Kerr Frequency Combs in a Bichromatically Pumped Nonlinear Fiber Ring Cavity

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Abstract *We report numerical and experimental studies of four-wave mixing processes emerging from dual-frequency pumping of a passive fibre ring cavity. We observe the emission of a periodic train of nearly-background-free soliton pulses associated with Kerr frequency combs.*

Introduction

Kerr frequency combs in optical resonator cavities have attracted considerable interest during the last decade as a complementary approach to comb formation based on mode-locked lasers. Microresonator frequency combs, in particular, may provide compact and energy-efficient coherent multi-wavelength sources for optical communication and spectroscopy applications. The formation of Kerr combs usually arises through modulation instability (MI) and cascaded four-wave mixing (FWM) processes[1]. Such nonlinear dynamics has been extensively studied in optical fibers to generate high-repetition-rate pulse trains since almost 30 years. Several different pumping configurations can be investigated[2-3], e.g., single continuous wave (cw) pumping with or without a weak seed (seeded MI), and bichromatic pumping implemented either by using two separate cw lasers of equal power, or by modulating a single cw pump laser. The latter approach directly involves multiple four-wave mixing processes, and the pulse repetition rate can be simply determined by the frequency of the initial beating.

In the special case of resonant cavities, most previous works have focused on monochromatic cw pumping either with or without parametric seeding. However, several theoretical studies have demonstrated the benefits of the dual pumping configuration[4-6], e.g., for the generation of frequency combs without a pump intensity threshold and the possible emission of a periodic train of background free soliton pulses. Recent experimental works in microresonators[7-8] have confirmed the threshold-less comb generation process and its potential for frequency-degenerate parametric oscillation via dual pumping.

We report here on an extensive experimental study of the dual-pumped configuration in a passive nonlinear fiber ring cavity that confirms the presence of a rich variety of different comb states as the pump intensity and cavity detuning are changed. Experimental observations are well supported by numerical simulations of the Ikeda map based on the split-step Fourier method.

Numerical simulations

First we provide an overview of the predicted comb states from numerical simulations, where the nonlinear fiber ring cavity with anomalous dispersion (more details given in the next section) is bichromatically pumped. Our modelling is based on the integration of the following Ikeda map:

$$\frac{\partial A^m(z,t)}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 A^m(z,t)}{\partial t^2} + i\gamma\left|A^m(z,t)\right|^2 A^m(z,t) \quad (1)$$

$$A^{m+1}(0,t) = \sqrt{1-\alpha}A^m(L,t)\exp(i\phi_0) + \sqrt{R}A_{in}(t) \quad (2)$$

Where A^m represents the envelope of the intracavity optical field at the m^{th} round trip in the cavity, and A_{in} is the external pump field. Both A^m and A_{in} are expressed in a reference frame moving with the group velocity at the carrier frequency. z and t represent the propagation distance inside the cavity and the time in this reference frame, respectively. L is the cavity length and R represents the reflection coefficient of the coupler forming the cavity. In the following, we will refer to the normalized detuning of the cavity, defined as $\Delta = 2\,(2\pi\, k - \phi_0)/\alpha$, where k designates the nearest resonance and α represents the total power lost per roundtrip.

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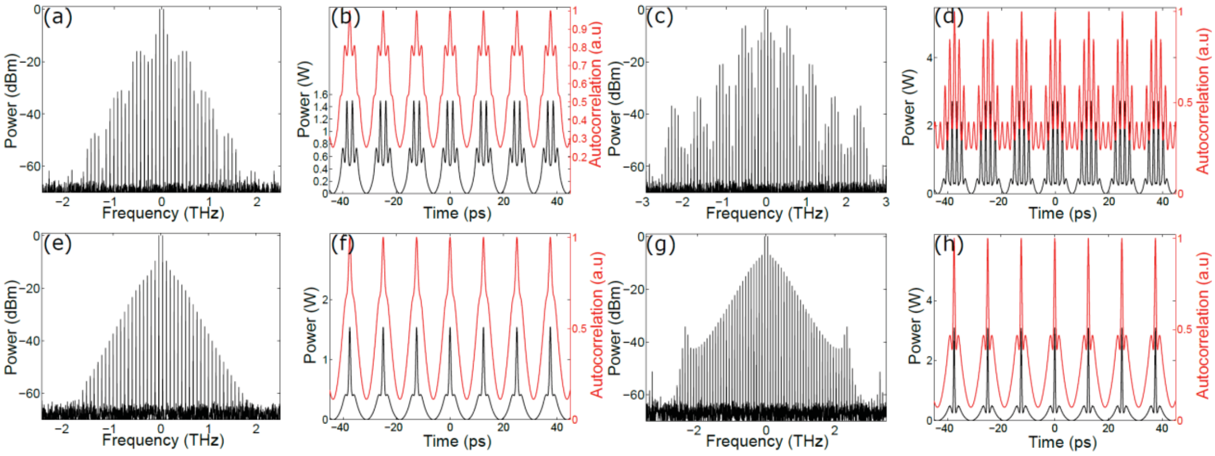

