Two distinct noise-like pulsing regimes of a dispersion-managed figure-eight fiber laser

Olivier Pottiez[1*], Baldemar Ibarra-Escamilla[2], Evgeny Kuzin[2], Juan-Carlos Hernández-García[2], Andrés González-García[3] and Manuel Durán-Sánchez[4]

[1]*Centro de Investigaciones en Óptica (CIO), Loma del Bosque 115, Col. Lomas del Campestre, León, Gto. 37150, Mexico*

[2]*Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), L. E. Erro 1, Sta. Ma. Tonantzintla, Pue. 72824, Mexico*

[3]*Instituto Tecnológico Superior de Guanajuato, Carretera Guanajuato-Puentecillas km.10.5, Predio El Carmen, Guanajuato, Gto. 36262, Mexico*

[4]*Mecatrónica, Universidad Tecnológica de Puebla, Ant. Camino a la Resurrección 1002-A Parque Industrial, Puebla, Pue. 72300, Mexico*

[*]E-mail: pottiez@cio.mx

1. Introduction

Passively mode-locked fiber lasers are versatile and low-cost sources of ultrashort pulses that are attractive for applications. Although initially developed for the generation of extremely short, sub-picosecond pulses, these lasers are now also used for the production of longer pulses with very high energies, in particular in the normal dispersion regime [1].

Recently, a novel category of pulses, the noise-like pulses [2-6], have attracted a lot of interest because of their high energy, wide spectrum (potentially beyond 100 nm [4]) and low coherence length, which makes them attractive for important applications such as supercontinuum generation [7] and sensing [8], among others. Fundamentally, a noise-like pulse is a large, ~ns collection of thousands of ultrashort (sub-ps) pulses with randomly varying amplitudes and durations that are packed together. Although the details of the inner pulses are extremely variable in time, the global properties of the noise-like pulse, like its overall duration, average inner pulse duration and spectral width remain constant, so that in a sense noise-like pulsing can still be seen as a stable mode-locking regime. In practice, the noise-like pulsing regime is easily recognized by its double-scaled autocorrelation trace, with a narrow coherence peak riding a wide and smooth pedestal, and by a very smooth optical spectrum. These two basic signatures of this particular mode locking regime are found with very few variations in the literature, in both normal and anomalous-dispersion cavities.

In this work, we show experimentally that, in spite of this apparent uniformity, two distinct regimes can be distinguished in a passively mode-locked fiber laser, each of them leading to the formation of noise-like pulses but with different properties.

2. Experimental setup

The device under study is a dispersion-managed figure-eight fiber laser [9] (Fig. 1). The resonator section of the laser (left) comprises 55 m of dispersion compensating fiber DCF (dispersion = -38 ps/nm/km) and the nonlinear optical loop mirror (NOLM, right side of Fig. 1) is made of 100 m of standard fiber (17 ps/nm/km). The resonator also includes two sections of normal-dispersion erbium-doped fiber, EDF1 (3 m) and EDF2 (2 m), with 30 dB/m absorption at 1530 nm, which are pumped at 980 nm (pump powers are Pp1 = 300 mW and Pp2 = 200 mW, respectively). A polarizer ensures linear polarization at the NOLM input, whose angle ψ can be adjusted by a half wave retarder (HWR). A polarization controller (PC) made of two retarder plates is used to maximize the power through the polarizer. An optical isolator ensures unidirectional laser operation. Two output couplers with 10% output coupling are used as the laser output ports. The net cavity dispersion is estimated to -0.28 ps/nm for a total cavity length of 189 m.

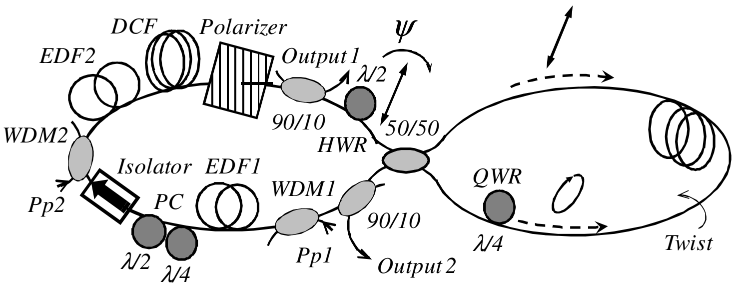

Figure 1 Scheme of the figure-eight laser under study.

