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Passive Q-Switching of an Erbium-Doped Fiber Laser Using a Tin Phthalocyanine-Based Saturable Absorber in the C-Band Region

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Abstract. Fiber lasers have drawn a lot of interest because of their excellent beam quality, adaptability, and effectiveness in a range of applications. A development of reliable and effective saturable absorbers for Q-switching, which enables the generation of pulsed laser output, is an essential factor in developing fiber laser technology. This study explores the potential of tin phthalocyanine as a saturable absorber for passive Q-switching in a fiber laser system. The goal of this study is to determine how effectively this material produces steady Q-switched pulses. The process includes incorporating SnPC with polyvinyl alcohol to create a saturable absorber film, which is subsequently incorporated into a passive fiber laser configuration. Q-switched pulses are successfully recorded after increasing the pump power to 84.5 mW, and they maintain stable up to 180.4 mW. These stable Q-switched pulses work at a wavelength of 1556.8 nm. The key performance measures include a maximum repetition rate of 98.1 kHz, a minimum pulse-to-pulse interval of 11.8 µs, and a peak pulse energy of 93.3 nJ.

Keywords. Tin phthalocyanine, Q-switched laser, EDFL, Thin film, C band

1. Introduction

Fiber lasers are extensively utilized in various fields, including material processing, telecommunications, and biomedical applications, due to their high efficiency, superior beam quality, and compact design. A critical feature of fiber lasers is the generation of pulsed laser output, particularly for applications requiring ultrafast laser pulses. Saturable absorbers (SAs) play an essential role in enabling passive Q-switching and mode-locking in fiber lasers, facilitating the production of short, high-intensity pulses(Ahmad, Mokhtar, et al., 2024). The pursuit of new and effective SA materials has spurred investigations into various organic and inorganic substances, with metal phthalocyanines receiving significant attention due to their outstanding nonlinear optical properties. The SAs concepts back date to the early stages' generation of Q-switched by using organic dye in 1960. Since then, many of SA types have been explored by the researchers, with each its own advantages and drawbacks. The SA such as graphene, a two-dimensional material with exceptional optical and electrical properties, has appeared as a promising material due to its ultrafast carrier dynamics and broadband absorption[(Geim & Novoselov, 2007). However, the fabrication of high-quality graphene SAs often involves complex and expensive techniques, such as chemical vapor deposition or epitaxial growth. Then, the Transition metal dichalcogenides (TMDs), another class of two-dimensional materials, have been explored as Sas. However, the performance of TMDs quite limited by their narrowband absorption and relatively slow recovery time(Wang et al., 2015). Black phosphorus (BP) has been gaining attention for its tunable bandgap and strong light matter interaction(Ismail et al., 2016). The BP SA have shown a good saturable absorption property in visible and infrared region. However, the BP prone a degradation upon exposure to the ambient conditions(Ahmad et al., 2025; Wood et al., 2014).

Among metal phthalocyanines (MPcs), Tin (II) phthalocyanine (SnPc) has demonstrated considerable potential as a saturable absorber, attributed to its strong nonlinear absorption, high thermal stability, and tunable absorption in the near-infrared (NIR) region. Integrating SnPc into fiber laser systems could enhance pulse generation, thereby improving the efficiency of both Q-switching and mode-locking. Previous research has shown the effectiveness of similar metal phthalocyanines, such as Zinc phthalocyanine (ZnPc), in erbium-doped fiber lasers (EDFLs), where stable Q-switched pulses were successfully achieved(Soboh et al., 2020). These findings indicate that SnPc, with its comparable structure and optical properties, could also serve as an effective solution for ultrafast pulsed lasers.

