New generation regimes of fiber lasers mode-locked due to nonlinear polarization evolution effect and their applications

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Fiber lasers mode-locked due to non-linear polarization evolution (NPE) are relatively simple and efficient tool for ultra-short pulse generation what makes them an object of intensive study last years. Compared to lasers mode-locked with the use of saturable absorbers NPE-lasers have simpler and robust design due to absence of a “weak” elements with respect to radiation power. All-normal dispersion NPE-mode-locked lasers allow producing relatively high-energy pulses without wave-breaking in contrast to soliton lasers. Moreover, one can further increase pulse energy by elongating cavity of the lasers. Since pulse repetition rate of passively mode-locked lasers is inverse proportional to cavity length, the pulse energy grows linearly with cavity length at fixed average pump power. Thus for example pulses with energy as high as 3.9 uJ was achieved in 3.8-km-long passively mode-locked master oscillator [1].

The unique feature of NPE-mode-locked lasers is an exceptionally wide set of generation regimes what makes them an ideal platform for investigations in non-linear dynamics [2]. Thus, NPE-based ultra-fast oscillators are capable to produce pulse train at fundamental repetition frequency as well as its harmonics. The lasers can generate pulses of different temporal and spectral shape and, as it was found recently, with different pulse-to-pulse stability [3,4]. Pulse stability can vary in a wide range – from conventional stable pulse generation regimes (with negligible fluctuations of $10^{-6}..10^{-4}$) via slight phase and intensity fluctuations toward strong pulse disorder and noise-bursts formation. Since both pump power increase and laser cavity elongation impedes stable pulse generation [5] one can expect mainly partial coherence pulse generation in ultra-long NPE-based lasers, what makes such pulses particularly interesting due to its higher energy level compared to conventional fully-coherent bell-shaped laser pulses with smooth shape profile. However to the best of our knowledge practical applicability of such pulses has not been studied yet. In this work we investigate novel partially coherent generation regimes of fiber lasers passively mode-locked due to NPE and compare their practical applicability with conventional fully-coherent ultra-short laser pulses.

In our work we use all-normal dispersion NPE-mode-locked ring fiber laser shown in Fig 1a. The laser consisted of 4-m long active ytterbium fiber, two fiber-based polarisation controllers PC1 and PC2 and a 6-m-long stretch of passive SMF-28 fiber used for cavity elongation and boosting of the output pulse energy. To improve convergence of the solution to the limiting cycle, the numerical model includes also a spectral filter with a 30-nm band-width what exceeds considerably the typical band-width of generated laser pulses. In experiments implicit spectral filtering is performed by wavelength-dependent gain of the active fiber as well as effective Lyot filter action of optical fiber and FPBS. Our numerical simulation based on a set of generalized Schrödinger equations yields a large variety of single-pulse lasing regimes with different settings of PC1 and PC2. According to pulse-to-pulse fluctuations all these regimes can be divided into three groups: conventional stable pulse trains, noise-like bursts and intermediate regimes. Figure 1 b shows typical examples of simulated ACF and spectrograms for three different generation regimes similar to [4] obtained for analogous laser of another cavity length within the same numerical model.

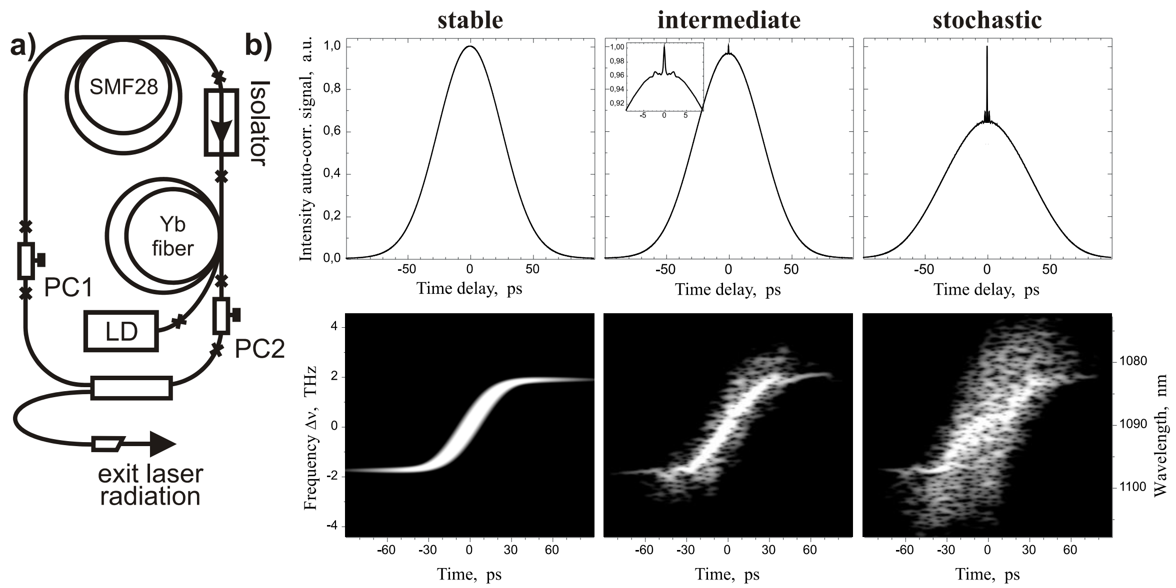

Fig.1. (a) Laser scheme, (b) ACF and spectrogram for different generation regimes.

In particular, in stochastic generation regime the laser produces a train of wave-packets consisted of random sub-pulses. The optical phase of such wave-packets strongly fluctuate what impedes pulse compression via chirp compensation. Transient lasing regime exhibits much smaller phase and intensity fluctuations what makes possible up to tenfold optical pulse compression in a linear dispersive medium, however compressed partially coherent pulses are still far from being spectral limited. In stable regime laser pulses have virtually no fluctuations in intensity and phase and thus can be compressed almost to Fourier limit.

Conventional ultra-short laser pulses generated in stable regime have a vast area of applications, including optical combs and metrology, medical imaging, femtochemistry, micro-machining, super-continuum generation, parametric frequency conversion, T-rays generation and detection and many others. Partial coherence of laser pulses produced in other regimes may impose some limitations on their applicability which are considered in this work. In particular, phase fluctuations prevent using such pulses for optical frequency metrology and frequency comb generation. However partially coherent picosecond pulses may be attractive for medical imaging, micromachining and super-continuum generation. Using numerical simulations we show for the first time that second-harmonic generation efficiency of partially coherent pulses may be comparable to or just a dozen per cents less than for conventional stable pulses generated by the same laser. Since the energy of partially coherent pulses and their long-time stability are potentially higher than for stable lasing regimes, and stochastic pulses are much easier to obtain in long and ultra-long cavities, they may constitue an attractive alternative to conventional laser pulses.

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