In conventional figure-eight lasers, the NOLM, whose nonlinear switching characteristic is responsible for pulsed operation, is a power-imbalanced device [10]. In contrast, the scheme shown in Fig. 1 is symmetric in power (a 50/50 coupler is used), but asymmetric in polarization. Indeed, a polarization imbalance is created by a rotatable quarter-wave retarder (QWR) inserted asymmetrically in the loop [11]. Hence, the clockwise (CW) beam is linearly polarized, whereas the counter-clockwise (CCW) beam is turned elliptic by the QWR. The two counter-propagating beams thus have different polarization states, and polarization-dependent nonlinear phase shift (or equivalently nonlinear polarization rotation, NPR) constitutes the switching mechanism. Fiber is twisted at a ratio of 5 turns/m, which ensures that the ellipticity of each beam is maintained along the loop [12]. By tuning the orientation of the HWR, the polarization difference between the counter-propagating beams can be adjusted, allowing to tune the NOLM switching power from a minimal value theoretically to infinity [13,14].

3. Results and discussion

For properly adjusted wave retarders, a mechanical stimulation (a slight kick) yields the formation of a stable train of mode-locked pulses (Fig. 2). The period of 920 ns indicates that one single pulse is circulating in the cavity (fundamental mode locking). On the other hand, the measurement of a double-scaled autocorrelation and a smooth optical spectrum confirms that noise-like pulsing operation is invariably obtained. In some instances, very long (several ns) pulses with a rectangular envelope and a relatively narrow spectrum (only a few nm wide and symmetric around its maximum) are observed (Fig. 3a-c). If the HWR is rotated in the proper direction, so as to increase the NOLM switching power, the pulse peak power increases, as it adjusts itself to the variation of the NOLM switching power, which corresponds to maximal NOLM transmission and thus minimal loss in the cavity. The pulse duration gradually decreases as its peak power increases, because the pulse energy is roughly constant under fixed pump power. This evolution in the time domain is accompanied in the spectral domain by a gradual increase of the bandwidth, due to stronger nonlinear effects when peak power rises. Hence simple HWR adjustments allow adjusting the pulse temporal and spectral properties [5,6].

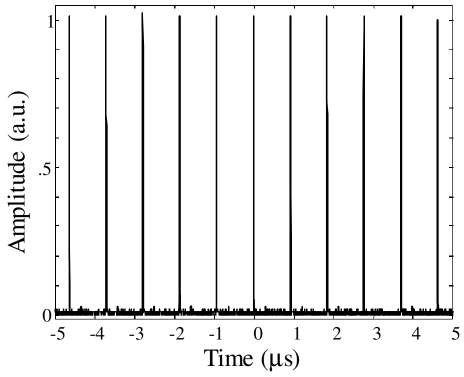

Figure 2 Oscilloscope trace of the noise-like pulse train.

For a given orientation of the HWR, when the noise-like pulse duration is as short as ~1 ns and the full width at half maximum (FWHM) bandwidth has reached ~10 nm, the laser switches abruptly to a distinct pulsing regime. Although the basic characteristics of the noise-like pulsing regime are conserved, the pulse properties are clearly different. In the time domain, the pulse envelope is now much shorter (~100 ps or less) and its shape is no longer flat-topped. Besides, the optical spectrum is now as wide as several tens of nm, and is typically very asymmetric, due to stronger Kerr nonlinearity and Raman self-frequency shift (Fig. 3d-f). As in the previous regime, the pulse properties in this short-pulse regime can be adjusted over some range if the HWR is further rotated. If the HWR is returned to the transition position, the laser switches back to the long-pulse regime, showing that this transition is revertible.

