Extreme Events in Passively Mode-Locked Lasers with normal dispersion –

Wonkeun Chang, The Australian National University
Jose M. Soto-Crespo, Instituto de Optica, C.S.I.C.
Peter Vouzas, The Australian National University
Nail Akhmediev, The Australian National University

Status – Generation of stable pulse trains is important for numerous laser applications where ultrashort optical pulses are needed. Yet, increasing demand for pulses with more extreme characteristics has shifted the focus towards highly nonlinear, non-stationary regimes of laser operation. Of particular interest is the study of the chaotic pulses generated by passively mode-locked lasers. Being an interesting object of nonlinear chaotic dynamics, they may also have important practical applications such as for generating supercontinua without the use of special fibers [1].

One particular type of chaotic pulses that have been reported in various experiments is the so-called noise-like pulses (NLPs), which were first observed in a fiber ring laser [2], and thereafter in various mode-locked laser configurations [3–5]. Experimentally, this regime of laser operation is characterized by its broad and smooth spectrum accompanied by the auto-correlation trace which has a sharp peak sitting on top of a broad pedestal. These features may indicate that there are multiple incoherent pulses that are bunched and traveling together in the laser cavity. However, the chaotic nature of the ultrashort structures in NLPs makes it difficult to experimentally resolve the fine details of the pulse and their shot-to-shot characteristics. Besides, it is not always clear if all reported NLPs refer to the same type of pulses. Thus, more studies are needed in this area.

Relying on numerical simulations is often more viable approach for investigating these pulses. One of the main techniques used in the modeling of passively mode-locked lasers is the master equation approach [6]. This method averages the effect of the components comprising the cavity, allowing one to study passively mode-locked lasers using a single partial differential equation. It essentially leads to a complex cubic-quintic Ginzburg-Landau equation (CGLE), which is the equation of minimal complexity that admits stable pulse-like solutions.

Contribution by the authors – In its normalized form, the CGLE is given by:

$$i\psi_z + \frac{D}{2}\psi_{tt} + |\psi|^2\psi + \upsilon|\psi|^4\psi = i\delta\psi + i\varepsilon|\psi|^2\psi + i\beta\psi_{tt} + i\mu|\psi|^4\psi,$$

where ψ is the complex envelope of the optical field, t is the time in a frame of reference moving with the pulse and z is the propagation distance along the unfolded cavity. The subscripts denote the derivatives with respect to the corresponding variable. On the left-hand side, D denotes the cavity dispersion, being anomalous when $D > 0$ and normal if $D < 0$, and ν is the quintic refractive index coefficient. Dissipative terms are written on the right-hand side where δ denotes linear gain/loss, β is the gain bandwidth coefficient, and ε and μ are the cubic and quintic gain/loss coefficients, respectively. The correspondence between these parameters with those of a mode-locked laser system depends on the particular design of the cavity and the mode-locking mechanism [7].

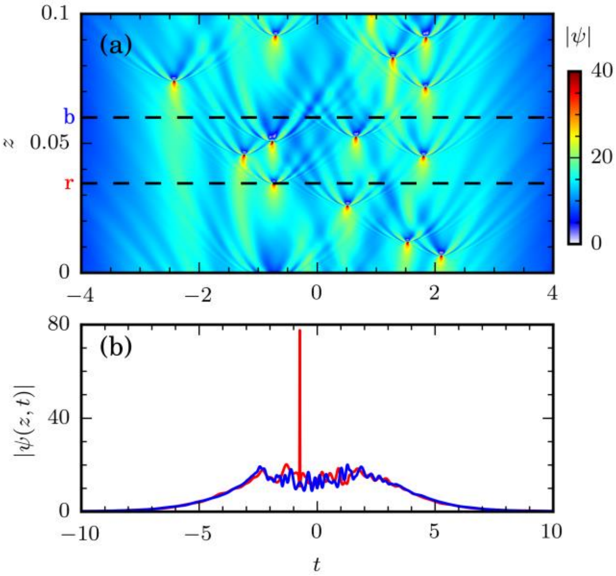

Figure 1 – Chaotic soliton obtained for the CGLE parameters $D = -2.7$, $\upsilon = -0.002$, $\delta = -0.08$, $\beta = 0.18$, $\varepsilon = 0.04$ and $\mu = -0.000025$. (a) Pulse amplitude evolution along z. The amplitude of the spikes exceeds the maximum color scale which is set to 40 for the sake of clarity of the whole pattern. (b) Pulse profiles at two different z, labeled 'b' and 'r' in (a) for blue and red profiles, respectively.