Over the past decade, innovative two-dimensional (2D) materials, including phthalocyanines (SnPc), topological insulators, and transition-metal dichalcogenides, have shown great potential as saturable absorbers (SAs)(Ahmad, Salam, et al., 2024). These materials are generally incorporated into fiber laser cavities by placing thin film forms between two fiber ferrules, taking advantage of their unique optical characteristics ultrafast relaxation times, high optical nonlinearity, and wide optical absorption ranges(Ali et al., 2023b). The Q-switched and mode-locked fiber lasers can be realized by the integration of a saturable absorber (SA) materials into the laser cavity. However, these SA materials have inherent limitations that can affect their laser performance(Ahmad, Salam, et al., 2024; Ali et al., 2023a; N. F. B. Z. Farina Saffa Binti Mohamad Samsamnun, 2024).

The nonlinear optical properties of SnPc have been studied across various applications, including organic solar cells and sensors. However, its potential as a saturable absorber in fiber lasers is particularly noteworthy for ultrafast photonics. Research on other tin-based compounds, such as Tin (IV) oxide and Tin selenide (SnSe), has revealed excellent saturable absorption characteristics in fiber laser systems, resulting in the generation of high-power, passively Q-switched pulses with narrow pulse widths and high repetition rates(Ma et al., 2021; Sun et al., 2018). These results suggest that tin-based materials, including SnPc, can be effectively employed in fiber laser systems for pulse generation.

Moreover, SnPc exhibits reverse saturable absorption (RSA), a property that enhances its suitability for high-intensity pulse generation. RSA increases light absorption as intensity rises, leading to efficient pulse modulation. This characteristic has been successfully utilized in other materials, such as tin disulfide (SnS_2), which has been employed to generate mode-locked pulses in erbium-doped fiber lasers(Niu et al., 2017). In this study, we investigate the application of Tin (II) phthalocyanine as a saturable absorber in an erbium-doped fiber laser to generate pulsed laser output. We examine its nonlinear optical properties, including modulation depth and saturation intensity, and assess its performance in achieving passive Q-switching and mode-locking. The findings of this study contribute to the expanding research on metal phthalocyanine-based saturable absorbers, emphasizing the potential of SnPc for advanced ultrafast photonic applications(Cherian, 2008; Greif et al., 2013).

2. Tin Phthalocyanine SA preparation and characterization

SnPc belongs to the phthalocyanine (Pc) family, featuring a central tin (Sn) atom coordinated within a macrocyclic Pc ligand. This ligand is composed of four isoindole units connected by nitrogen atoms, creating a highly conjugated ring structure. The metal-phthalocyanine (MPc) family, to which SnPc belongs, is particularly notable for optical and electronic applications due to the sensitivity of π-π* transitions within the Q-band(Yamashita et al., 1998). In this study, we fabricated the SnPc film SA using the embedding method with polyvinyl alcohol (PVA) as the host matrix. Initially, a PVA solution was prepared by dissolving 1 g of PVA powder (Sigma Aldrich, CAS: 9002-89-5) in 100 ml of deionized (DI) water, stirring continuously until the PVA was fully dissolved, forming a clear solution. Following this, 2.5 mg of SnPc powder was added to 5 ml of the PVA solution in a laboratory bottle. The resulting mixture was stirred for 48 hours to achieve a uniform dispersion of SnPc particles within the PVA matrix. Once thoroughly mixed, the solution was cast onto a petri dish and left to dry at room temperature, forming a SnPc film SA. This embedded SnPc film was then characterized to assess its optical properties and suitability as a saturable absorber for laser applications. Figure 1 provide visual representation of the complete fabrication process.

