Noise-like Pulses from an All-Normal-Dispersion Fiber Laser with Weakened Spectrum Filtering

Zhicheng Zhang, Sha Wang, and Jun Wang

Abstract—Noise-like pulses (NLP) are extremely sought after in many fields. Here, we experimentally and numerically investigated the generation of noise-like pulses in an all-normal-dispersion fiber laser with weak spectrum filtering. With the insertion of the grating as a tunable spectrum filter, the laser operates at a stable dissipative soliton state with a 3.84 ps duration. Replacing the grating with a mirror, NLPs with double-scale intensity autocorrelation trace is ultimately attained. Numerical simulations are performed in detail and demonstrated that with the absence of a spectrum filter, the stable state cannot be established but form the random pulse cluster. The random pulse cluster achieves dynamic stability with suitable feedback, and the NLP is ultimately generated. The NLP here is directly evolved by the initial noise, and no other states occur during its evolution. These explorations could deepen the understanding of NLP and enrich the complex dynamics of the ANDi ultrafast fiber laser.

Index Terms—ultrafast fiber laser, all-normal dispersion, noise-like pulses, spectral filtering.

I. INTRODUCTION

Ultrafast fiber lasers are extremely sought in many fields. Various pulse states can be formed in normal or anomalous dispersion, such as conventional soliton [1], stretched pulse [2], self-similar soliton [3], dissipative soliton (DS) [4], dissipative soliton resonance [5], noise-like pulse (NLP) [6], etc. Among these, NLPs have gained recent research interests due to their low temporal and spatial coherence [7–9]. NLPs exhibit a fine inner structure of many narrow sub-pulses (a few hundred femtoseconds in width) with randomly varying intensity and duration, and on propagation through dispersive fiber NLPs do not broaden significantly [10]. They are widely used in optical coherence tomography and supercontinuum generation where low coherence, broad-spectrum, and high peak power are required [11, 12]. Besides, NLPs contain very complex fine structures and dynamics providing a benchmark to study extreme events like optical rogue waves [13]. Reports reveal that NLP will be formed if laser parameters deviated from the ordinary operation conditions [14–18]. In 1997, Horowitz et al. first demonstrated the NLPs in an Er-doped mode-locked fiber laser and supposed that NLPs are caused by a polarization-dependent delay effect introduced by fiber birefringence [19]. While Smirnov et al. presented that NLP can also occur in weakly birefringent fiber lasers [20]. On the other hand, Tang et al. concluded that NLP generation is caused by the combination of the soliton collapse and cavity positive feedback for dispersion-managed fiber lasers [15]. Aguerregaray et al. proposed that NLPs are caused by the Raman-driven destabilization of mode-locked long-cavity fiber lasers [21]. Recently, the all-normal dispersion (ANDi) fiber laser plays a dominant role in achieving high power and energy ultrafast pulse [4, 22–25]. In this context, the NLPs generated in ANDi fiber lasers have also been widely explored [17, 18, 20, 26–29]. In Ref. [20], Smirnov et al. observed NLPs in an ANDi laser, and point out that small intensity fluctuation introduced by the polarization controllers can result in the NLPs. In Ref. [14], Li et al. proposed that NLPs are attributed to the amplitude modulation introduced by negative feedback and the peak-power-limiting effect of the mode-locker. One can find that the reported NLPs in the ANDi laser is a usual result initiated from DS pulse while increasing pump power or/and adjusting polarization, and most of these studies mainly focused on how NLP is transformed from the coherent stable pulses. A natural question is: can NLP directly evolve by the initial noise in ANDi fiber lasers? Moreover, in addition to the saturable absorber, the spectrum filter is also employed as a crucial component to modulate the pulse in the ANDi laser [25], its impact on NLP generation still needs to be further explored.

In this work, the spectrum filter is explored to attain the NLPs in the ANDi fiber laser. We experimentally demonstrate that the transition from DS to NLP can be achieved by weakening the filtering effect. With the insertion of the grating as a spectrum filter, the laser is at a stable DS state with a 3.84 ps duration. Replacing the grating with a mirror, NLP with a double-scale intensity autocorrelation trace can be attained. To offer a detailed description of the pulse dynamics, we erect the theoretical model based on the pulse-tracing and the simulation results emphasize that NLP directly evolves from the initial noise in ANDi fiber lasers under weak spectrum filtering. In this case, the stable coherent state cannot be established but forming the random pulse cluster, and the pulse cluster achieves dynamic stability with suitable feedback, i.e., NLP is generated.

This work was supported by the National Natural Science Foundation of China (61975137). Corresponding author: Zhicheng Zhang.

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The experiment setup and results are given in Section II. Then, Section III presents the simulation model and results. Finally, conclusions are made in Section IV.

