-Shaped Fiber Coated with Zn(II) Schiff-Base Complex

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Abstract. Schiff-base zinc(II) complexes have recently attracted interest as nonlinear optical materials owing to their tunable molecular structure, strong electronic delocalization, and high optical stability. In this work, a D-shaped fiber coated with a Zn(II) Schiff-base complex was developed as a novel saturable absorber (DSF-Zn SA) for Q-switched operation in a C-band erbium-doped fiber laser (EDFL). The Zn(II) complex was synthesized via a two-step condensation and coordination process, producing a material with a measured modulation depth of 8.0%. Integration of the DSF-Zn SA into the EDFL cavity enabled stable Q-switched lasing within a pump range of 35.21–76.75 mW. The laser emitted at 1558.6 nm with a pulse width of 5.63 µs, a repetition rate of 45.56 kHz, and a maximum pulse energy of 110.40 nJ. The device exhibited strong nonlinear absorption and excellent operational stability, demonstrating the Zn(II) Schiff-base complex's suitability for compact and efficient ultrafast photonic applications.

Keywords. D-shape fiber, Zn(II) Schiff-base complex, saturable absorber, Q-switched, EDFL.

1. Introduction

Pulsed fiber lasers emit light in rapid, well-defined bursts rather than as a continuous output beam. By confining the laser emission to extremely short durations ranging from microseconds to picoseconds, they can produce very high peak powers while maintaining moderate average power levels. This capability enables precise control of energy delivery, minimizing thermal damage and enhancing process accuracy. Owing to these characteristics, pulsed fiber lasers have become indispensable in modern photonics, finding widespread use in materials processing, biomedical surgery, spectroscopy, micromachining, and advanced scientific research where ultrafast and high-intensity light sources are required(Li et al., 2023; Liu et al., 2023; Yamashita & Set, 2025).

One common technique for generating short pulses in fiber lasers is the Q-switching operation. This method works by controlling the quality factor (Q-factor) of the laser cavity to produce pulses rather than continuous output. During operation, the Q-factor is initially kept low to allow energy to accumulate in the gain medium and then rapidly increased, releasing the stored energy as a short, intense optical pulse. Q-switching can be achieved using either active modulators, such as acousto-optic or electro-optic devices, or passive modulators that rely on saturable absorbers.

The incorporation of a saturable absorber (SA) as a passive optical modulator has become a key approach for enabling Q-switched operation in fiber lasers. An SA allows light transmission at high optical intensities while absorbing low-intensity light, resulting in self-starting pulse generation (Zhao et al.). The semiconductor saturable absorber mirror (SESAM) is the most established and commercially successful SA. However, its practical use is constrained by high fabrication costs and limited spectral bandwidth. As a result, extensive research has been directed toward developing alternative SAs that offer faster recovery times, stronger nonlinear optical responses, and broader operating ranges to meet the demands of modern ultrafast photonic systems.

A wide range of nanomaterials has been experimentally investigated as passive modulators for Q-switched fiber lasers, each demonstrating unique advantages and inherent limitations. For instance, tungsten carbide (WC) nanoparticles coated on a D-shaped optical fiber act as a durable and broadband saturable absorber covering wavelengths from 400 nm to 2500 nm, enabling ultrafast pulse generation at 1560 nm and 1932 nm in erbium- and thulium-doped laser cavities (Wang et al., 2023). Similarly, copper selenide (CuSe) nanosheets exhibit a strong nonlinear absorption coefficient of approximately −3.67 cm GW^{-1} at 1560 nm. When incorporated into a polyvinyl alcohol (PVA) matrix with a modulation depth of 3.8 % or directly deposited on a D-shaped fiber with a modulation depth of 5.6 %, these materials facilitate stable Q-switched laser operation with a remarkably low threshold of 42 mW (Xu et al., 2024).