By solving the CGLE numerically for the set of parameters given in the caption of Figure 1, we obtained a chaotic dissipative soliton with noise-like features as shown in Figure 1. This particular soliton consists of a localized background with chaotically appearing spikes on top of it. Only the tails of the solution have a regular exponential decay. The tails do not change much along z. The false color plot of the field amplitude $|\psi|$ in the (t, z)-plane shown in Figure 1(a) clearly demonstrates that spikes appear irregularly across the pulse. These spikes are exceptionally narrow both in t and z direction in comparison to the width of the whole soliton.

The pulse profiles are plotted in Figure 1(b) at two different locations in z, one showing a typical pulse without the spike (blue), and another slice captured when the spike is present (red). The amplitude of the spike is ~80. This is 5 times higher than the average amplitude of the pulse, which amounts to the intensity amplification factor of 25.

The spikes shown in Figure 1 have the main features of dissipative rogue waves studied earlier in [8–10]. Figure 2 presents a probability density function (PDF) of the peak amplitudes in logarithmic scale calculated for the same set of CGLE parameters as in Figure 1. The PDF is obtained using the following approach. Firstly, the consecutive profiles separated by the z-interval of 0.02 are found to be completely uncorrelated. As a second step, all local maxima appearing in the chaotic region on top of each pulse profile separated by $dz = 0.02$ for 50 different realizations are recorded. Finally, the density of probability was calculated for each value of the amplitude after collecting the data of millions of local maxima. The amplitude slots have been chosen sufficiently small for the curve to be smooth but large enough to have adequate number of data within each slot.

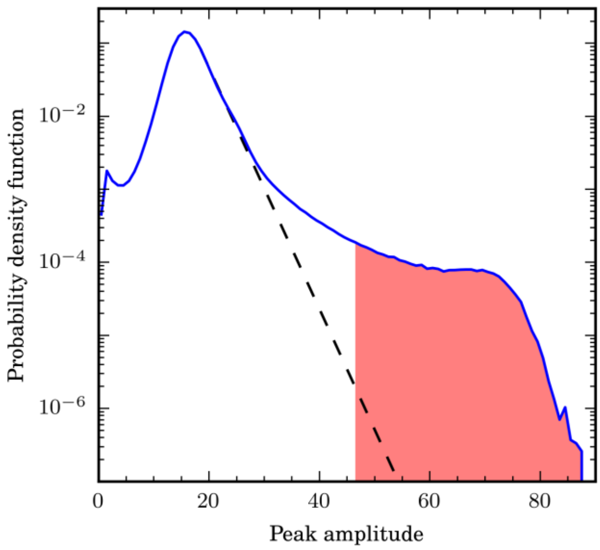

Figure 2 – Probability density function (PDF) of the peak amplitudes in logarithmic scale calculated for the same set of CGLE parameters as in Figure 1. The black dashed line represents the best fit for the exponential tail of the PDF. The red area corresponds to rogue wave events.

The maximum probability is at around the amplitude of the soliton and decreases at each side of this maximum. The data with very small amplitudes have been removed, and the significant wave-height (SWH) is calculated as the mean amplitude of the highest third of the recorded amplitudes, which is 20.8. Using the definition of rogue waves as the waves that have an amplitude exceeding 2.2 times the significant wave-height, its threshold amplitude is at 45.8. This indicates that all spikes that appear and disappear in this solution are dissipative optical rogue waves.

The elevated tail of the PDF is clearly seen in Figure 2. This region corresponds to the chaotically appearing spikes. The probability here is several orders of magnitude higher than that of a simple exponential fit to the main part of the PDF (dashed black line). The total probability of appearance of rogue waves is calculated as an integral of the area below the PDF curve above the rogue wave threshold (shaded in red in Figure 2). This probability is found to be 0.003 for the data presented here.