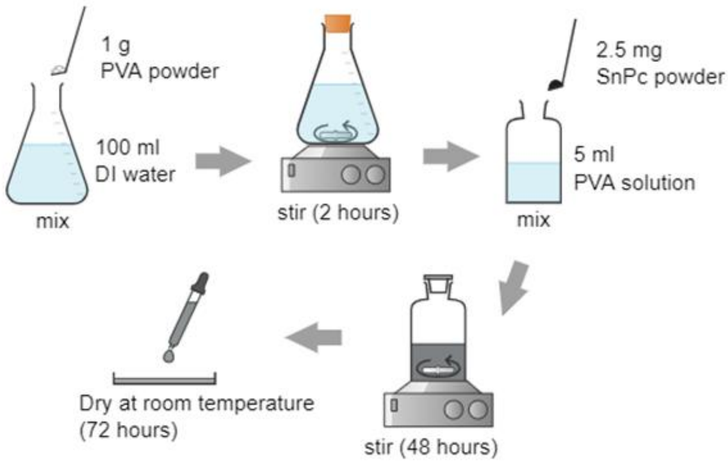
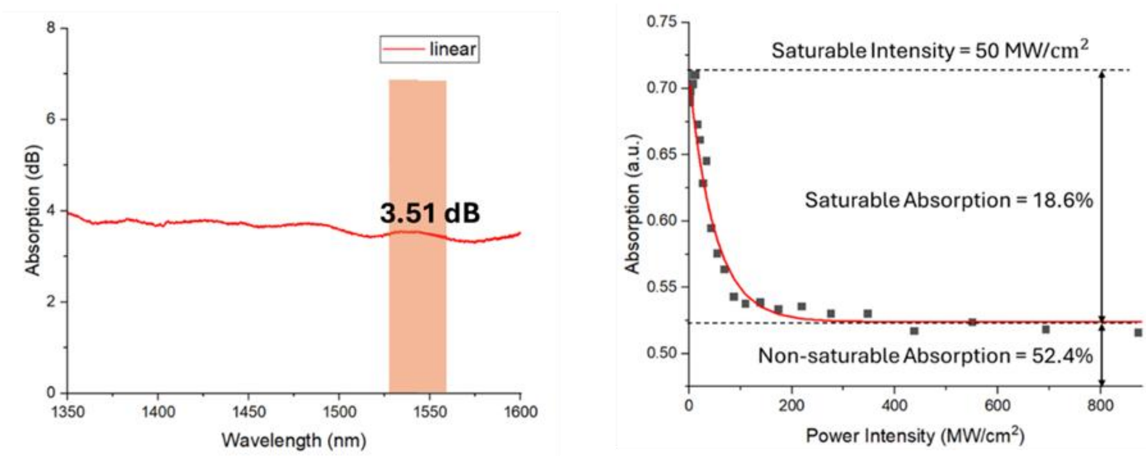


Figure 1. Complete fabrication procedure for SnPc film SA.

An analysis of the optical characteristics of the SnPc film was conducted to evaluate its potential for generating short pulses. The linear absorption of the SnPc film saturable absorber was measured across different wavelengths using a white light source and an optical spectrum analyzer, revealing baseline absorption characteristics. Figure 2 (a) shows the linear absorption profile, indicating 3.51 dB absorption at 1556.8 nm wavelength. The film's nonlinear properties were then assessed via power-dependent transmission technique. As depicted in Figure 2 (b), the absorption changes with power density, fitting well with the saturation model equation(Zheng et al., 2012):

$$\alpha(I) = \frac{\alpha_S}{1 + \frac{I}{I_S}} + \alpha_{NS}$$

where α is optical absorption, α_S is saturable absorption, I is input light intensity, I_S is saturation intensity and α_{NS} is non-saturable absorption. The nonlinear analysis reveals a saturation intensity of about 50 MW/cm², where absorption significantly reduces. The saturable absorption is 18.6%, indicating the portion that decreases at saturation, while the constant non-saturable absorption is approximately 52.4%. This nonlinear response confirms the SnPc film's effectiveness as a saturable absorber for Q-switched pulse generation.



(a) **(b)**

Figure 2. Optical characterization of SnPc film (a) linear (b) nonlinear absorption profile.

