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Fiber Laser Generation in the C-Band: Leveraging Organic Material in the Erbium-Doped Fibers

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Abstract

In recent years, the increasing demand for compact, sustainable, and cost-effective laser technologies has prompted the exploration of organic materials as alternatives to conventional inorganic saturable absorbers (SAs). Among these, Polyaniline (PANI) has emerged as a promising candidate due to its favorable nonlinear optical properties, ease of fabrication, and environmental friendliness. This study investigates the application of PANI as a SA in Q-switched Erbium-Doped Fiber Lasers (EDFLs) operating within the C-band (1530 - 1565 nm), a critical range for optical telecommunications. The objective was to assess PANI's performance in comparison with traditional inorganic materials, focusing on key metrics including pulse energy, emission wavelength, repetition rate, and signal-to-noise ratio (SNR). The experimental setup employed a 1.55 µm Q-switched EDFL configuration with PANI incorporated into the laser cavity. Results showed that PANI produced a maximum pulse energy of 52 nJ, a repetition rate of 78.13 kHz, and an SNR of 60.4 dB. While inorganic materials demonstrated superior pulse energy and repetition rate, PANI exhibited stable and repeatable performance across varying pump powers. This indicates its suitability for applications that prioritize consistent pulse delivery over peak performance—such as telecommunications, biomedical imaging, and spectroscopy. The findings highlight PANI's potential as a viable, eco-friendly, and cost-effective saturable absorber, offering a practical balance between efficiency and sustainability. Future research should focus on enhancing its performance through hybrid organic-inorganic composites and further investigating other organic materials for advanced fiber laser applications.

Keywords

Polyaniline (PANI), Saturable Absorber, Q-Switched EDFLs, Eco-Friendly Laser Technology

1. Introduction

Erbium-Doped Fiber Lasers (EDFLs) are key technologies in telecommunications, medical diagnostics, and material processing due to their efficient operation in the C-band (1530 - 1565 nm) [1]. A central component in these lasers is the saturable absorber (SA), which enables passive Q-switching by adjusting intracavity losses, resulting in high-energy, short-duration pulses [1]. Traditionally, inorganic SAs, such as carbon nanotubes and graphene, have been used in EDFLs because of their excellent nonlinear optical properties [2]. However, there is growing interest in organic materials as sustainable and cost-effective alternatives for SAs. Among these, Polyaniline (PANI), a conductive polymer, has gained attention for its tunable properties, ease of fabrication, and potential environmental benefits [3].

Fiber lasers operate based on the principle of stimulated emission of radiation. They produce coherent light by amplifying photons in a specific direction, which is essential for precise applications in fields like telecommunications and material processing [4]. The properties of lasers, such as intensity, coherence, and directionality, make them essential for many industries.

A key mechanism in laser operation is stimulated emission, which is influenced by factors like photon number, laser line shape, and interaction between light and matter. These principles are important for understanding advanced laser systems and phenomena such as Purcell enhancement and super radiance in nano-lasers [5]. Additionally, advances in laser machining and femtosecond laser inscription have improved laser precision, impacting efficiency and surface quality [6].

Q-switching is important for producing short, intense pulses by modulating the laser cavity's quality factor (Q). Passive Q-switching, which uses saturable absorbers, controls energy storage and releases it as powerful pulses. For example, materials like VS2 nanosheets have shown great potential as SAs in Er-doped fiber lasers, achieving high repetition rates and stability [7]. Ongoing research into materials like TiOxNy thin films is improving the versatility of Q-switching in laser systems [8].

The C-band (1530 - 1565 nm) is crucial for optical communication because of its low attenuation and high bandwidth, making it ideal for long-distance, high-capacity data transmission. Recent innovations, such as soliton crystal micro-combs, show the C-band's potential to support ultra-high data rates [9]. It also plays a key role in optical modulation techniques, enabling efficient data transmission and supporting secure, high-speed communication technologies [10].

