SQUARE PULSE SWITCHABLE OPERATIONS IN L-BAND FIBER RING LASER

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Abstract. We demonstrate the generation of single, two and three square shaped pulses in a co-doped Er:Yb anomalous dispersion fiber ring laser. Benefiting from increased nonlinear effects due to long cavity, various square pulse patterns are formed depending on the cavity parameters. The experimental results contribute to a better understanding of square pulse characteristics and the dynamics of multiple pulse patterns formation.

Key words: fiber ring laser, anomalous dispersion, square pulse patterns.

1. INTRODUCTION

In the last decades, the rapid development of optical fibers and technologies has enabled new experiments to further understand the nonlinear dynamics inside fiber lasers. Mode-locked fiber lasers are widely used as platforms for generating ultrashort pulses and have attracted much attention due to their operation lifetime, stability, compactness and their wide range of applications in fields such as optical communications, biomedical, microscopy, sensing, material processing, and defense [1–3]. Also, fiber lasers present a large platform for investigating nonlinear phenomena in fundamental physics. From a dynamical point of view, they exhibit a variety of behaviors due to nonlinear interactions, dissipative structures, and self-organization effects. Different nonlinear dynamics have been observed in fiber lasers regardless the dispersion regime or the mode-locking mechanism. They can operate in single or multiple pulsing regimes in the cavity [4]. Depending on the cavity parameters, multiple soliton distributions such as soliton molecules [5–7], multi-soliton compounds [8, 9] and soliton explosions [10–14] can be observed.

Recently, single square wave pulses (SWPs) in passively mode-locked fiber lasers have attracted much attention due to their special dynamics and versatile applications [15–19]. Dissipative soliton resonance (DSR), as a kind of SWP, was first investigated theoretically in 2005 by Komarov et al. [20] who predicted that pulse width could increase without breaking for a specific set of parameters. This first
predication was confirmed later in 2009 by solving the complex cubic-quintic Ginzburg–Landau equation [21, 22]. Akhmediev et al. [23] demonstrated that the energy and width of DSR pulses could scale with the pump power owing mainly to the peak power clamping (PPC) effect in the cavity. Since then, various DSR patterns have been thoroughly investigated in various mode-locking setups and dispersion regimes [24–28]. Based on the reports concerning DSR pulses, this SWP can operate without wave breaking when the pump power increases. Under certain circumstances, multiple square pulsing operation occurs in passively mode-locked fiber lasers and allows the generation of regimes such as step-like pulses [29, 30] or harmonic DSR pulses [31]. This behavior is different from the pulse-breaking characteristic of classic passively mode-locked lasers and is in contrast with the theory [22] because the cavity periodicity was not included in the model. Another kind of SWP was recently demonstrated in passively mode-locked fiber laser, and in contrast with DSR, it can operate in different states. When the nonlinearities are high enough in the cavity, solitons tend to exhibit nonlinear behaviors, which leads to various pulse shapes. This kind of SWP was called noise-like pulses (NLPs) because of their typical autocorrelation trace and optical spectrum [32–35]. Versatile multiple rectangular NLPs in a NALM based fiber laser were recently demonstrated with high nonlinearities where they could evolve into various patterns depending on cavity parameters [36]. It was also reported that NLP could coexist with high order harmonic solitons molecules in a similar experimental configuration [37]. Lately, Ma et al. [38] demonstrated the generation of harmonic SWP that can operate in both single and dual pulse states. Based on various previous reports, we can assume that SWP whether DSR or NLP can operate at multiple pulsing state when nonlinearities are increased in the cavity. All these observations and results have been fundamental in understanding soliton dynamics in fiber lasers.

In this paper, we experimentally demonstrate that by carefully selecting cavity parameters we obtain multiple nanosecond square pulses in a passively mode-locked fiber laser through nonlinear polarization evolution mechanism. Depending on these parameters, a single square pulse profile can evolve into various patterns. In contrast with [36], we conduct our experiment in a fiber ring laser in the anomalous dispersion regime and we investigate in detail the behavior of each operation in terms of average power, energy, peak power, and pulse width.