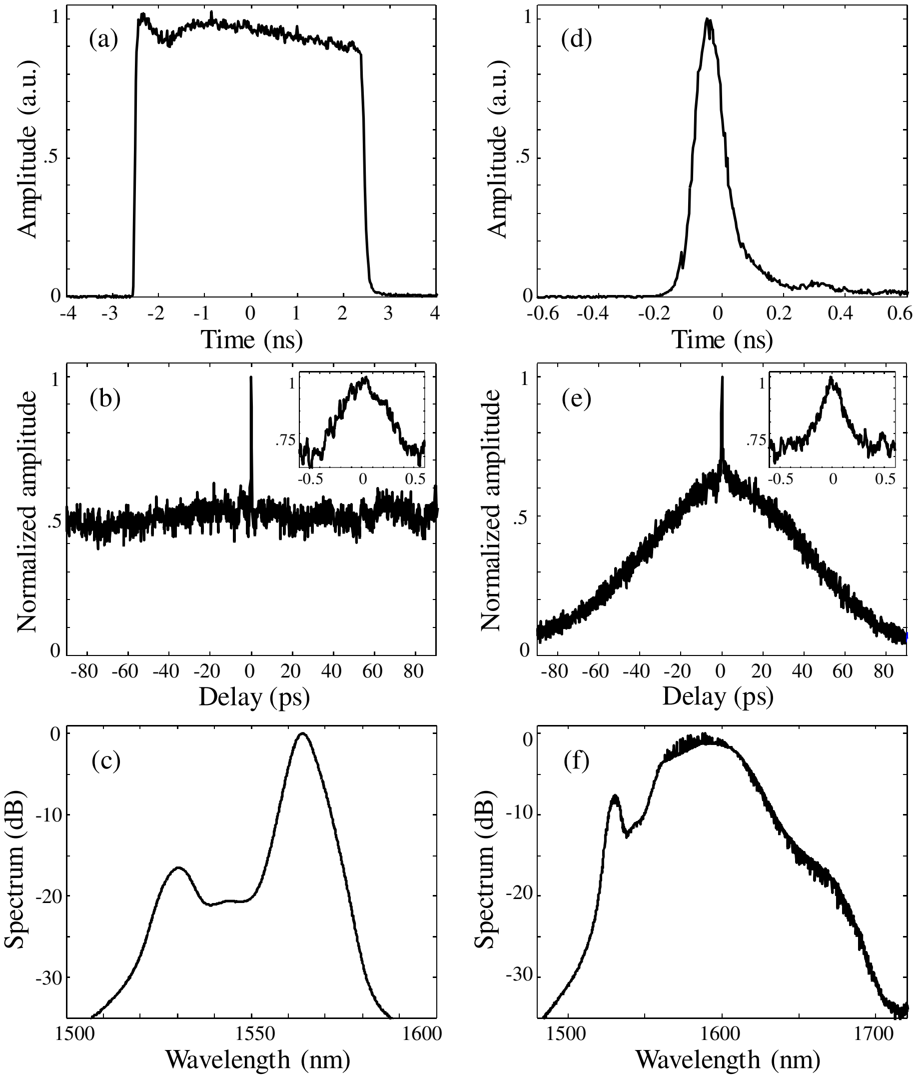

Figure 3 Measurements of the long (a-c) and short (d-f) noise-like pulses. (a,d) Sampling scope traces of the pulses detected using a 25-GHz photodetector; (b,e) autocorrelation traces (inset shows a close-up of the coherence spur); (c,f) optical spectra measured at output 2.

The existence of a long- and a short-noise-like-pulse regime can be understood by considering the strong dispersion map and slightly normal net dispersion of the cavity, and by observing the evolution of the pulse spectrum along one round-trip in each regime. In order to gain some insight on this evolution, we measured the spectrum at outputs 1 and 2. In the short-pulse regime, the spectrum, although several tens of nm wide at both outputs, was 10-20 nm narrower at output 1 than at output 2, showing that the spectrum suffers significant variations along the cavity in regime. Indeed, in dispersion-managed systems, the different interaction between nonlinearity and dispersion in each segment causes the spectrum to be narrower in the normal-dispersion fiber section and wider in the anomalous-dispersion section [15]. Besides, the strongly nonlinearly broadened spectrum is filtered by the much narrower gain bandwidth at each round-trip, which reinforces the difference between bandwidths observed at different points in the cavity. In such a situation where the optical bandwidth varies significantly along the cavity, the net (or average) dispersion is no longer a good indicator of the effective dispersion in the system. Indeed, because the spectrum is broader in the anomalous dispersion section, this section has a stronger impact on pulse shaping than the normal dispersion segment. Hence, even if the net dispersion is zero or even slightly normal, the *effective* dispersion can be anomalous [15]. We believe that the short-pulse regime is observed when the effective dispersion is turned anomalous as a consequence of the strong spectral variations undergone by the pulses during each round-trip. Anomalous dispersion is then able to balance the nonlinearity-induced chirp, which mitigates temporal broadening and yields noise-like pulses as short as 100 ps or less. These pulses are very similar to those observed in [5], in a figure-eight laser operating in the strongly anomalous dispersion regime.

On the other hand, the spectra measured at outputs 1 and 2 in the long-pulse regime are nearly identical. The much lower values of peak power in this regime explain that spectral broadening is moderate and that the optical bandwidth remains much narrower than the gain bandwidth. Hence the spectrum suffers little variation as the pulse propagates in the cavity. In the slightly normal net dispersion regime, the dispersion-induced chirp is not able to compensate for the nonlinear chirp, leading to very long pulses in this regime. These pulses are comparable to those observed in a similar cavity with strongly normal net dispersion [6].