Saturable absorbers in EDFLs generate short, high-energy pulses by becoming transparent at high intensities, thus controlling intracavity light and enabling pulse output. Studies on 2D materials, such as SnS_2 and TiS_2, show their effective absorption properties and potential to improve the stability and efficiency of Q-switched lasers [11]. Other materials like $Mo_2Ti_2C_3Tx$ MXene are being explored for their high modulation depth and potential for high-performance mid-infrared lasers [12].

Organic materials like PANI are gaining importance due to their unique properties. PANI, with its high porosity, surface area, and tunable optical properties, has shown promise as an SA in laser systems [13]. Composites of PANI, especially with materials like graphene and carbon nanotubes, offer enhanced conductivity and stability, making them suitable for advanced laser technologies [14]. Organic materials provide several advantages, including low-cost production, eco-friendliness, and tunable optical properties for specific applications, such as organic photodetectors and electrochromic devices [15].

PANI has proven effective as a saturable absorber in fiber lasers, improving pulse stability and repetition rates. The addition of nanoparticles like nickel has enhanced PANI's broadband saturable absorption, aiding the development of high-performance pulsed lasers across various wavelengths [16]. These advancements highlight PANI and other organic materials as sustainable and efficient SAs for future laser systems.

2. Fabrication of PANI Thin Film for Saturable Absorber

A Polyaniline (PANI) thin film was synthesized by combining PVA (Polyvinyl Alcohol) with PANI using the solvent-casting technique. This method involves depositing a solution mixture of PVA and PANI onto a clean petri dish's surface. PVA was chosen for its excellent film-forming properties, tensile strength, emulsification ease, and high-water solubility, making it an ideal host material. It exhibits minimal absorption of white light and has a high melting temperature of 200˚C, which is suitable for high-intensity laser applications. The fabrication process is cost-effective and hazard-free.

The fabrication process began with preparing a PVA solution: 1 g of PVA powder was dissolved in 120 mL of deionized water at 90˚C for 24 hours with stirring at 300 rpm. PANI powder was then mixed with the PVA solution to create a free-standing thin film. Approximately 30 mg of PANI powder was dissolved in 30 mL of PVA solution and stirred at room temperature for 24 hours, followed by 45 minutes of ultrasonic treatment. This process was repeated twice.

Approximately 5 mL of the PANI-PVA solution was transferred to a petri dish and exposed to ambient air for 48 hours, resulting in a dry PANI-PVA thin film with a diameter of 3 cm and a thickness ranging from 17 - 25 μm. The density variations of the film were controlled by adjusting the volume of the solution used.

Field emission scanning electron microscopy (FESEM) at 1000× magnification was used to analyze the film's morphology. The SEM images revealed uniform dispersion of PANI particles, which were well-integrated within the polymer matrix. Energy dispersive X-ray (EDX) analysis confirmed the elemental composition, verifying the presence of PANI in the thin film.

The optical characteristics of the synthesized PANI film were examined, showing light absorption characteristics suitable for laser applications. The film exhibited a noticeable increase in absorption around the 1.55 μm wavelength range, indicating its potential for effective interaction in fibre laser systems.

Non-linear saturable absorption behaviour of the PANI thin film was investigated using a twin-balanced detector technique. The absorption properties were analyzed with a mode-locked laser operating at a repetition rate of 1.885 MHz and a pulse width of 3.62 ps. A 3 dB coupler was used to direct part of the pulse toward the saturable absorber, while the rest passed through a bare single-mode optical fibre. The data fitting confirmed that the film exhibited significant modulation depth, with a saturation intensity (Isat) of 10 MW/cm^2. The thin films are typically around 50 μm thick and the recovery time is estimated to be around 1 picosecond [17].

This study reveals that adjusting the film thickness can further enhance the modulation depth and reduce non-saturable absorption. The PANI film exhibited a high quality of saturable absorption, remaining within the thermal damage threshold, and demonstrated promising performance for use as a saturable absorber in fibre laser systems (**Figure 1**).