Beyond these examples, numerous emerging materials, including transition-metal dichalcogenides (TMDs)(Liu et al., 2022), MXenes (Wu et al., 2025), MAX phase (Wadi et al.), topological insulators (TIs) (Haris et al., 2019) , black phosphorus (BP) (Li et al., 2016), and organic compounds (S Wadi et al., 2024), have been explored for their tunable bandgaps, high modulation depths, and wide spectral response. However, each material also poses challenges, such as limited optical damage thresholds, environmental instability (particularly BP oxidation), and complex fabrication or integration processes.

Schiff base zinc(II) complexes have recently emerged as promising candidates for nonlinear optical and photonics applications owing to their structural tunability, strong electronic delocalization, and excellent photostability. These complexes combine the rigidity of the imine (C=N) framework with the electron-donating and accepting properties of the organic ligand, enabling efficient intramolecular charge transfer when coordinated with Zn(II) ions(Kargar et al., 2022; Liang et al., 2022). Such coordination not only enhances fluorescence and charge-transfer efficiency but also induces broad optical absorption across the ultraviolet-visible-near-infrared spectrum, a key prerequisite for saturable absorber functionality. (Gusev et al., 2021) demonstrated that Zn(II) Schiff-base compounds possess strong ligand-centered and metal-to-ligand charge-transfer transitions, responsible for their high luminescent efficiency and nonlinear optical response. Similarly, (Sahudin et al., 2025) reported N, N′-bis[4-(hydroxysalicylidene)] phenylenediamine complex with significant fluorescence enhancement upon analyte interaction, validating its efficient electron-transfer and excited-state dynamics. Collectively, these studies indicate that Zn(II) Schiff-base complexes exhibit desirable features such as pronounced nonlinear absorption, rapid carrier recovery, and high thermal stability, making them highly suitable as SAs for short-pulsed fiber lasers.

In this work, we report the development of a D-shaped optical fiber coated with a Zn(II) Schiff-base complex solution, synthesized via a two-step condensation and coordination process, to function as an efficient saturable absorber (DSF-Zn SA). The fabricated device exhibited a clear nonlinear optical response with a measured modulation depth of 8.0%, confirming its strong saturable absorption behavior. When integrated into an erbium-doped fiber laser cavity, the DSF-Zn SA enabled stable Q-switched pulse generation with excellent temporal and spectral stability. These results highlight the Zn(II) Schiff-base complex as a promising and durable SA material, offering significant potential for future ultrafast photonics and fiber-laser technologies.

2. SA device fabrication

2.1. D-shape fiber preparation

In this study, a saturable absorber (SA) device was fabricated using a side-polished optical fiber structure, commonly referred to as a D-shaped fiber, which was coated with a Zn(II) Schiff-base complex solution (denoted as DSF-Zn complex). The D-shaped fiber configuration was selected due to its superior mechanical robustness, excellent reusability, and higher optical damage threshold compared with conventional film- or microfiber-based SAs. Its extended interaction length allows for stronger and more stable nonlinear light–matter coupling, which is advantageous for achieving efficient passively Q-switched laser operation.

The side-polished D-fiber platform used in this work has been widely adopted for SA integration owing to its robust evanescent field coupling geometry. Recent studies employing similar wheel-ground D-fiber structure coated with various SA materials have reported comparable residual cladding thickness and insertion loss values (Aiman Rosol et al., 2026; Jafry et al., 2021; Rosol et al., 2024), confirming the reproducibility of this fabrication approach across different SA materials. The residual cladding thickness of ~79.2 μm and the ~3 dB insertion loss achieved in the present work are consistent with values reported in these studies, providing additional confidence in the evanescent-field coupling efficiency of the DSF-Zn SA device.