II. EXPERIMENT SETUP AND RESULTS

2.1 Experiment setup

The schematic of the all-normal dispersion fiber oscillator is shown in Figure 1. 30 cm highly Yb<sup>3+</sup> doped fibers (YDF) (Liekki Yb1200-4/125 1200 dB@976 nm) with a calculated GVD of 26.2 fsec<sup>2</sup>/m are used as the gain medium. The fiber represented in black is about 4 m HI1060 fiber with GVD~24.7 fsec<sup>2</sup>/m, i.e., a single-mode fiber (SMF) at 1 µm. The net cavity dispersion is around 0.11 ps<sup>2</sup>. A 976 nm laser diode (LD) with a maximum pump of 350 mW is coupled into the cavity through a wavelength-division multiplexer (WDM). The fiber collimators (C1 and C2) transmit the signal to the spatial path. The quarter-wave plate (QWP1 and QWP2), half-wave plate (HWP1), and polarization splitting prism (PBS1) are served as a nonlinear polarization rotation (NPR) device to realize mode-locking. Meanwhile, PBS1 is also employed as the output coupler. The Faraday rotator (FR), HWP2, and longitudinally placed PBS2 act as an isolator by controlling the polarization, and this part plays the role in protecting the pump.

2.2. The formation of dissipative soliton

Firstly, we insert 300 lines/mm grating to form a single pass Gaussian filter [30]. Stable coherent pulses can be attained by controlling the mode-locker, and the output performances are measured under a 350 mW pump power. An ultrafast photodetector (Thorlabs™, model FDS025) with a rise time of 47 ps and a Rohde & Schwarz™ oscilloscope with a bandwidth of 2 GHz are used to characterize the pulse train. The output pulse trains observed in time windows of 6 ms and 200 ns are shown in Figures 2(a) and 2(b), respectively. One can observe that the pulse interval is around 23.5 ns, and the corresponding repetition rate is about 42.5 MHz. It is in line with the calculated value with cavity length. Furthermore, an autocorrelator (Femtochrome™, model FR-103WS) with a time resolution ratio of 1 fs is adapted to parse the pulse. It can be seen from Figure 2(c) that the duration is about 3.84 ps after Gaussian fitting. Figure 2(d) shows the output power versus the pump. The laser starts a continuous-wave (CW) operation when the pump is about 60 mW. The self-started mode-locking can be obtained as the pump exceeds 180 mW. The output power increases almost linearly with the pump, the maximum output is ~92.8 mW, and the envelope efficiency is around 32%. It can be further calculated that the maximum single pulse energy is ~2.2 nJ and the peak power is about 573 W. A spectrum analyzer (Yokogawa™, AQ6370C) is further employed to characterize the spectrum. As presented in Figure 2(d), the spectrum is with steep edges, the central wavelength is around...
1030 nm and a 3-dB width is ~11.3 nm. Owning these typical features, it can be analyzed that the pulse generated is the dissipative soliton [25]. To offer a detailed description of the pulse stability, the radio frequency (RF) spectrum is also measured by an RF analyzer (Keysight™, model N90000B). As shown in Figures 2(e) and (f), the fundamental repetition rate is about 42.5 MHz, and the signal-to-noise ratio is higher than 80 dB. Combining with the above parameters, one can observe that the mode-locking is very stable. During the experiment, the stable mode-locking can be maintained for several hours.

2.3 The formation of noise-like pulse

To investigate the impact of a spectrum filter, instead of the grating with a plane mirror, and fix the other parameters. In this case, only NLP can be attained, whether ergodically adjusting the waveplate or controlling the pump power. The measured pulse trains are shown in Figures 3(a) and (b). It can be observed that the pulses have a large random amplitude fluctuation, and the pulse interval is around 23.3 ns, corresponding repetition rate of about 43 MHz. Noise-like pulse is composed of many random sub-pulses, the autocorrelation trace with a spike is the typical feature (Figure 3(c)) [19]. The measured width of the pedestal is about 40.2 ps. As presented in Figure 3(d), the self-started noise-like pulse mode-locking can be obtained as the pump exceeds 280 mW, and the maximum output is about 108.2 mW. The calculated envelope efficiency and single pulse energy are around 37% and 2.5 nJ. The spectrum has an irregular shape, the central wavelength is at around 1030 nm and the 3-dB width is about 5.4 nm. We also measured its RF spectrum, as shown in Figures 3(e) and (f). The fundamental repetition rate is about 43 MHz, and the signal-to-noise ratio is about 60 dB. Different from the dissipative soliton mode-locked state, the RF spectrum has a small modulation and a sidelobe. Analyzing the above pulse dynamics, one can observe that the mode-locking is not stable, but it is in line with the characteristics of NLP.