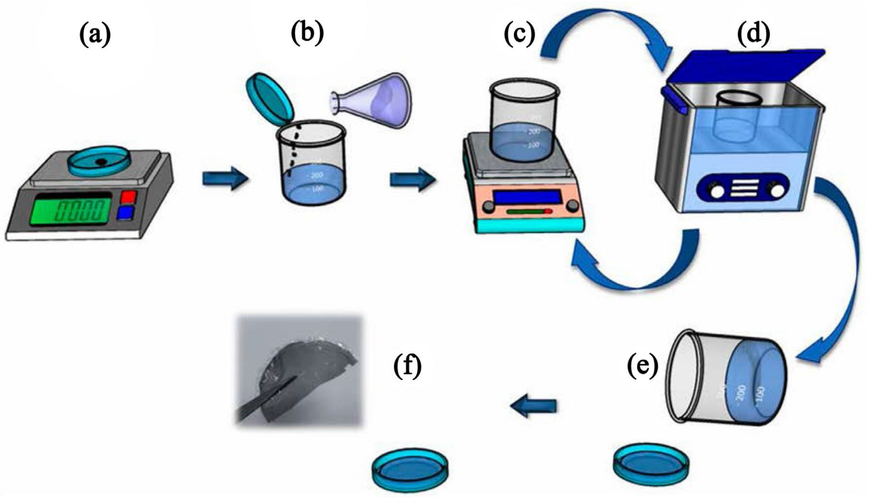

Figure 1. Sequential steps in Polyaniline PVA film synthesis: (a) PANI powder weighing, (b) Mixing with PVA solution, (c) Stirring, (d) Ultrasonication, (e) Pouring into petri dish, (f) Thin film formation through drying [18].

3. Experimental Setup

The 1.55 μm Q-Switched Erbium-Doped Fiber Laser (EDFL) system was carefully designed to ensure efficient and stable operation. The setup begins with a 980 nm laser diode, which acts as the primary pump source. The output from the diode is directed into a 980 nm wavelength division multiplexer (WDM) that separates the light into 980 nm and 1550 nm wavelengths. The 980 nm light is then passed into an erbium-doped fiber (EDF), which amplifies the signal. The 1.8-meter-long EDF was chosen for its stability and efficiency.

An isolator is included to ensure unidirectional light flow and prevent back reflections, which could destabilize the system or damage the laser diode. The optical path includes FC/PC fiber ferrules, connected via a clean fiber adapter, with a 2 mm × 2 mm organic material thin-film saturable absorber (SA) placed between the components. This SA modulates the light within the cavity, enabling Q-switching. An index-matching gel is used to reduce unwanted reflections, ensuring optimal coupling.

The system also features a 90:10 optical coupler to control light distribution within the cavity. As shown in Figure 2, 90% of the light is sent back into the cavity at 1550 nm, while the remaining 10% is used for diagnostic measurements. The cavity length and placement of the components are optimized for stability and efficiency, with the system operating in the anomalous dispersion region to ensure stable pulse generation.

Several diagnostic tools are used to monitor the system's performance. A 300 MHz digital storage oscilloscope and a spectrum analyzer are used to observe the pulse laser's time and frequency domain features. A high-resolution optical spectrum analyzer captures continuous-wave and Q-switched spectral data, while an optical power meter measures the laser diode's output at different pump settings.