The DSF structure was fabricated through an ultraprecision wheel-grinding process (Fig. 1) designed to expose the fiber evanescent field region with high accuracy. A standard single-mode optical fiber (SMF-28) with a 125 μm cladding diameter was used as the substrate. One end of the fiber was spliced to an amplified spontaneous emission (ASE) source for input power delivery, while the other end was connected to an optical power meter (OPM) for real-time monitoring of transmission loss. Prior to polishing, the polymer buffer layer covering the target region was carefully stripped, and the exposed cladding was thoroughly cleaned with isopropyl alcohol to remove surface contaminants, ensuring a smooth and uniform contact surface for precise material removal. The prepared section of the fiber was then gently pressed against a rotating wheel lined with fine-grit abrasive paper, and the cladding was gradually abraded under constant monitoring. During polishing, the transmitted optical power was continuously measured to control the removal depth, and the process was stopped once an insertion loss of approximately 3 dB was reached. This loss level indicates optimal evanescent field exposure, sufficient to enable efficient interaction with the Zn(II) complex coating while minimizing propagation loss. Microscopic inspection of the polished region using an optical microscope (Medilux 12) confirmed a residual cladding thickness of about 79.2 μm, as illustrated in Fig. 2, verifying the successful formation of the D-shaped fiber structure. The enlarged evanescent field at this depth ensures strong nonlinear interaction between the guided light and the Zn(II) complex layer, making the DSF-Zn complex device highly effective and durable for short pulse generation.

2.2. Synthesis of zinc complex solution

The Zn(II) Schiff-base complex was synthesized through a controlled two-step condensation process to obtain a material suitable for saturable absorber (SA) fabrication. In the first step, 1,2-phenylenediamine weighing 0.283 g (2.5 mmol) reacted with 0.722 g (5 mmol) of 2,4-dihydroxybenzaldehyde in 40 mL of ethanol under reflux conditions at 75 °C for 30 minutes to form the Schiff base ligand. In the second step, 0.458 g (2.5 mmol) of zinc(II) acetate was introduced into the reaction mixture, and the solution was further refluxed at the same temperature for 3 hours with continuous magnetic stirring to ensure uniform coordination between the ligand and the metal ion. The completion of the reaction was verified using thin-layer chromatography (TLC). After cooling to room temperature, a yellow solid precipitate formed, which was collected by vacuum filtration and washed thoroughly with 60 mL of ethanol, 40 mL of deionized (DI) water, and 40 mL of diethyl ether. The purified compound was then oven-dried overnight, ground into a fine powder, and stored in a vacuum desiccator to preserve its stability. For SA device fabrication, the Zn(II) complex was dissolved in dimethyl sulfoxide (DMSO) to prepare a 5 mM solution, which was subsequently used to coat the polished surface of a D-shaped optical fiber, forming a DSF-Zn complex SA device.

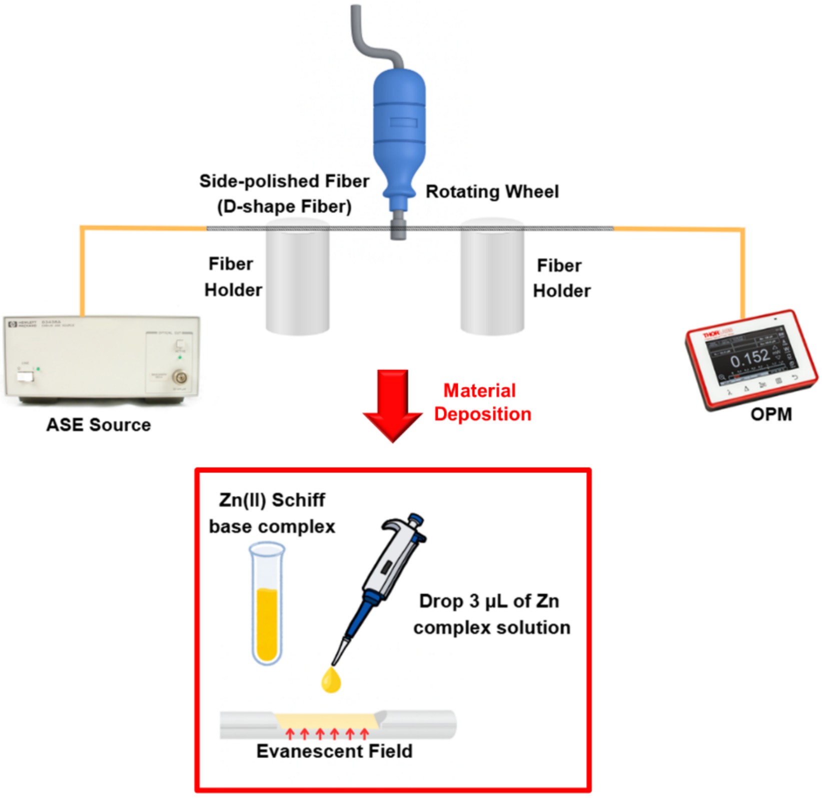

Figure 1. Fabrication of D-Shape Fiber and deposition of the Zn complex solution.