2. EXPERIMENTAL SETUP

Figure 1 depicts the schematic of fiber laser setup used in our experiment. It is based on a simple all fiber ring cavity configuration. To achieve high gain and output power, we use a C-band double clad V-groove Er:Yb 1 W fiber amplifier from Keopsys. The maximum achievable output power in continuous lasing operation is 1 W, ensured by the 5 W pumping power. Several laser diodes operating at 980 nm pump a 5 m-long double-clad fiber that has a second order dispersion of −0.021 ps²/m.
To ensure large anomalous dispersion together with large pulses duration, we add a piece of 500 m single mode fiber (SMF) so that the net cavity dispersion in the anomalous regime is about \(-11.872 \text{ ps}^2/\text{m}\). The total cavity length is about 520 m, which corresponds to a round-trip time of 2.6 \(\mu\text{s}\) corresponding to a free spectral range of about 384 kHz. Two polarization controllers (PCs) were used with a polarization sensitive isolator to control the nonlinear losses. A polarization-insensitive isolator (PI-ISO) was employed to force unidirectional operation of the cavity. A 10/90 output coupler is used to extract 10% of the power from the cavity.

![Fig. 1 – Schematic of a passively mode-locked ring laser.](image)

The output intensity is analyzed using a high-speed photodetector (TIA-1200), and visualized with a fast oscilloscope (Keysight DSO81304B, 13 GHz, 40 GSa). The maximum output power is measured using a 3W integrating sphere (Thorlabs SC416). The spectral properties are analyzed with an optical spectrum analyzer (Anritsu MS 9710C) and the pulse duration is measured with an optical autocorrelator with a scanning range of \(\pm100 \text{ ps}\) (Femtochrome FR-103 XL). An electronic spectrum analyzer (Rohde & Schwarz FSP Spectrum Analyzer 9 kHz to 13.6 GHz) is used to characterize the radio frequency spectrum of the laser.

3. RESULTS AND DISCUSSION

The proposed laser self-starts when the pump power reaches 400 mW. Above this threshold, the laser operates in irregular multiple pulsing soliton regime depending on the adjustment of the polarization controllers. When the pump power reaches 700 mW, a single square pulse per cavity roundtrip is formed inside the cavity as shown in Fig. 2. The oscilloscope trace of the pulse train is shown in Fig. 2a, where the interval is 2.6 \(\mu\text{s}\), corresponding to the cavity roundtrip. By zooming on the pulse, we measure in Fig. 2b the width of the square pulse around 12 ns. Since the cavity losses have been adjusted to operate in the L-band [39, 40], the optical
spectrum exhibits a central wavelength at 1615 nm with a 3-dB spectral bandwidth of around 15 nm. Figure 2c shows the optical spectrum trace of the generated pulse with a resolution of 0.03 nm. Figure 2d shows the RF spectrum recorded with a resolution of 1 kHz. The repetition rate is about 384 kHz corresponding to the 2.6 µs pulse interval and 520 m cavity length, indicating that the laser operates at the fundamental cavity frequency. The signal to noise ratio is about 50 dB indicating that the fundamental mode-locked laser is stable.

Fig. 2 – Mode-locked operation at the fundamental repetition rate: a) pulse train, b) characteristics of the single square pulse, c) corresponding optical spectrum, d) corresponding RF spectrum exhibiting the fundamental cavity frequency.

By fixing the polarization controllers we gradually increase the pump power from 700 mW to 1.7 W. It should be noted that the PCs used in this work are fiber squeezing PCs, thus we could not quantitatively study their influence on the formation of multi-pulse pattern. The variation of the square pulse with regards to different pump powers is presented in Fig. 3. When the pump power increases, the square pulse width broadens from 12 ns to reach 38 ns while the peak power remains nearly constant. The evolution of the pulse characteristics for different
pump power is presented in Fig. 3. The pulse width and energy increase linearly with the pump power without affecting the peak power. At a pump power of around 1.7 W, the pulse energy is around 65 nJ. The pulse width can be tuned from 11 to 38 ns. This evolution in the pulse characteristics is in agreement with both DSR pulses and rectangular NLPs [24, 26, 28, 32, 33, 36, 41].