3. Experimental Setup

This Q-switched Erbium-Doped Fiber Laser (EDFL) setup depicted in Figure 3, utilizes a 1.8-meter-long erbium-doped fiber (EDF) as the gain medium to amplify light in the 1.5 µm region. A 980 nm laser diode serves as the pump source, injecting energy into the EDF through a 980/1550 wavelength division multiplexer (WDM). The WDM selectively couples the pump light into the EDF, enabling efficient energy transfer. An optical isolator ensures unidirectional light flow to maintain cavity stability while the SA mechanism initiates Q-switching by modulating the light intensity, producing short, high-energy pulses. The SA mechanism was assembled by attaching a small piece at 1 mm x 1 mm dimension of SnPc film between two ferrules of an FC/PC fiber. A small amount of index-matching gel was applied to the fiber end before connecting the ferrules via a fiber adapter. An 80/20 output coupler is placed at the end of the cavity, extracting 20 % of the circulating light for laser performance analysis. The remaining 80% of energy is retained in the cavity to sustain continuous Q-switched pulse formation.

The spectral analysis of the generated EDFL Q-switched was inspected using optical spectrum analyzer (OSA - ANRITSU, MS9710C). Meanwhile its temporal activity was assessed using the 350 MHz digital storage oscilloscope (GWINSTEK, GDS-3352) and a 7.8 GHz radio frequency spectrum analyzer (RFSA) (ANRITSU, MS2683A) that incorporates a 7 GHz InGaAs photodetector. The output power of the pulse train was measured using a Thorlabs optical power meter (PM100D) paired with a photodetector (PD: S145C).

4. Results and Discussion

4.1. Q-Switched Operation

The Tin Phthalocyanine Saturable Absorber (SnPC-PVA SA) was deliberately extracted from the laser cavity to explore the possibility of self-Q-switching phenomena occurring within the Erbium-Doped Fiber Laser (EDFL) cavity in the absence of the SnPC-PVA SA. Despite the existence of a diverse array of pump power variations, the resulting outcome was confined to the attainment of a continuous-wave (CW) laser. The successful operation of the continuous-wave (CW) laser was observed under the application of a pumping power of 81 mW. The successful accomplishment described herein was facilitated by the incorporation of the SnPc SA film within the cavity of the erbium-doped fiber laser (EDFL) via the implementation of a fiber-ferrule platform structured in a sandwich configuration. As the pump power was incrementally increased to 84.5 mW, a sequence of stable Q-switched laser pulses was observed.

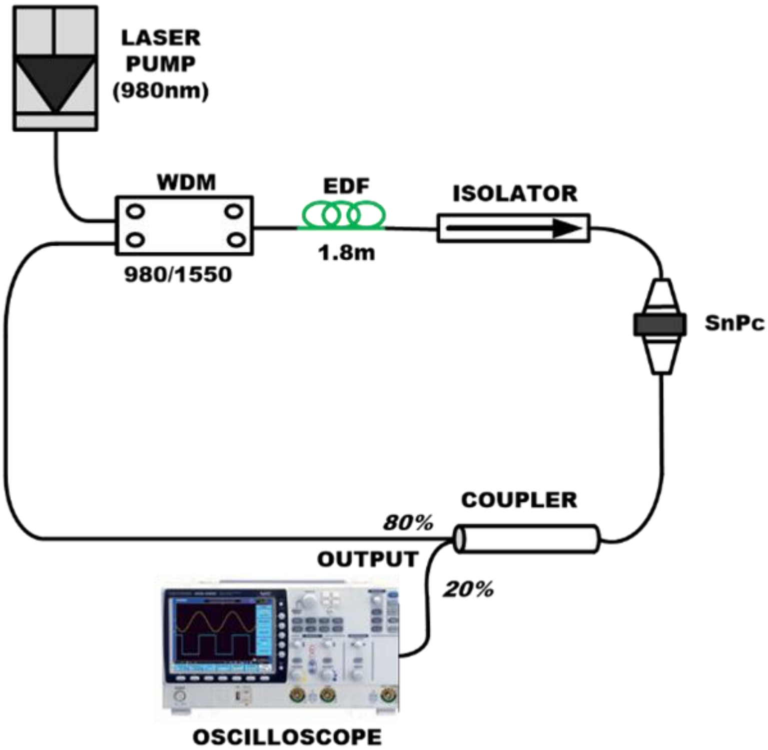


Figure 3. Laser configuration of Q-switched EDFL based of SnPc film SA.

