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Invited Paper

Mode-locked fiber lasers with significant variability of generation regimes

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ABSTRACT

We demonstrate a great variability of single-pulse (with only one pulse/wave-packet traveling along the cavity) generation regimes in fiber lasers passively mode-locked by non-linear polarization evolution (NPE) effect. Combining extensive numerical modeling and experimental studies, we identify multiple very distinct lasing regimes with a rich variety of dynamic behavior and a remarkably broad spread of key parameters (by an order of magnitude and more) of the generated pulses. Such a broad range of variability of possible lasing regimes necessitates developing techniques for control/adjustment of such key pulse parameters as duration, radiation spectrum, and the shape of the auto-correlation function. From a practical view point, availability of pulses/wave-packets with such different characteristics from the same laser makes it imperative to develop variability-aware designs with control techniques and methods to select appropriate application-oriented regimes.

1. Introduction

Mode-locked fiber lasers are widely used as sources of ultra-short optical pulses [1–6]. The growing use of fiber lasers for this purpose is supported by customer demand for reliable femto- and pico-second lasers with a long (or, better, unlimited) operation lifetime and without any need for manual adjustments. Fiber lasers mode-locked due to non-linear polarization evolution (NPE) may satisfy these requirements [7,8] as they make direct use of their resonators' non-linear properties and are able to generate pulses with durations as short as 50 fs and even less [9,10]. Being at the same time a promising tool and a unique platform for observing spectacular non-linear optical interactions, NPE mode-locked fiber lasers attract much attention from both scientists and laser engineers. Such lasers support a large variety of generation regimes [11], including pulses of different shapes [12–15], multi-pulse lasing at different fundamental repetition frequency multiples [16], as well as complex soliton structures [14,16] and soliton rains [17]. In the present work, we limit our analysis to single-pulse lasing, that is, when only one laser pulse/wave-packet is present over a single round trip of the cavity. However, as our results show, even within such a limited case, a large variety of lasing regimes is found, which may considerably (up to an order of magnitude or even more) differ from each other in pulse energy, duration, bandwidth, etc., and may dramatically differ from each other in pulse structure being either "conventional" (single-scale) smooth pulses or double-scale pulses (wave-packets) with complex internal structure and phase fluctuations [18]. This has an important practical impact, calling for a variability-aware design of laser systems with embedded control techniques and methods to select appropriate output pulses.

2. Experimental setup

The setup used in our experiments is similar to those described in our previous studies [18–20], see Fig. 1. The fiber laser has a ring cavity with a wave-division-multiplexing (WDM) used to couple in the pump radiation. Either 2 m-long Er- or 8 m-long Yb-doped optical fiber is used in different experiments as the active medium, both of which produce qualitatively similar results at net-normal and all-normal cavity dispersion respectively. Either SMF-28 or normal-dispersion fiber (NDF) is used to elongate the cavity and thus increase pulse energy. Output laser radiation is extracted through a fiber polarization beam splitter (FPBS) or through an additional coupler inserted into the cavity. Mode-locked operation was achieved by adjusting fiber polarization controllers PC1, 2. Operation regimes were studied with the help of a fast oscilloscope, an optical spectrum analyzer (OSA), and an optical pulse auto-correlator.

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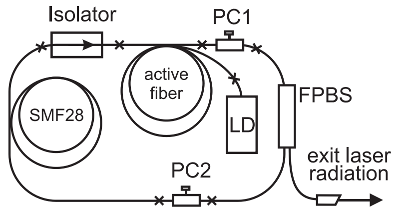

Fig. 1. Laser layout used in experiments. LD—laser diode, FPBS—fiber polarization beam splitter, PC1, 2—fiber polarization controllers.

3. Numerical model

In order to investigate the variety of possible single-pulse lasing regimes and their properties, we used a well-established numerical model based on a set of modified, non-linear Schrödinger equations for orthogonal polarization components of the field envelope [21]:

$$\frac{\partial A_x}{\partial z} = i\gamma\left\{|A_x|^2 A_x + \frac{2}{3}|A_y|^2 A_x + \frac{1}{3}A_y^2 A_x^*\right\} + \frac{g_0/2}{1+E/(P_{sat}\cdot\tau)}A_x - \frac{i}{2}\beta_2\cdot\frac{\partial^2 A_x}{\partial t^2} \tag{1}$$

$$\frac{\partial A_y}{\partial z} = i\gamma\left\{|A_y|^2 A_y + \frac{2}{3}|A_x|^2 A_y + \frac{1}{3}A_x^2 A_y^*\right\} + \frac{g_0/2}{1+E/(P_{sat}\cdot\tau)}A_y - \frac{i}{2}\beta_2\cdot\frac{\partial^2 A_y}{\partial t^2} \tag{2}$$

where A_x, and A_y are the orthogonal components of the field envelope, z is the longitudinal coordinate, t – time, $\gamma = 4.7 \times 10^{-5}$ (cm W)$^{-1}$, $\beta_2 = 23$ ps^2/km – non-linear and dispersion coefficients, $g_0 = 540$ dB/km – unsaturated gain coefficient, $P_{sat} = 52$ mW – saturation power for the active fiber. In order to accelerate simulations and spare computational resources, we reduced cavity length to 10 m, which corresponds to cavity round-trip time $\tau = 48$ ns. Similarly to [18,19], we integrated Eqs. (1) and (2) over 10^4 round-trips, using white noise as the initial condition for the first iteration. The term proportional to g_0 describes saturated optical gain and therefore was omitted while simulating pulse propagation in a passive fiber. Polarization controllers were taken into account through applying unitary matrices. Eqs. (1) and (2) were integrated numerically using step-split Fourier method. We checked carefully that the main results of this paper were not influenced by variation of numerical integration step, step number, mesh width, and number of mesh points, provided that these parameters were chosen in proper limits.