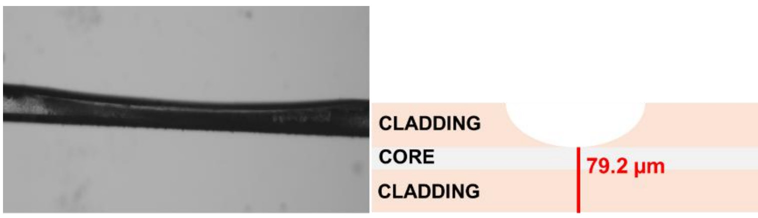

Figure 2. Microscopic image of the DSF.

2.3. Optical Characterization of DSF-Zn SA

The nonlinear optical response of the fabricated DSF-Zn SA was characterized using the balanced twin-detector technique. A mode-locked fiber laser operating at a central wavelength of 1558 nm, with a pulse duration of 3.1 ps and a repetition rate of 1.775 MHz, served as the excitation source. The transmission characteristics were analysed based on the standard intensity-dependent saturable absorption model (equation 1), from which key parameters were extracted.

$$\alpha(I) = \frac{\alpha_S}{1+\frac{I}{I_{sat}}} + \alpha_{ns} \quad (1)$$

In this model, α_s denotes the saturable absorption component, α_{ns} represents the non-saturable absorption, and I_{sat} corresponds to the saturation intensity. The nonlinear transmission curve, shown in Fig. 3, reveals that the DSF-Zn complex exhibits distinct saturable absorption behaviour with an α_s of 8.0 %, α_{ns} of 23.1 %, and an I_{sat} value of 20 MW/cm^2. These results confirm that the Zn(II) Schiff-base complex effectively modulates light intensity and possesses strong nonlinear absorption characteristics, making it suitable for use as a passive optical modulator in ultrafast fiber laser systems.

To contextualize these values, Table 1 compares the key nonlinear optical parameters of the present DSF-Zn SA with selected SAs reported for pulsed laser generation. The saturation intensity of 20 MW/cm^2 obtained in this work is comparable to those of MgPc and ITO, and significantly higher than those of CuPc and rhodamine 6G. This indicates that the DSF-Zn SA does not require excessively high optical intensity to reach saturation while still maintaining an 8% modulation depth suitable for stable Q-switched operation.

Table 1. Comparison of nonlinear absorption parameters of the DSF-Zn SA with selected SAs.

Material	Integration method	α_s (%)	α_{ns} (%)	I_{sat} (MW/cm^2)	Ref.
ITO	D-shaped coating	3.5	60	40.32	(Nizamani et al., 2020)
MgPc	Film	5.0	50.8	23	(Zabidi et al., 2025)
CuPc	Film	8.8	3.9	7	(Wadi et al., 2024)
Rhodamine 6G	Arc-shaped coating	15.2	75.5	4.45	(Ahmad et al., 2025)
Zn complez	D-shaped coating	8	23.1	20	This work

The relatively high non-saturable absorption (α_{ns} = 23.1%) observed in the DSF-Zn SA can be attributed to three factors: the residual linear absorption of the DSF-Zn at the operating wavelength, scattering loss introduced by the coated layer on the polished DSF interface, and the effective coating thickness formed during drop casting. Although this value increases the intracavity loss and can reduce slope efficiency, the device still provides sufficient saturable absorption to initiate stable Q-switching. Future optimization can be achieved by controlling the deposited volume of DSF-SA, coating uniformity, and polishing depth to reduce insertion loss while maintaining strong nonlinear modulation.