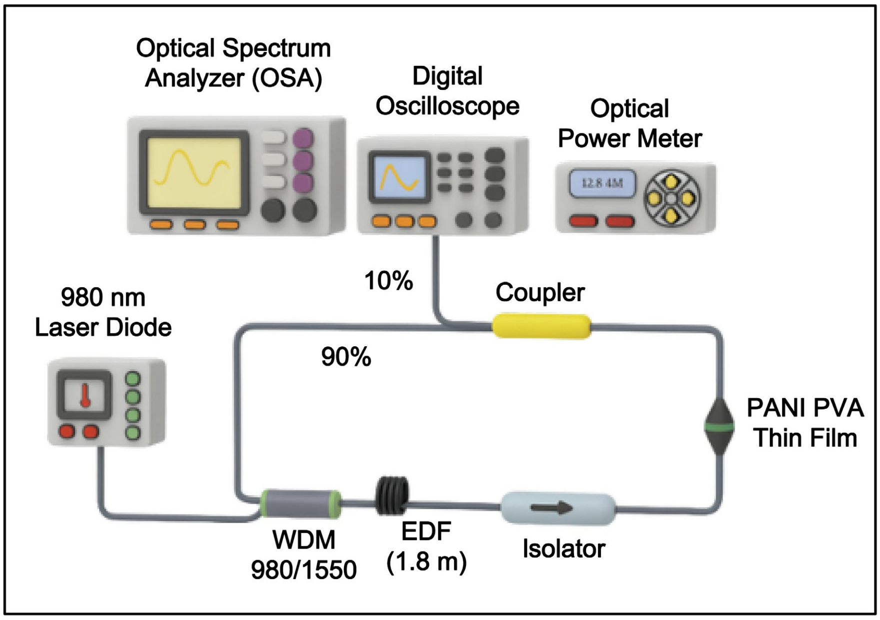

Figure 2. Ring cavity configuration with PANI-PVA film SA for Q-switched EDFLs.

The setup underwent iterative tuning to ensure precise alignment and optimal component performance. This careful calibration resulted in a reliable, high-performance Q-switched EDFL system, capable of producing stable laser pulses for advanced applications. The study of pump powers in Erbium-Doped Fiber Amplifiers (EDFAs) is crucial for understanding the effective power utilized for amplification, as it is influenced by factors such as coupling efficiency and fiber transmission losses. The pump powers in the study reflect the optical power launched into the EDF, not the output from the diode, which is a significant distinction. Measurement uncertainty, often ranging from 1% to 5% [19], is a critical aspect that can affect the reported pump powers, and future studies should include these uncertainties to enhance reproducibility and reliability (**Figure 3**).

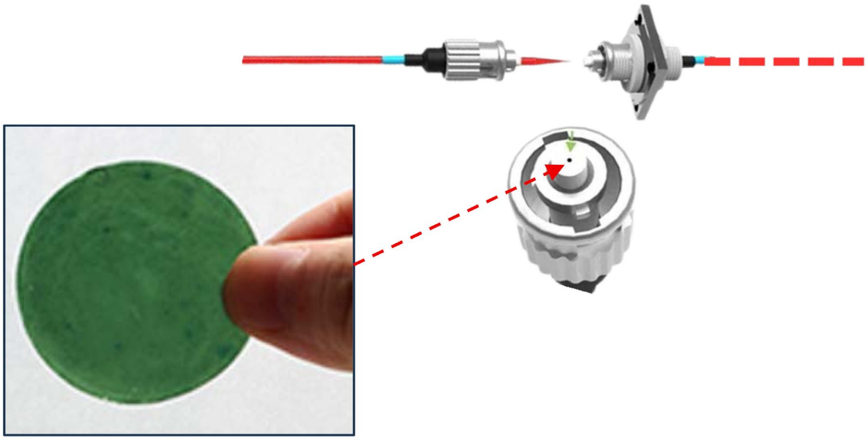

Figure 3. Polyaniline PVA thin film incorporates into ring cavity.

4. Result and Discussion

The results presented in this section reveal the effects of varying pump power on the performance metrics of PANI, providing insights into its suitability for different laser applications. Key findings, including optical spectrum characteristics, pulse energy, output power, and SNR, demonstrate how PANI performs as a saturable absorber in Q-switched EDFLs. This discussion highlights the strengths and limitations of PANI, offering valuable perspectives on its potential in fiber laser systems, particularly in applications where pulse stability and moderate power output are crucial. The derivation of pulse energy and peak power from the oscilloscope data and the 90:10 coupler ratio is essential to accurately assess the performance of the Q-switched Erbium-Doped Fiber Laser (EDFL) system. The oscilloscope measures the instantaneous peak voltage of the pulse, which, when combined with the system's known parameters, allows for the calculation of peak power. The 90:10 coupler ratio plays a crucial role, as it divides the power between the output and the reference. In this case, 90% of the power is directed towards the main output, and 10% is used for diagnostic measurements. Pulse energy can be derived using the relationship between the average power (P_{av}) and the repetition rate (f) as $E = P_{avg}/f$, Where P_{avg} is the average power, and f is the repetition rate of the laser[citation]. The average power can be derived from the measured voltage and the coupler ratio. In addition, Peak power is calculated using the formula, $P_{\text{peak}} = E/\tau$, Where E is the pulse energy and τ is the pulse duration [20]. The pulse duration can be calculated from the repetition rate.