Remarkably, the Q-switching operation exhibited a persistent behaviour even when the pump power was augmented to a higher value of 180.4 mW. The Q-switched pulses were observed to operate at a central wavelength of 1556.8 nm, as demonstrated in Figure 4 (a). The pulse trains of the Q-switched laser at three distinct pump powers are illustrated in Figure 4 (b), (c), and (d). The experimental findings indicate that the pulse output exhibited a consistent and stable pulse train when the pump power was varied between 84.5 mW and 180.4 mW. Remarkably, an observed phenomenon was the reduction in pulse-to-pulse interval from 16.7 µs to 11.8 µs as the pump power was progressively increased. The trend of pulse interval reduction was consistently observed until the upper limit of pump power was reached at 180.4 mW. The measured pulse-to-pulse interval exhibited a notable variation, which can be attributed to the discrepancy between the minimum and maximum pump power provided. This variation was quantified to be 4.9 µs. The observed repetition rate and pulse width patterns exhibit a striking similarity to the characteristic attributes commonly observed in Q-switched fiber lasers. The pulses that were observed exhibited a conspicuous lack of amplitude modulation, indicating the absence of self-mode-locking phenomena caused by Q-switching.

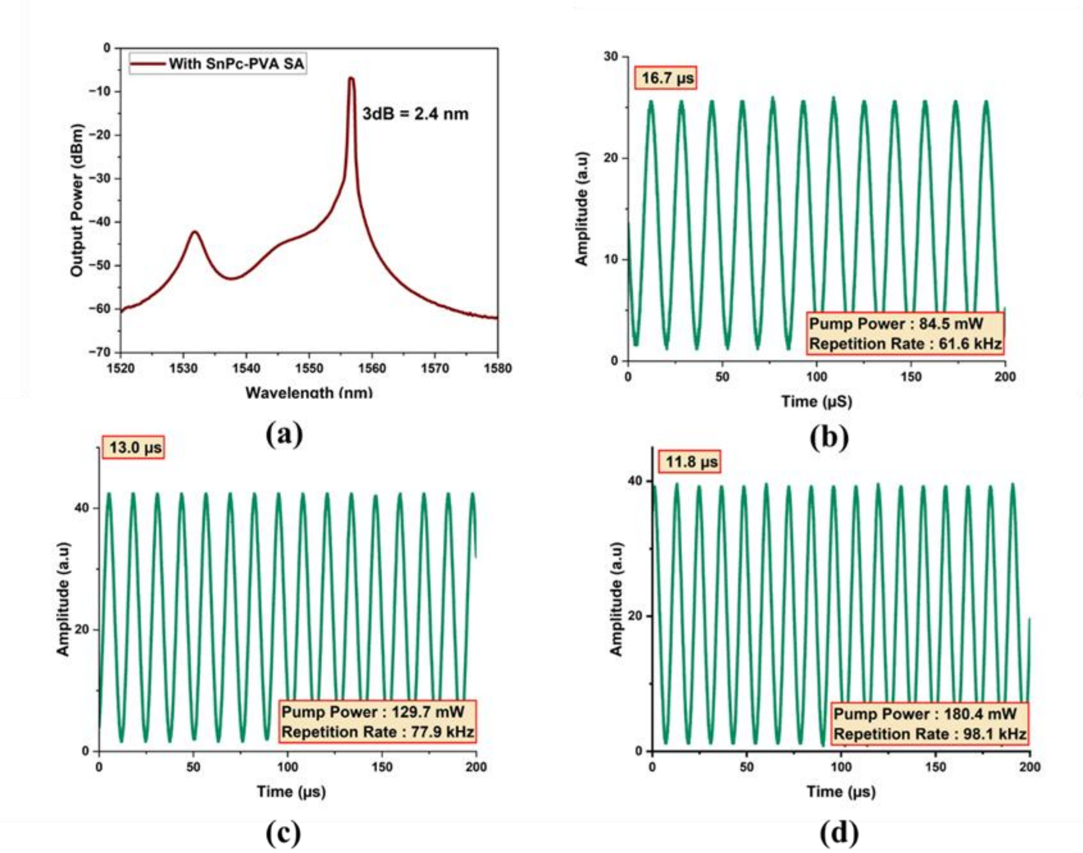


Figure 4. The output characteristics of the mode locked EDFL (a) Output Spectrum centred 1556.8 nm (b) oscilloscope pulse train at 84.5 mW (c) oscilloscope pulse train at 129.7 mW (d) oscilloscope pulse train at 180.4 mW

Figure 5 (a) displays the radio frequency (RF) spectra acquired from the diode at a power level of 180.4 mW. The RF spectrum exhibits the presence of numerous harmonics, encompassing a frequency range of 1.6 MHz. The most prominent frequency in this spectrum is determined to be 51.2 kHz. After careful examination, it was noted that the signal-to-noise ratio (SNR) of the radio frequency (RF) signal at the given frequency surpassed 50 dB. This discovery offers additional empirical evidence of the stability of the