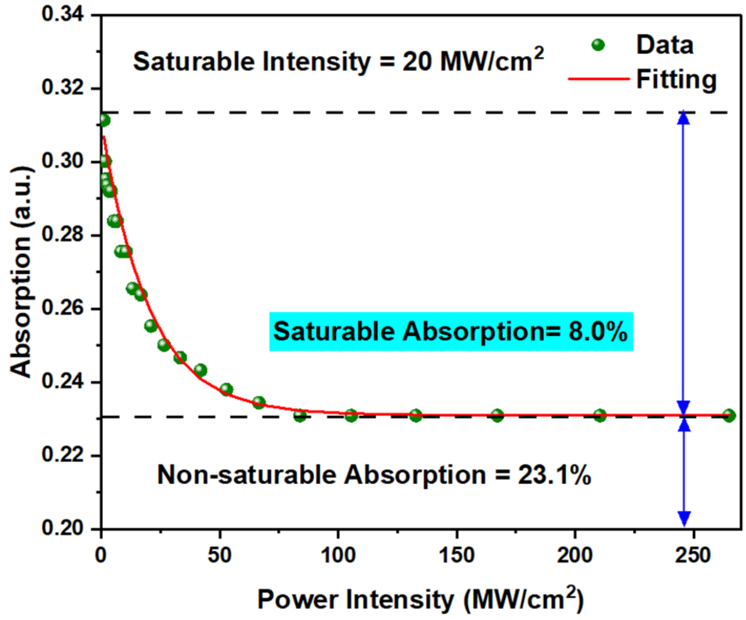

Figure 3. Nonlinear absorption profile of DSF-Zn SA

3. EDFL configuration

The laser cavity configuration designed for Q-switched operation using the DSF-Zn complex SA is illustrated in Fig. 4. The setup employed a 980 nm laser diode as the pump source, providing excitation to a 0.9 m erbium-doped fiber (EDF) through a 980/1550 nm wavelength division multiplexer (WDM). The EDF has a core/cladding diameter of 4/125 µm, a nominal NA of 0.20, an absorption coefficient of approximately 30 dB/m at 1530 nm and supports emission in the 1530–1610 nm wavelength range. The amplified signal from the EDF was directed through an optical isolator to ensure unidirectional light propagation and to suppress unwanted back reflections that could destabilize laser operation. The fabricated DSF-Zn SA was incorporated into the cavity before the 80/20 fiber coupler, which served to extract 20% of the laser output while recirculating the remaining light within the cavity to sustain lasing.

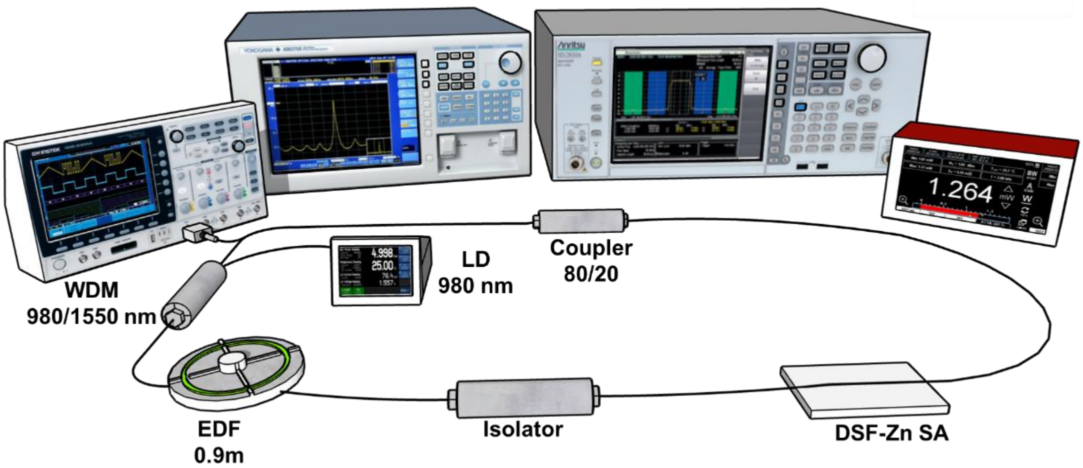

Figure 4. Q-switched EDFL cavity setup based on DSF-Zn SA.