4.1. Pulse Energy, Repetition Rate and Wavelength

The performance of Polyaniline (PANI) as a saturable absorber in Q-switched Erbium-Doped Fiber Lasers (EDFLs) showed promising results. As the pump power increased, pulse energy also increased, reaching a maximum of 52 nJ at the highest pump power of 159.84 mW. At lower pump powers, the pulse energy was 3.5 nJ at 113.68 mW. The repetition rate for PANI increased from 44.72 kHz at the lowest pump power to 78.13 kHz at the highest, demonstrating its consistent ability to handle different levels of pump power. PANI emitted light within the C-band (1530 - 1565 nm), with a central wavelength at 1544.8 nm, making it well-suited for telecommunications. The spectral width for PANI was measured at 7.5 nm, indicating its stable and narrow emission, which is beneficial for high-precision applications.

4.2. Signal-to-Noise Ratio (SNR)

The Signal-to-Noise Ratio (SNR) was measured to assess the quality of the laser pulses. The SNR for PANI was 60.4 dB, indicating a stable output with relatively low noise. Despite the moderate SNR, PANI demonstrated stable pulse quality, making it a suitable choice for applications where consistency is more important than the highest SNR, such as biological imaging and telecommunication.

4.3. Comparison of Organic and Inorganic Materials

PANI offers consistent performance and is an eco-friendlier option compared to traditional inorganic materials. It is ideal for applications that do not demand the highest peak power but require stable pulse delivery. While other materials may offer higher pulse energy, PANI's performance is sufficient for a wide range of applications, especially when considering its cost-effectiveness and environmental sustainability.

5. Conclusions

This study examined the use of Polyaniline (PANI) as a saturable absorber (SA) in Q-switched Erbium-Doped Fiber Lasers (EDFLs) showed that PANI performs well, achieving a maximum pulse energy of 52 nJ and a repetition rate of 78.13 kHz at the highest pump power. The Signal-to-Noise Ratio (SNR) was 60.4 dB, indicating stable performance. PANI proved to be a reliable alternative for certain applications, offering an eco-friendly and cost-effective solution compared to traditional inorganic materials. This research highlights the potential of organic materials, particularly PANI, for use in fiber laser systems, making it a promising choice for telecommunications, biological imaging, and other laser-based technologies. While PANI showed promise, its pulse energy and SNR performance could be further improved. Additionally, its long-term stability in high-power systems requires further exploration. Future research should focus on enhancing PANI's performance and exploring its use in real-world applications (**Figures 4-9**) (**Table 1**).

Table 1. Comparison of the Q-switched EDFL's performance utilizing various SA materials.

SA materials	Laser performance metrics					
	Central wavelength (nm)	Max. repetition rate (kHz)	Min. pulse width (µs)	Max. output power (nJ)	SNR (dB)	Refs.
V_2O_5 PEG	1562.4	97.2	4.71	3.2	45	[21]
P_3HT	1562	78.63	3.79	1.183	49.7	[22]
FlrPic	1560.4	87.4	3.4	10.72	61	[23]
Ti_2SnC	1531.3	105.9	3.0	6.65	65.4	[24]
$CuFeO_2$	1559.2	193.7	42.5	59.6	74	[25]
PANI	**1544.6**	**78.13**	**5.99**	**4.9**	**60.4**	***This study***

