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Spectrally resolved shot-to-shot nonlinear dynamics of a passive PCF ring cavity

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Abstract: The global experimental bifurcation diagram of a passively pumped PCF ring cavity is analyzed. We observe unequal shot-to-shot evolution of different spectral regions of the cavity pulse, and confirm this using two independent measurement techniques.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.5295) Photonic crystal fibers

Optical feedback and especially nonlinear dynamics in fiber-loop systems have extensively been studied over the last three decades [1–3]. In contrast to conventional optical fibers, which have been employed in the majority of the existing schemes, photonic crystal fiber (PCF) enables a precise control of the dispersive properties of the nonlinear element in the ring cavity. In particular, the zero dispersion point can be tailored to lie in the vicinity of the pump wavelength.

Here, we report on the observation of the fast reshaping of the spectral content of the cavity pulse within a passive PCF ring cavity, which takes place within single round-trips. An endlessly single-mode PCF of length 20 cm with a zero-dispersion wavelength at 1052 nm is placed into a free-space ring cavity, synchronously pumped by 13 nJ, 140 fs sech-shaped pulses from an Yb:KYW laser at a repetition rate of 75 MHz (Fig. 1). The pump wavelength is 1042 nm and lies in the normal dispersion regime, which prevents soliton dynamics [4]. To achieve a maximum cavity pulse lifetime, a pellicle beam splitter with a reflectivity of $R_p = 8\%$ was used to couple into the cavity and a fraction of approximately $R_{obs} = 1\%$ of the cavity pulse energy was extracted as a probe signal.

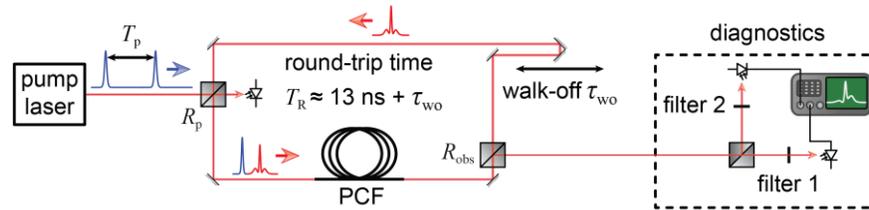


Fig. 1: Sketch of the synchronously pumped PCF ring cavity. The “diagnostics” box illustrates the splitting of the ejected beam into two non-overlapping spectral parts, which are synchronously recorded.

We analyze the cavity dynamics by sweeping the per-round-trip walk-off τ_{wo} between the cavity pulse and the pump pulse-train via the delay line and recording the total output energy using a 1 GHz photodiode [3]. An example of the full bifurcation diagram for a pump pulse energy of 0.59 nJ is shown in Fig. 2(a). Each single vertical slice corresponds to approximately 300 consecutive cavity pulse energies. The bifurcation diagram has three distinct regimes (labeled on the figure): for large values of τ_{wo} , consecutive pulses do not interact with each other and the overall dynamics remains in a steady state. When the walk-off value is very small, however, the dynamics is highly complex and the system exhibits mostly chaotic behavior. In the intermediate region we can identify steady state, period-multiplication and limit-cycle dynamics. Each of these three regions actually contains a highly complicated succession of dynamical states that may strongly differ quantitatively as well as qualitatively even upon small changes of τ_{wo} .

To acquire information about the dynamics and unambiguously decipher the underlying physical processes we used two approaches:

(1) We split the output beam in two, spectrally filtered each part and synchronously recorded the evolution with fast photodiodes (Fig. 1). This allows us to reveal the dynamics of each ejected pulse within two specific spectral bands: below 1000 nm and above 1050 nm. As shown in Fig. 2, these non-overlapping spectral bands can exhibit anticyclic (Fig. 2b) or even independently varying spectral content (Fig. 2c) and in-phase dynamics (Fig. 2d). Since the configuration allows only a single pulse to exist inside the cavity at any time, the observed dynamics can only be explained by different interference conditions between the pump pulse and the two measured spectral bands, something that has to our knowledge not previously been reported in any femtosecond pumped ring cavity configuration.

(2) In order to access even more information about the cavity pulse, we used a dispersive Fourier transformation technique to directly evaluate its spectral content [5]. The whole spectrum of every single consecutive pulse could then be monitored with a fast oscilloscope even at repetition rates of the order of 100 MHz.