This configuration enables the strong interaction between the propagating optical field and the Zn(II) Schiff-base complex coating on the D-shape fiber, facilitating intensity-dependent absorption that supports passive Q-switching. The use of a compact, all-fibre design ensures stable operation, efficient energy modulation, and ease of integration into existing fiber laser systems.

4. Results and Discussion

Preliminary testing of the laser cavity without the DSF-Zn SA revealed only continuous wave (CW) emission, with no evidence of pulsed operation across the entire range of available pump powers. However, after the integration of DSF-Zn SA into the cavity, stable Q-switched pulses were successfully generated when the pump power was increased from 35.21 mW to 76.75 mW. Beyond this range, the Q-switching regime gradually diminished, indicating saturation of the SA nonlinear response. The disappearance of the Q-switching regime at pump powers above 76.75 mW is likely caused by a combination of SA over-saturation and cavity-related effects. At high intracavity intensity, the available ground state absorption in the DSF-Zn becomes strongly bleached (transparent), reducing the modulation contrast required for stable energy build-up and release. In addition, local heating at the coated DSF region and scattering from the coating interface may increase effective intracavity loss, while nonlinear effects in the fiber cavity can disturb the balance between gain, loss, and SA recovery.

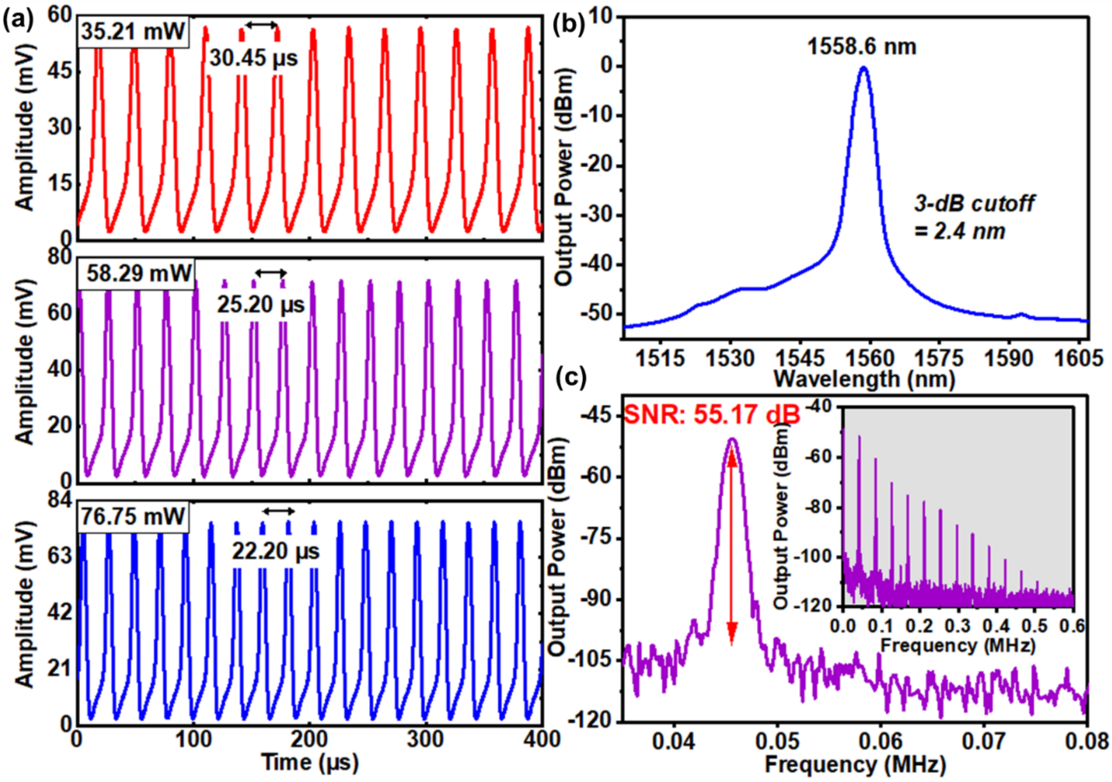

Figure 5. Laser performance for Q-switched operation in terms of (a) pulse train at three distinct pump powers, (b) Optical spectrum and (c) RF spectrum.