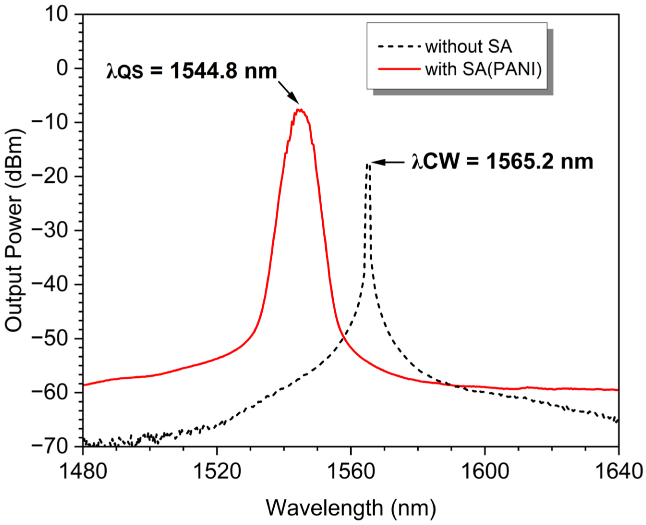

Figure 4. Spectral output of a Q-switched EDFL with and without Polyaniline (PANI) as the saturable absorber. λQS = 1544.8 nm, λCW = 1565.2 nm.

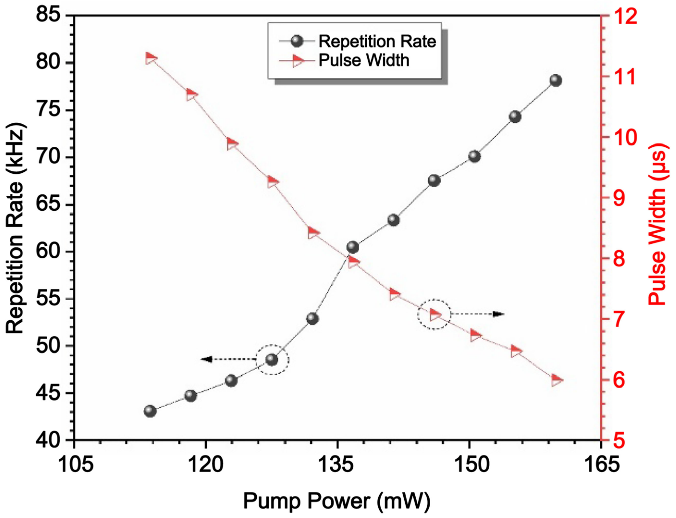

Figure 5. Repetition and pulse width variation with pump power.

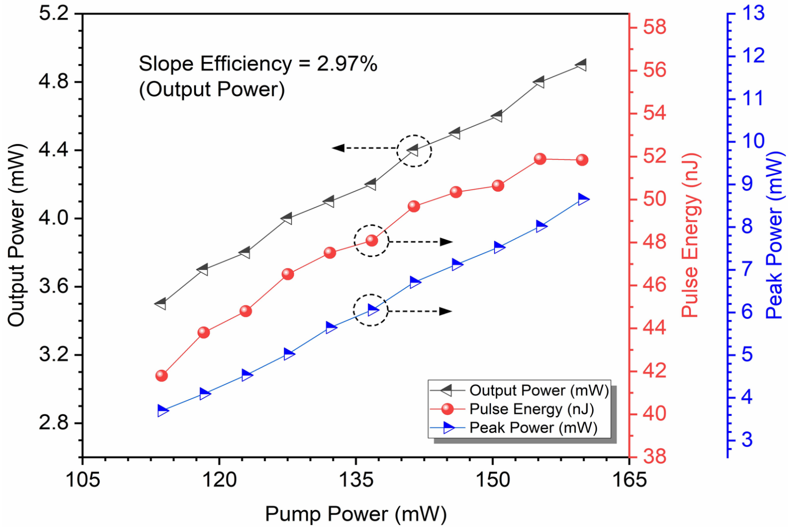

Figure 6. Output power, pulse energy, and peak power variation with pump power.