Q-switching operation. Figure 5(b)(c) presents a visual depiction of the laser pulse characteristics in relation to the pump power. Figure 5 (b) demonstrates the relationship between the average output power, single pulse energy, and pump power. The Q-switched functionality displayed consistent behavior as the pump power was varied from 84.5 mW to 180.4 mW. On the other hand, there was a consistent and steady increase in the average output power, which ranged from 5.0 mW to 9.2 mW. The increase in pump power will result in a higher gain, resulting in an increase in pulse energy due to the faster accumulation of Q-switched pulses. Based on our extensive research, it has been established that a single pulse can potentially achieve a maximum energy value of 93.3 nJ. Figure 5 (c) illustrates the correlation between the pulse repetition rate and width as the pump power increases. It is interesting to observe that the repetition rate of the mode-locked fiber laser remains consistent regardless of the length of the cavity. In the case of Q-switched pulses, the rate of generation depends on the level of saturation of the surface area (SA). Figure 5 (c) clearly demonstrates a strong correlation between the laser's repetition rate and the pump power. There is a clear relationship between the increase in observed frequency, from 61.6 to 98.1 kHz, and the corresponding increase in pump power, from 84.5 to 180.4 mW. The observed increase in repetition rate can be attributed to the enhanced saturation rate exhibited by the SA mechanism, which is influenced by higher pump power. Upon careful analysis, it becomes clear that there was a significant reduction in pulse width, specifically from 7.8 to 4.9 µs, as the pump power was gradually increased from 84.5 to 180.4 mW. It is worth mentioning that as the pump power increases, there is a proportional increase in the rate of photon density growth, in addition to the observed slope efficiency of 4.2%. This phenomenon is indicative of the duration of energy storage. Consequently, the occurrence of accelerated pulse formation leads to an increased repetition rate.