As a result, the Q-switched pulse train gradually weakens and returns toward unstable or continuous-wave-like operation beyond the optimum pump range. The temporal pulse trains, illustrated in Fig. 5(a), were recorded at three representative pump powers, 35.21 mW, 58.29 mW and 75.76 mW, demonstrating a clear reduction in peak-to-peak spacing from 30.45 μs to 25.20 μs and 22.20 μs, respectively, corresponding to an increase in repetition rate with higher pump levels. At the maximum pump power of 76.75 mW, the optical spectrum shown in Fig. 5(b) indicated laser emission centered at 1558.6 nm with a 3 dB bandwidth of 2.4 nm, a pulse duration of 5.63 μs, and a repetition rate of 45.56 kHz. To evaluate temporal stability, the radio frequency (RF) spectrum of the generated pulses was analyzed. As shown in Fig. 5(c), a signal-to-noise ratio (SNR) of 55.17 dB was obtained with clear harmonic peaks extending up to 0.6 MHz, indicating high pulse stability and consistent Q-switched laser performance enabled by the DSF-Zn complex saturable absorber.

The long-term operational stability of the laser was evaluated by maintaining continuous lasing for a duration of 70 minutes. Throughout this period, the output spectrum was recorded every 10 minutes to monitor spectral consistency, as illustrated in Fig. 6(a). The spectral profiles exhibited minimal fluctuation across all time intervals, confirming that the laser maintained stable output characteristics without wavelength drift or intensity degradation. This result demonstrates the strong robustness of the Q-switching mechanism and verifies that the DSF-Zn complex SA provides reliable and sustained pulse generation over extended operation.

Fig. 6(b) presents the variation of output power, pulse energy, and peak power as a function of pump power. All three parameters show a clear linear growth trend with increasing pump power from 35.21 mW to 76.75 mW. The measured output power increased from 1.89 mW to 5.03 mW, while the corresponding pulse energy and peak power rose from 58.21 nJ to 110.40 nJ and from 6.89 mW to 19.63 mW, respectively. These results indicate efficient energy conversion within the laser cavity and confirm the excellent optical response of the DSF-Zn complex in supporting stable and scalable Q-switched operation. The repetition rate of the Q-switched pulses also increased nearly linearly with pump power, rising from 32.47 kHz at 35.21 mW to 45.56 kHz at 76.75 mW, as shown in Fig. 6(c).

The measured 8.0% modulation depth, moderate saturation intensity, and good long-term stability also suggest that the DSF-Zn has potential for mode-locked pulse generation. However, femtosecond operation would require further cavity optimization, particularly precise dispersion management, reduction of non-saturable loss, and control of the SA interaction length. By shortening or rebalancing cavity dispersion and improving the coating uniformity on the DSF platform, the DSF-Zn SA may support stable soliton or femtosecond mode-locked operation in future work.

5. Conclusion

In conclusion, this work successfully demonstrates Q-switched operation in an EDFL utilizing a D-shaped fiber coated with a Zn(II) Schiff-base complex (DSF-Zn SA) as the nonlinear optical modulator. The Zn(II) complex was synthesized through a two-step condensation and coordination process and uniformly deposited onto the polished fiber surface to form an efficient saturable absorber. The fabricated DSF-Zn SA exhibited a clear nonlinear response with a modulation depth of 8.0 %, confirming its strong saturable absorption behaviour. When integrated into the EDFL cavity, stable Q-switched pulses were achieved over a pump range of 35.21 to 76.75 mW. At the maximum pump power, the laser emitted at a central wavelength of 1558.6 nm, delivering pulses with a 5.63 μs pulse width, 45.56 kHz repetition rate, and maximum pulse energy of 110.40 nJ.