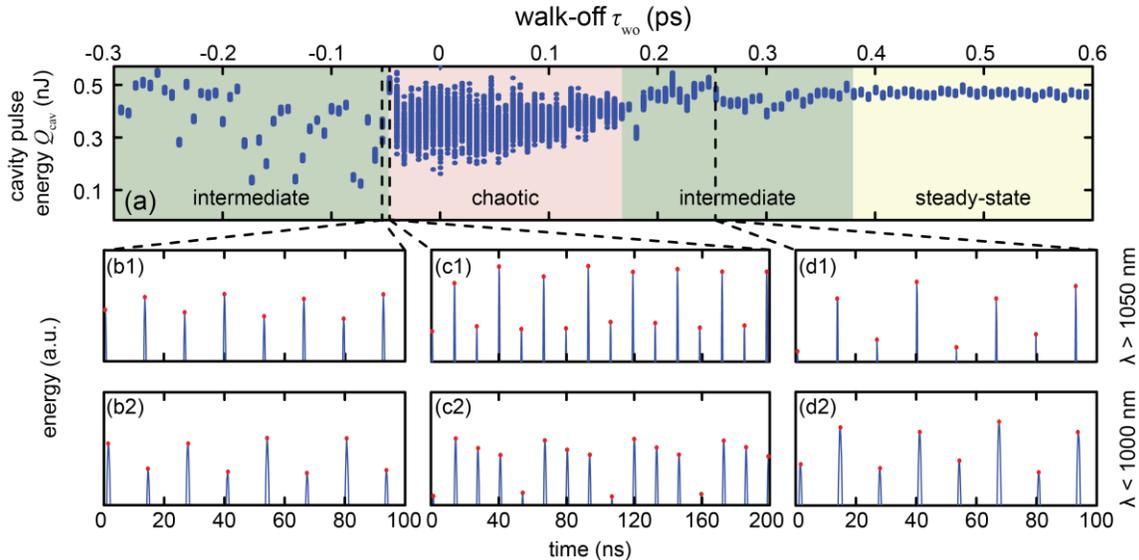


Fig. 2: (a) Experimental bifurcation diagram of the total cavity pulse energy plotted against the walk-off τ_{wo} for an input pulse energy of 0.59 nJ. The shaded regions indicate steady state, intermediate and chaotic regimes. (b-d) Temporal evolution of pulse energy within two spectral bands above 1050 nm (upper row) and below 1 μm (lower row): (b) spectrally anticyclic period-2 behavior; (c) independent period-4 (below 1 μm) and period-2 behavior (above 1050 nm); (d) in-phase period-2 behavior.

Fig. 3 shows an example of a cavity pulse exhibiting period-2 dynamics, where the top curve (Fig. 3a) was recorded using a reference photodiode installed behind the observation beam-splitter. The lower curve (Fig. 3b) displays the dispersively Fourier transformed signal corresponding to the cavity pulse-spectrum, where a perfectly periodic alternation between two distinct spectral states can be identified. The spectral content of each pulse clearly changes from one loop to the next, although it returns to its original state every other round trip. This is the first experimental observation of spectral reconfiguration in the nonlinear dynamical cycle of a passively pumped ring cavity in the 100 fs regime.

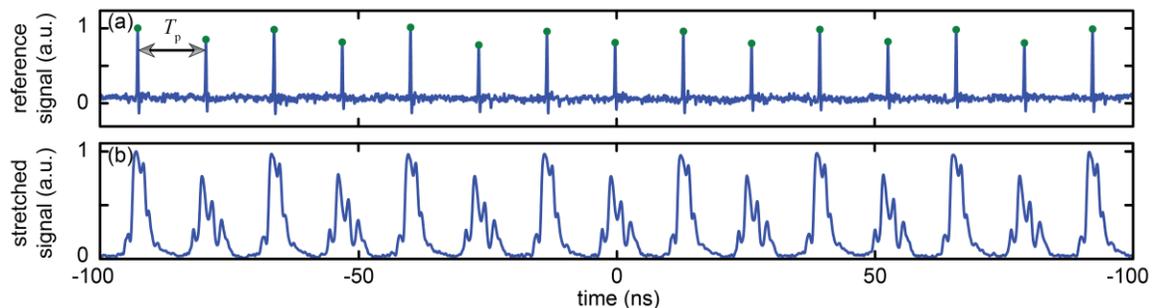


Fig. 3: Evolution of (a) total pulse energy and (b) corresponding dispersively Fourier transformed signal.

In conclusion, the ability of experimentally observing the full spectral content of the cavity pulse in every round-trip enables detailed studies of the nonlinear dynamics of passive ring cavities.

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