Concluding remarks – A chaotic dissipative soliton with extremely short spikes that appear randomly on its top is an unusual solution of the CGLE. It is very likely that this solution can be found only for normal average cavity dispersion. The PDF of the peak amplitude shows that these spikes have an elevated probability of occurrence, and can be classified as dissipative rogue waves. The whole structure has common features with NLPs but is unique in that the noise-like features are defined by the spikes on top of the soliton.

There may be multiplicity of other types of NLPs in passively mode-locked lasers. One type of them has been presented here. These numerical findings may stimulate experimental observations of such pulses. In the past, many discoveries obtained by solving the CGLE have been observed experimentally. The new solutions presented here can be considered as a first step in the detailed study of a new phenomenon.

References

[1] A. Zaytsev, C.-H. Lin, Y.-J. You, C.-C. Chung, C.-L. Wang, and C.-L. Pan, “Supercontinuum generation by noise-like pulses transmitted through normally dispersive standard single-mode fibers,” Opt. Express **21**, 16056–16062 (2013).

[2] M. Horowitz, Y. Barad, and Y. Silberberg, “Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser,” Opt. Lett. **22**, 799–801 (1997).

[3] L. M. Zhao, D. Y. Tang, T. H. Cheng, H. Y. Tam, and C. Lu, “120 nm bandwidth noise-like pulse generation in an erbium-doped fiber laser,” Opt. Commun. **281**, 157–161 (2008).

[4] O. Pottiez, R. Grajales-Coutiño, B. Ibarra-Escamilla, E. A. Kuzin, and J. C. Hernández-García, “Adjustable noiselike pulses from a figure-eight fiber laser,” Appl. Opt. **50**, E24–E31 (2011).

[5] A. Boucon, B. Barivau, J. Fatome, C. Finot, T. Sylvestre, M. W. Lee, P. Grelu, and G. Millot, “Noise-like pulses generated at high harmonics in a partially-mode-locked km-long Raman fiber laser,” Appl. Phys. B **106**, 283–287 (2012).

[6] H. A. Haus, “Theory of mode locking with a fast saturable absorber,” J. Appl. Phys. **46**, 3049–3058 (1975).

[7] A. I. Korytin, A. Yu. Kryachko, and A. M. Sergeev, “Dissipative solitons in the complex Ginzburg-

Landau equation for femtosecond lasers," Radiophys. Quantum Electron. **44**, 428–442 (2001); A. Komarov, H. Leblond, and F. Sanchez, "Quintic complex Ginzburg-Landau equation model for ring fiber lasers," Phys. Rev. E **72**, 025604(R) (2005).

[8] J. M. Soto-Crespo, Ph. Grelu, and N. Akhmediev, "Dissipative rogue waves: Extreme pulses generated by passively mode-locked lasers," Phys. Rev. E **84**, 016604 (2011); A. Zaviyalov, O. Egorov, R. Iliew, and F. Lederer, "Rogue waves in mode-locked fiber lasers," Phys. Rev. A **85**, 013828 (2012); C. Lecaplain, Ph. Grelu, J. M. Soto-Crespo, and N. Akhmediev, "Dissipative rogue waves generated by chaotic pulse bunching in a mode-locked laser," Phys. Rev. Lett. **108**, 233901 (2012).

[9] A. F. J. Runge, C. Aguergaray, N. G. R. Broderick, and M. Erkintalo "Raman rogue waves in a partially mode-locked fiber laser," Opt. Lett. **39**, 319–322 (2014).

[10] Z. Liu, S. Zhang, and F. W. Wise, "Rogue waves in a normal-dispersion fiber laser," Opt. Lett. **11**, 1366–1368 (2015).

Acknowledgments and Funding Information

The authors acknowledge the support of the Australian Research Council (DE130101432, DP140100265 and DP150102057). The work of JMSC was supported by MINECO under contract TEC2012-37958-C02-02, and by C.A.M. under contract S2013 / MIT-2790. JMSC and NA acknowledge the support of the Volkswagen Foundation.