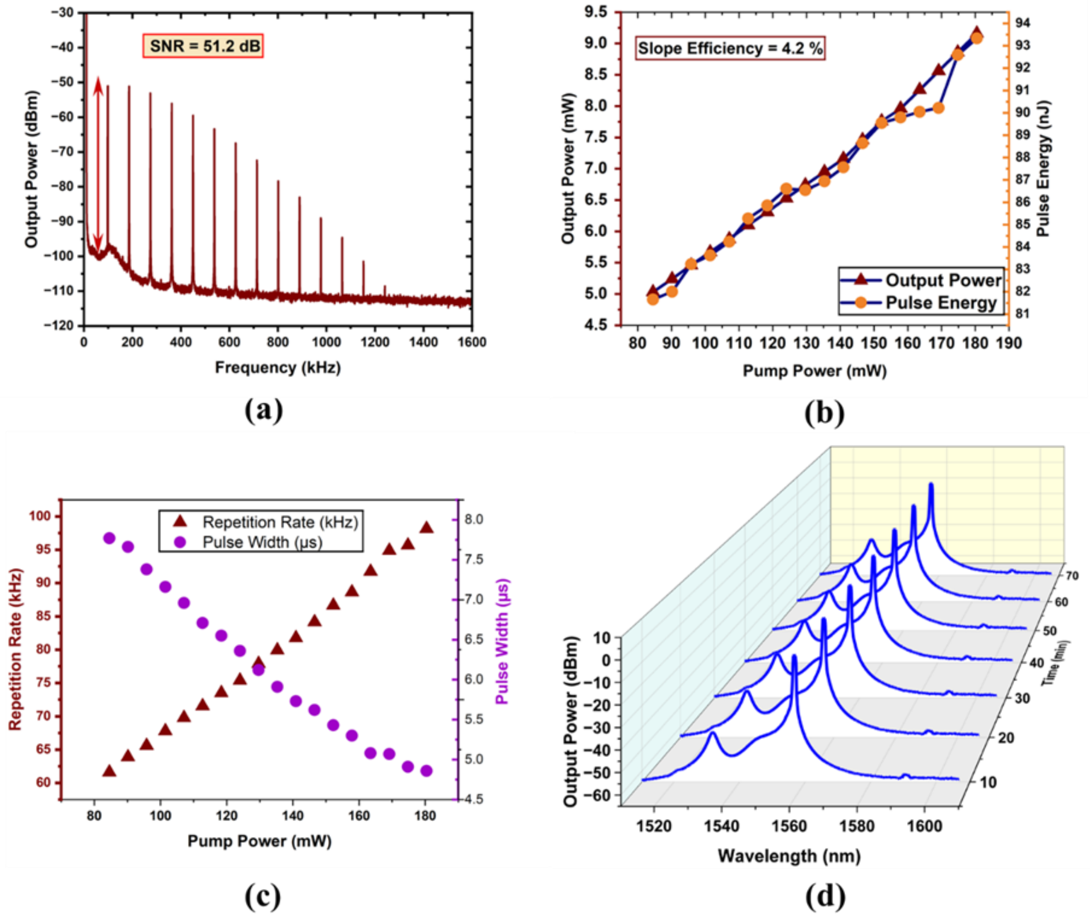


Figure 5. The output characteristics of the mode locked EDFL (a) RF spectrum with initial span of 1.6 MHz (b) optical output power vs pulse energy (c) repetition rate vs pulse width (d) stability over 70 minutes span.

Furthermore, it is crucial to acknowledge that the laser setup being discussed did not include a polarization controller because it was determined that the impact of polarization on the laser and pulsing operations was negligible. Based on the observations, it can be concluded that the manipulation of the cavity's polarization state had minimal impact on both the optical spectrum and the characteristics of the pulse trains. To further obtain the pulse characteristics, the signal was put under stability test for over 70 minutes to identify any fluctuations in the signal. As in Figure 5(d) the pulse generation with 10 minutes interval did not shows any obvious differences indicating the thermal effects within the SA and the gain medium were well-managed.

5. Conclusion

The results show that tin phthalocyanine is an excellent saturable absorber for Q-switching in fiber lasers, providing steady performance across a wide range of pump powers from 84.5 mW to 180.4 mW. Furthermore, the system demonstrated excellent long term spectral stability confirming the viable pulses in Q-switched pulse generation. This research adds to the development of low-cost, efficient Q-switched fiber lasers with potential applications in fields needing reliable pulsed laser outputs. Tin phthalocyanine's shown high repetition rate, steady operation, and robust pulse characteristics make it a potential material for future developments in pulsed fiber laser technology.

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