III. THEORETICAL MODEL AND SIMULATION

3.1 Theory model

For exploring the pulse dynamics, we erected a theoretical model based on the pulse-tracing. The simulation cavity is consistent with the experiment, which mainly consists of 0.3 m Yb³⁺ doped fibers, 4 m SMF, a Gaussian bandpass filter, an NPR mode locker, and a 35% output coupler. The pulse evolution in fiber is described by the generalized nonlinear Schrödinger equation [31]:

\[
\frac{\partial u}{\partial t} = -i \beta_2 \frac{\partial^2 u}{\partial \omega^2} + \frac{g}{2} u + i \gamma |u|^2
\]

(1)

Where \( u \) is the slow-varying envelope, \( t \) and \( z \) are the retarded time and transmission distance; \( \gamma \) represents the nonlinear coefficient, setting to 4.7 \( W^{-1} km^{-1} \) for SMF and 5 \( W^{-1} km^{-1} \) for YDF; \( \beta_2 \) is the second-order dispersion, setting to 26.2 \( fs^2/mm \) for YDF and 24.7 \( fs^2/mm \) for SMF. Higher-order dispersion and nonlinear effects were ignored. The formula \( g = g_{avg} \times g(\omega) \) can calculate the gain coefficient with a gain spectrum \( g(\omega) \) in the Lorentzian profile. The \( g(\omega) \) is with a center wavelength \( (\lambda_0) \) of 1030 nm and gain bandwidth of 50 nm. Considering the gain saturation, there are:

\[
g_{avg} = \frac{g_0}{1 + |u|^2/d\text{sat}/E_{\text{sat}}}
\]

(2)

In Eq. (2), \( g_0 \) is the small-signal gain at the central wavelength, which is set to 10 \( m^{-1} \) for YDF and 0 \( m^{-1} \) for SMF; \( E_{\text{sat}} \) represents the gain saturation energy, which is relative to pump power [32], setting \( E_{\text{sat}} = 9.5 \) nJ.

The NPR mode-locker exhibits a sinusoidal shape
transmissivity verse instantaneous power, the transmissivity can be written as [14, 17, 33]:

\[
|T_{NPR}|^2 = \sin^2(\alpha)\sin^2(\beta) + \cos^2(\alpha)\cos^2(\beta) + \frac{1}{2} \sin(2\alpha)\sin(2\beta)\cos(\Delta\varphi_L + \Delta\varphi_NL)
\] (3)

Where \(\alpha\) and \(\beta\) represent the azimuth angles of the polarizer and the analyzer, concerning the fast axis of the fiber. \(\Delta\varphi_L = \Delta\varphi_\text{0} + 2\pi(1 - \delta\lambda/\lambda_0)\) and \(\Delta\varphi_NL = 2\gamma\lambda PC\cos(2\alpha)/3\), denoting the linear and nonlinear phase delays, respectively. \(L\) and \(P\) are the total length of the cavity and instantaneous pulse power. \(\Delta\varphi_\text{0}\) and \(L_B\) are the initial phase delay, birefringence beat length, and the wavelength detuning. The parameters are set as \(\alpha = 0.28\pi\), \(\beta = 0.36\pi\), \(\Delta\varphi_\text{0} = 0.25\pi\), \(\delta\lambda/\lambda = 0\), and \(L_B = 1\). The NPR mode-locker can operate in the positive or negative feedback regime. The critical feedback power (CFP) is the power at which the feedback is transformed from positive to negative [17]. The simulated NPR transmission curve calculated by Eq. (3) is shown in Figure 4(a) (blue line). Considering the transmittance rate \(T\) is also related to the saturated absorption of the NPR, the CFP from positive feedback to negative feedback occurs at the maximum product of instantaneous power \(P\) and the corresponding transmittance rate \(T\) [34], as present in Figure 4(a) red line. That is, when the power is lower than the CFP, the higher the peak power, the larger the NPR transmittance, i.e., positive feedback.

A bandwidth \((\Delta\lambda)\) tunable first-order Gaussian spectrum filter is further adopted [35]. There exist three kinds of spectral filtering in this fiber oscillator: Gaussian spectrum filter introduced by the grating, gain filter introduced by the Yb\(^{3+}\) Gain medium, and sinusoidal filter introduced by NPR [16]. Since the nonlinear coefficient is related to wavelength, NPR can be both used as a mode locker and a spectral filter to promote the pulse evolution. The formula \(\gamma = 2\pi n_2/\lambda A_{eff}\) can calculate the nonlinear coefficient, where \(n_2\) and \(A_{eff}\) are the nonlinear-index coefficient and effective mode field area of the fiber, setting \(n_2 = 2.35 \times 10^{-22} \text{m}^2/\text{W}\), \(A_{eff} = 3.02 \times 10^{-11} \text{m}^2\), and \(P = 1550\) W. Figure 4(b) shows the calculated three kinds of spectrum filtering curves, and one can observed that the 8 nm Gaussian filter plays the leading role.