4. Results and discussion

The laser layout depicted in Fig. 1 includes two fiber polarization controllers, which provide several degrees of freedom, including the ability to trigger mode-locked operation and then switch between different generation regimes or adjust laser parameters. Since investigating lasing properties in multi-dimensional space is quite complicated, we confined ourselves to statistical study of different generation regimes. The approach consisted of choosing the polarization controller settings (tilt/slew angles) in a random way and integrating Eqs. (1) and (2) with white noise as the initial conditions. After a certain number (typically $10^3 \ldots 10^4$) of round-trips, we may obtain one of the following solutions: (i) quasi-CW laser operation (no mode-lock reached; thus Eqs. (1) and (2) and their numerical solution are not valid); (ii) multi-pulse mode-locked operation (that is, two or more pulses co-exist in the cavity); and (iii) single-pulse, mode-locked operation. If a single-pulse, mode-locked operation is reached after the fixed amount of cavity round-trips, the program saves the results (tilt angles of PC1, 2, pulse duration, energy, optical spectrum, temporal intensity distribution, etc.). Otherwise, no information is kept about this program run. In either case, the program selects a new combination of random PC settings and proceeds with the next run, thus accumulating information about single-pulse operation regimes.

The lasing regimes found in simulation demonstrate both quantitative and qualitative differences. Qualitatively, one can distinguish two main types of single-pulse generation regimes: fully coherent, single-scale, and double-scale pulses with complex inner structure [19]. Temporal distribution of radiation intensity for fully coherent pulses features a smooth envelope and can be described by a single parameter, that is, the envelope width (single-scale or "conventional" pulses). In contrast, temporal intensity distribution of the radiation of partially coherent pulses is stochastic: inside wave-packets with overall duration of several picoseconds to several nanoseconds; there are fast stochastic variations of radiation intensity with typical time scale of a hundred to several hundred femtoseconds.

Correspondingly, temporal distribution of radiation intensity for such pulses (wave-packets or double-scale pulses) is defined by two temporal parameters: the pulse-train envelope width and the typical intensity fluctuation time inside the train. Overall parameters of the entire wave packet, such as bandwidth, energy, and duration, fluctuate around their average values within a big range from one packet to another. Intensity fluctuations inside single wave-packets may also vary from relatively small values up to peak wave-packet intensity. Lasing regimes with strong intensity fluctuations are usually classified as noise-like generation.

Double-scale pulses have not yet received a universal designation. Different terms are found across the available literature: noise-like pulses [22,23], double-scale lumps [19], femtosecond clusters [24], etc. This type of pulse can be easily identified by a singular auto-correlation function shape featuring a narrow (100–200 fs) peak on a broader picosecond pedestal. Significant attention to these pulses is predominantly due to the presence of femtosecond components with high peak power, while the cavities of fiber lasers generating them may have relatively large dispersion.

There is also a series of intermediate possibilities between "conventional" laser pulses and noise-like generation which manifests a relatively small and variable fraction of intensity noise and phase fluctuations on the background of single-scale laser pulses [18]. Remarkably, even inside a single type of lasing (for example, single-scale or double-scale pulses), the studied laser supports a large variety of sub-regimes that correspond to different settings of PC1, 2 and thus differ vis-à-vis energy, duration, bandwidth, etc. Generated pulse parameters may vary by an order of magnitude or even more, depending on PC settings. Probability density functions (PDF) for rms-bandwidth (see Fig. 2(a) and (b)) and rms-duration (see Fig. 2(c) and (d)) obtained by randomly changing simulation PC settings are shown in Fig. 2. These PDFs reveal the extent of parameter variability in different realizations of two main single-pulse lasing regimes, namely conventional lasing (Fig. 2(a) and (c)) and double-scale pulse generation (Fig. 2(b) and (d)). For instance, rms-bandwidth varied in random simulation runs from 0.2 up to 3.9 nm for single-scale pulses and from 0.3 up to 7.4 nm for double-scale pulses being a function of PC settings. (Note that given values are pulse rms-bandwidth, which is usually several times as narrow as the spectrum's full width at half-maximum, FWHM. As an example, for Π-shaped spectrum, the ratio between spectral FWHM and rms-bandwidth is 3.5. For differently shaped spectra, this ratio may vary).

Another important difference between lasing regimes attainable at different angular settings of intra-cavity PCs is related to