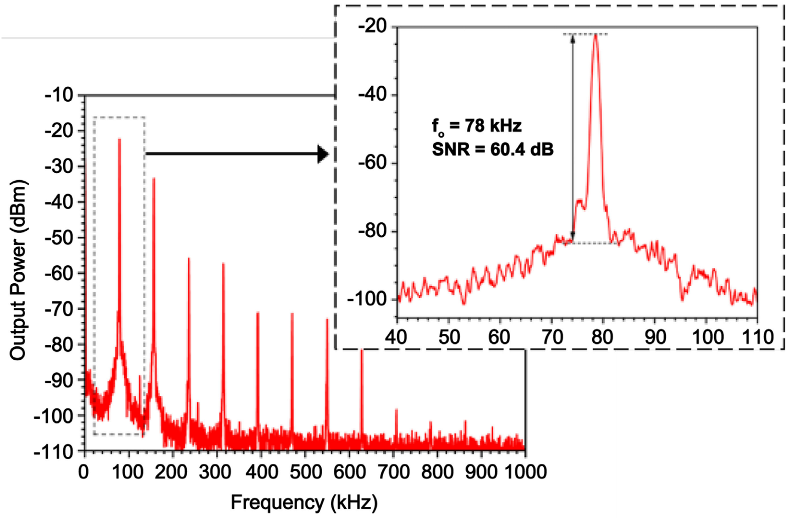

Figure 7. RF spectrum of 159.84 mW pump power of Q-Switch EDFLs using PANI.

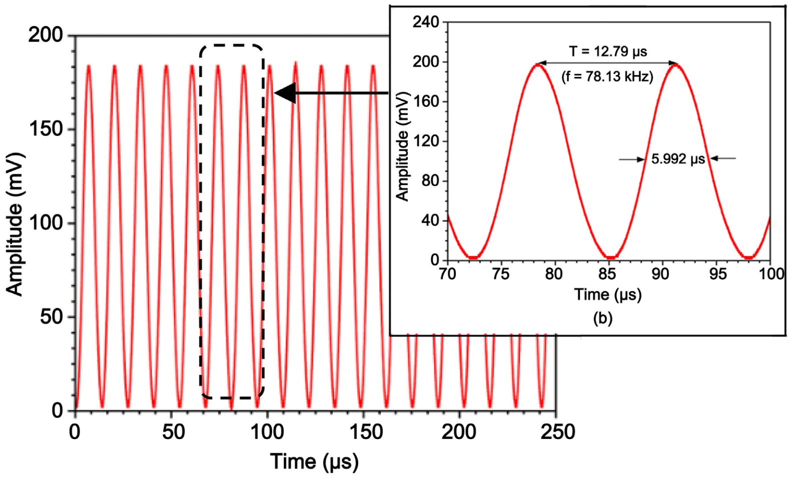

Figure 8. Pulse train at 159.84 mW and dual pulse envelopes for PANI.

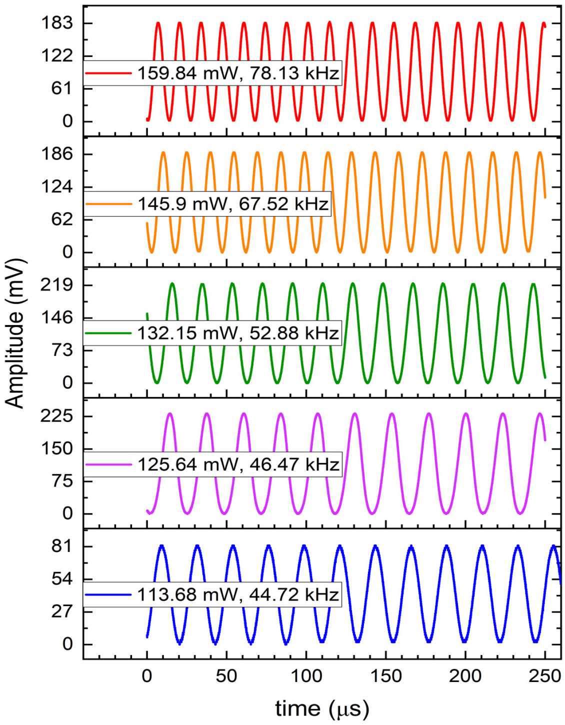

Figure 9. Pulse train evolution with pump power variation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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