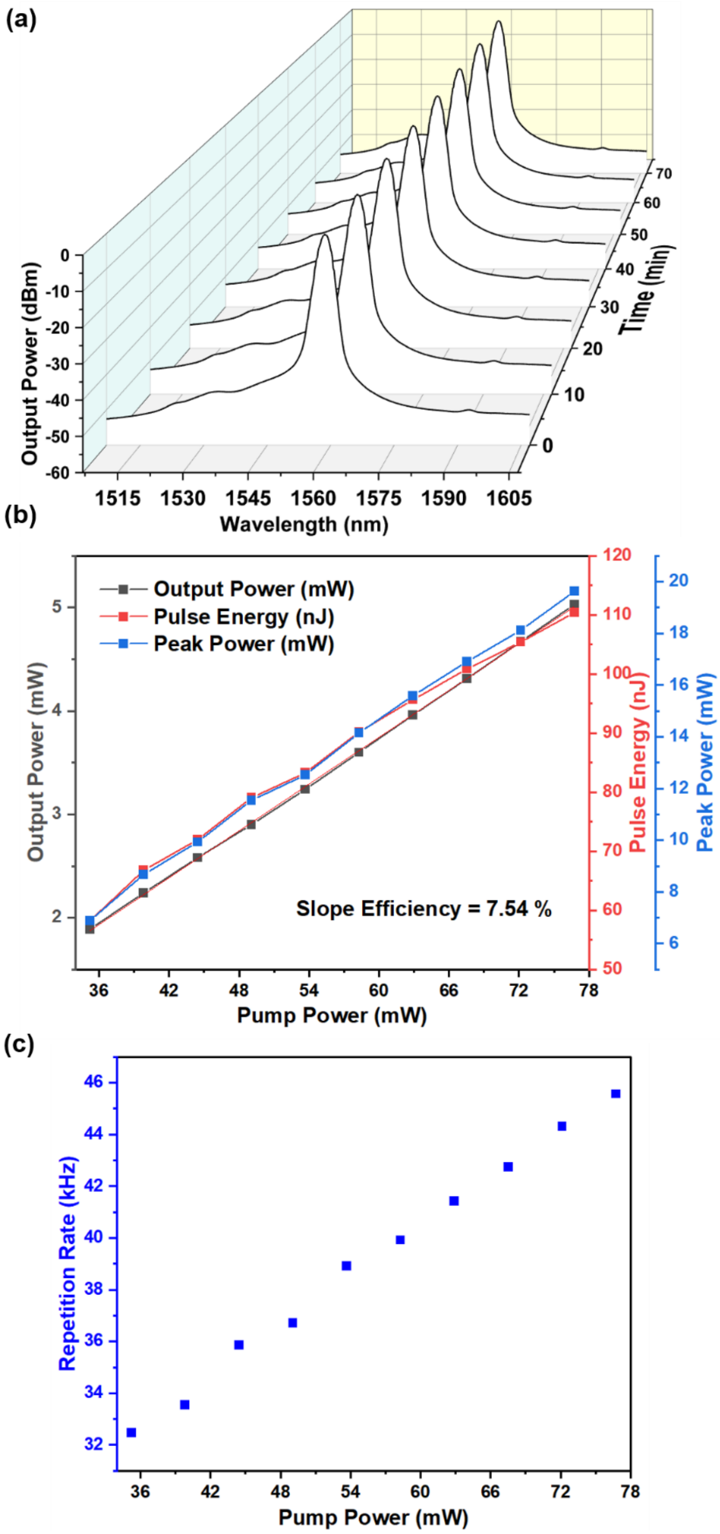

Figure 6. (a) Long-term stability of the Q-switched laser output. (b) Variation of output power, pulse energy, and peak power with pump power, (c) Dependence of repetition rate against pump power.

These results highlight the excellent nonlinear optical properties and photostability of the Zn(II) Schiff-base complex, establishing it as a highly promising saturable absorber material for compact and efficient ultrafast fiber laser applications. Furthermore, the moderate saturation intensity and stable nonlinear response indicate that this material can be further optimized for lower-loss DSF integration and possible femtosecond mode-locked fiber laser generation.

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