As it has been previously demonstrated, high nonlinear accumulation can lead to pulse breaking in soliton lasers [20]. The long length of the cavity would allow us to exploit such phenomena by contributing to the nonlinearity. When the pump power exceeds 1.7 W, the single square pulse breaks into two square pulses per roundtrip as shown in Fig. 4.

If we continue increasing the pump power till 2.8 W, the pulse width of each pulse broadens accordingly, as it can be seen in Fig. 5.
In Figure 6, the evolution of the pulse width and the energy for different pump powers starting from the threshold 700 mW is presented. When the pump power is tuned from 700 mW, the energy and pulse width increase as we have mentioned before till the pump power exceeds 1.7 W, then we have a dual square pulse operation: the first pulse width increases from 7 ns to 14 ns whereas the second pulse width increases from 6 ns to reach 13 ns, as it can be seen in Fig. 6a. Meanwhile, as it should be physically expected, the total energy per cavity round-trip increases linearly as presented in Fig. 6b regardless the number of pulses.

Above 2.8 W of pump power, the dual square pulse operation is lost, and we obtain a triple square pulse operation per roundtrip. Since our amplifier has a maximum pump power of 3 W, we investigate the behavior of the triple pulse
operation from 2.8 W till 3 W. In Figure 6a, the first pulse width increases from 13.8 ns to 15.71 ns, whereas the second increases from 12.83 ns to 15.22 ns and the third from 10.9 ns to 12.1 ns. The total energy per cavity roundtrip increases linearly with the pump power to reach a maximum of 152 nJ as exhibited in Fig. 6b. The triple pulse operation remains stable without any pulse breaking when we increase the pump power, and at the maximum pump power we record the temporal profile of our results in Fig. 7.

![Figure 7](image)

**Fig. 7** – Triple square pulse operation per cavity roundtrip at maximum pump power.

During the experiment, the spectral profile of the pulses did not change, but we have recorded a slight shift in the central wavelength varying from 1597 nm to 1615 nm while keeping the same 3 dB bandwidth of around 15 nm as shown in Fig. 8a. The shift in the central wavelength that is seen in Fig. 8b could be affiliated to a drift occurring due to a change in the ambient temperature.

![Figure 8](image)

**Fig. 8** – Variation of the spectrum for different pump powers: a) evolution of the spectral profile for different pump powers, b) 2D projection of the evolution.
We also studied the effect of hysteresis in the cavity by decreasing the pump power from 3 W till we reach 700 mW. In Figure 9, we can clearly see that we obtain the same behavior as before with a small difference in the size pulses. Indeed, after we reach 2.76 W, the triple pulse operation becomes a dual pulse operation, but the pulses width is different than the values we obtained before. The first pulse decreases from 34 ns to 31 ns and the second from 16 ns to 10 ns. When we reach 2.385 W, we obtain a single pulse per cavity which width is around 38 ns and decreases with the pump power till it reaches 9.62 W at 780 mW. The scenario of switching between different patterns is qualitatively the same as when we increase the pump power, but the switching powers are different.

In general, the square pulse characteristics through each operation and the complete experiment while increasing or decreasing the pump power are in agreement with DSR and NLP profiles [24, 26, 28, 32, 38]. In Figure 2, when the pumping power is increasing, the switching between single pulse and double pulse happens at 1.785 W whereas in Fig. 9a when we decrease the pump power, the switching between double and single pulse happens at 2.385 W. Therefore, in contrast with previous reports about the generation of multiple square pulses in a fiber laser [36, 38], we point out a large bistability domain of about 600 mW between single square and double square pulse operation.

4. CONCLUSION

In conclusion, we experimentally demonstrated the evolution of nanosecond square pulses patterns in an anomalous dispersion fiber ring laser. Starting from a noise-like single square pulse per cavity roundtrip, the laser can operate in multipulse state by adjusting the polarization controllers and tuning the pump power. We have studied in detail different aspects of pulse characteristics in the cavity and their evolution with increasing and decreasing pump powers. Furthermore, we have
pointed out the existence of a large bistability region between two adjacent multiple square pulse states. In agreement with the observations in Ref. [36], we have demonstrated the universality of multiple square pulse generation regardless the laser setup. Our results can help in further understanding the dynamics of large pulses in fiber lasers and their characteristics.

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