The total intracavity loss is set at around 10%. The simulation starts from arbitrary Gaussian-windowed white noise after the filter. We employed the split-step Fourier method to solve this model [36], and the time window and sampling points are set to 100 ps and 10,000. The time resolution is 10 fs. Usually, several tens of roundtrips are required for the solution to stabilize.

### 3.2 Simulation results and analysis

![Figure 5](image-url)

**Figure 5.** (a) Pulse envelope when \(\Delta\lambda\) varied; (b) Spectrum envelope when \(\Delta\lambda\) varied.

To investigate the influence of spectrum filtering on pulse dynamics, we increase filter bandwidth \(\Delta\lambda\) to simulate. Figure 5 shows the pulse and spectrum before the NPR mode-locker. When \(\Delta\lambda = 5\) nm, the stable pulse can be observed, and the pulse peak, duration, and energy are 0.99 kW, 5.54 ps, and 5.06 nJ. The self-phase modulation (SPM) effect makes the spectrum a sharper edge and large bandwidth of \(~25.7\) nm, and the "Cat's ear" spectrum proves the forming of dissipative soliton (DS) [25]. As \(\Delta\lambda\) increased from 5 nm to 15 nm, the output characteristics are always in line with the dissipative soliton,
while the pulse peak, duration, and energy are increased to 1.283 kW, 13.63 ps, and 17.4 nJ. Further weakening the spectrum filtering (Δλ > 15.5 nm), irregular pulse profiles can be observed. The pulse exhibits a fine inner structure of many narrow sub-pulses with randomly varying intensity and duration. We further simulated their autocorrelation trace to analyse the pulse state, as shown in Figure 6 (Δλ = 30 nm). Its intensity autocorrelation trace is two-scaled, consisting of a 29.3 ps pedestal and a 180 fs spike. The widths of the pedestal and the spike indicate the width of the wave packet and the average width of the sub-pulses inside the wave packet, respectively. The ratio of the spike to the pedestal is related to the density of the sub-pulse a larger ratio usually means a smaller sub-pulse density [26, 37]. In the simulation, we found the ratio is positively correlated with the filter bandwidth. The results indicate that weakening the spectrum filtering can realize the transition from DS to NLP state.

To explore the formation mechanism of NLP, we further simulated its pulse and spectrum evolution versus roundtrips, as present in Figures 7(b) and (b) (see Supporting documents). One can observe that the noise-like pulse here is directly evolved by the initial noise signal, and no transition states occur. The pulse dynamics are much different from previous explorations in the ANDi laser, in which NLP originate from strong spectrum filtering or mode-locker introduced amplitude modulation on the coherent stable pulses [14, 26]. In those cases, the NLP is a usual result initiated from DS pulse, and a stable transition state can be observed before NLP formation. The NLP evolution dynamics here are more consistent with the report on dispersion-managed oscillators [15].

In the ANDi fiber, the normal dispersion fiber will introduce the heavily up-chirp. In the absence of a suitable spectrum filter, the strong nonlinearity will lead to the explosive increase in new spectrum components, the stable state cannot be attained but form the random sub-pulses cluster. Figure 8 shows the peak power and energy versus roundtrips. Before the 69th cycle, since the peak power is lower than the CFT, the sub-pulses with higher peak experience a higher transmission, and is strengthened (see Supporting documents). The peak power is increased dramatically owing to the positive feedback. In addition, the wave packet has also been narrowed, since the attenuation of weak sub-pulses. At the 70th cycle, the peak power exceeds the CFT, and negative feedback will occur and stabilize the peak power. The random pulse cluster achieves
dynamic stability, and the NLP is ultimately generated. Random energy fluctuations can be observed in Figure 8(b), which is consistent with the experimental results. Combining the above analysis, strong nonlinearity and cavity feedback plays a key role in the formation of NLP in the ANDi fiber under weak spectrum filtering.

V. CONCLUSION

In conclusion, we have experimentally and numerically investigated the generation of noise-like pulses in an all-normal-dispersion fiber laser. The results emphasize that weakening the spectrum filtering can realize the transition from DS to NLP state. The NLP evolution dynamics are simulated in detail. Combining with previous reports, we can conclude that there is a great difference in NLP forming in the ANDi fiber laser with different spectral filtering effects. For strong spectral filtering, the amplitude modulation induced by reverse saturable absorption and the peak-power-limiting effect of the NPR plays a key role, and the NLP is a usual result initiated from the other stable pulse [14]. For weak spectrum filtering, strong nonlinearity and cavity feedback plays are the main incentives, the other stable pulse cannot be formed, NLP here is directly evolved by the initial noise. Convincingly, our work could help colleagues to further understand the NLP dynamics in the dissipative fiber laser system and assist their construction.

ACKNOWLEDGMENT

The authors would like to acknowledge Long Li and Xinxin Sun for their valuable help in paper writing.

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