4. Conclusions

In summary, we observed two distinct noise-like pulsing regimes in a figure-eight fiber laser. The laser can be switched from one regime to the other by controlling the pulse peak power, which is done by adjusting the switching power of the polarization-imbalanced NOLM through wave retarder adjustments. The long-pulse regime is associated with low peak power values, and is related to the normal net dispersion of the cavity, whose effect adds up with the nonlinearity and is responsible for the considerable temporal broadening of the pulse. In contrast, for higher peak powers, nonlinear spectral broadening becomes significant, and the different interaction between nonlinearity and dispersion in anomalous and normal fiber segments, together with the bandpass filtering effect of the bandwidth-limited gain are responsible for the fact that the pulse bandwidth is much narrower in the normal-dispersion fiber than in the anomalous-dispersion segment. This difference shifts the effective dispersion towards the anomalous dispersion regime. In this regime, dispersion and nonlinearities compensate each other to some extent, yielding much shorter noise-like pulses. By taking advantage of these two regimes, simple wave retarder adjustments allow tuning the duration of the noise-like pulses from less than 100 ps to more than 6 ns, and their FWHM bandwidth from ~4 nm to nearly 60 nm.

Acknowledgments

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References

[1] X. H. Li, Y. G. Wang, Y. S. Wang, Y. Z. Zhang, K. Wu, P. P. Shum, X. Yu, Y. Zhang and Q. J. Wang, “All-normal-dispersion passively mode-locked Yb-doped fiber ring laser based on a graphene oxide saturable absorber”, Laser Phys. Lett. **10**, p. 75108–1–5 (2013).

[2] M. Horowitz and Y. Silberberg, “Control of noiselike pulse generation in erbium-doped fiber lasers”, IEEE Photon. Technol. Lett. **10**, p. 1389–1391 (1998).

[3] S. Kobtsev, S. Kukarin, S. Smirnov, S. Turitsyn and A. Latkin, “Generation of double-scale femto/pico-second optical lumps in mode-locked fiber lasers”, Opt. Express **17**, p. 20707–20713 (2009).

[4] L. A. Vazquez-Zuniga and Y. Jeong, "Super-broadband noise-like pulse erbium-doped fiber ring laser with a highly nonlinear fiber for Raman gain enhancement", IEEE Photon. Technol. Lett. **24**, p. 1549–1551 (2012).

[5] O. Pottiez, R. Grajales-Coutiño, B. Ibarra Escamilla, E. A. Kuzin and J. C. Hernandez-Garcia, "Adjustable noise-like pulses from a figure-eight fiber laser," Appl. Opt. **50**, p. E24–E31 (2011).

[6] O. Pottiez, B. Ibarra-Escamilla, E. A. Kuzin, J. C. Hernandez-Garcia, A. Gonzalez-Garcia and M. Durán-Sánchez, "Multiple noise-like pulsing of a figure-eight fiber laser," Laser Phys. **24**, p. 015103–1–9 (2014).

[7] Y. Takushima, K. Yasunaka, Y. Ozeki and K. Kikuchi, "87 nm bandwidth noise-like pulse generation from erbium-doped fibre laser", Electron. Lett. **41**, p. 399–400 (2005).

[8] M. L. Dennis, M. A. Putnam, J. U. Kang, T.-E. Tsai, I. N. Duling III and E. J. Friebele, "Grating sensor array demodulation by use of a passively mode-locked fiber laser", Opt. Lett. **22**, p. 1362–1364 (1997).

[9] I. N. Duling III, "All-fiber ring soliton laser mode locked with a nonlinear mirror", Opt. Lett. **16**, p. 539–541 (1991).

[10] N. J. Doran and D. Wood, "Nonlinear-optical loop mirror", Opt. Lett. **13**, p. 56–58 (1988).

[11] E. A. Kuzin, N. Korneev, J. W. Haus and B. Ibarra-Escamilla, "Theory of nonlinear loop mirrors with twisted low-birefringence fiber", J. Opt. Soc. Am. B **18,** p. 919–925 (2001).

[12] T. Tanemura and K. Kikuchi, "Circular-birefringence fiber for nonlinear optical signal processing", J. Lightwave Technol. **24**, p. 4108–4119 (2006).

[13] O. Pottiez, E. A. Kuzin, B. Ibarra-Escamilla and F. Méndez-Martínez, "Theoretical investigation of the NOLM with highly twisted fibre and a λ/4 birefringence bias," Opt. Commun. **254**, p. 152–167 (2005).

[14] B. Ibarra-Escamilla, E. A. Kuzin, P. Zaca-Morán, R. Grajales-Coutiño, F. Mendez-Martínez, O. Pottiez, R. Rojas-Laguna and J. W. Haus, "Experimental investigation of the nonlinear optical loop mirror with twisted fiber and birefringence bias," Opt. Express **13**, p. 10760–10767 (2005).

[15] J. H. B. Nijhof, W. Forysiak and N. J. Doran, "Dispersion-managed solitons in the normal dispersion regime: a physical interpretation", Opt. Lett. **23**, p. 1674–1676 (1998).