Fig. 1: Numerical simulations of various comb states, obtained in the dual pumping configuration, as a function of input power and cavity detuning. (a,b) $\Delta = 1.1$, $P_0 = 0.15$ W; (c,d) $\Delta = 1.1$, $P_0 = 0.3$ W; (e,f) $\Delta = 1.6$, $P_0 = 0.12$ W; (g,h) $\Delta = 2.15$, $P_0 = 0.2$ W. In sub-figures (b,d,f,h), the temporal red (black) traces indicate autocorrelation (pulse profiles).

With a proper choice of pump power and cavity parameters, we may expect to be able to generate a periodic train of nearly-background-free soliton pulses associated with Kerr frequency combs. Figure 1 reports some of the distinct observed regimes in the spectral domain, as a function of detuning (Δ) and pump power ($P_0 = |A_{in}|^2$). These simulations also indicate the temporal profile of the generated pulse trains, and their corresponding autocorrelation trace for easy comparison with experiments. Here the frequency spacing between the two pumps was fixed to 80 GHz. The first two cases (Fig. 1(a,b) and Fig. 1(c,d)) relate to the formation of a train of stable multi-pulse structures inside the cavity (two and four pulses, respectively). Spectrally, these structures correspond to Kerr frequency combs formed by multiple four-wave mixing with an additional influence of the modulation instability gain profile. By increasing the detuning, we can reach a state where a train of stationary pulses are formed, which are associated with a triangular spectrum (Fig. 1(e,f)). The pulses duration is of the order of 450 fs. For a detuning corresponding to the bistable regime of the cavity (Fig. 1(g,h)), we induce the formation of a train of cavity soliton-like pulses driven by the modulated temporal field instead of a monochromatic cw field[9]. In Fig. 1(g) we can also observe the presence of two pairs of peaks due to resonant radiation generated by the circulating soliton-like pulses.

Experimental results

Figure 2 depicts our experimental setup based on a resonant passive fiber ring cavity made of a 27-m-long segment of highly nonlinear optical

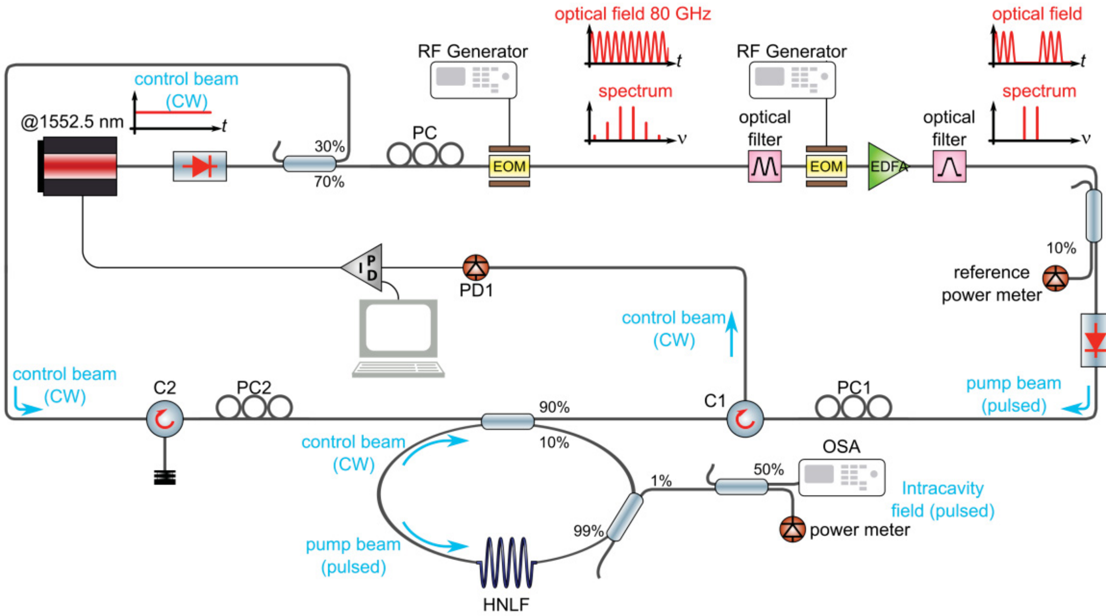

Fig. 2: Experimental setup. PC: polarization controller. EOM: electo-optical modulator. EDFA: Erbium-doped fiber amplifier. C: optical circulator. PD: photo-diode. HNLF: highly nonlinear optical fiber. OSA: optical spectrum analyzer.

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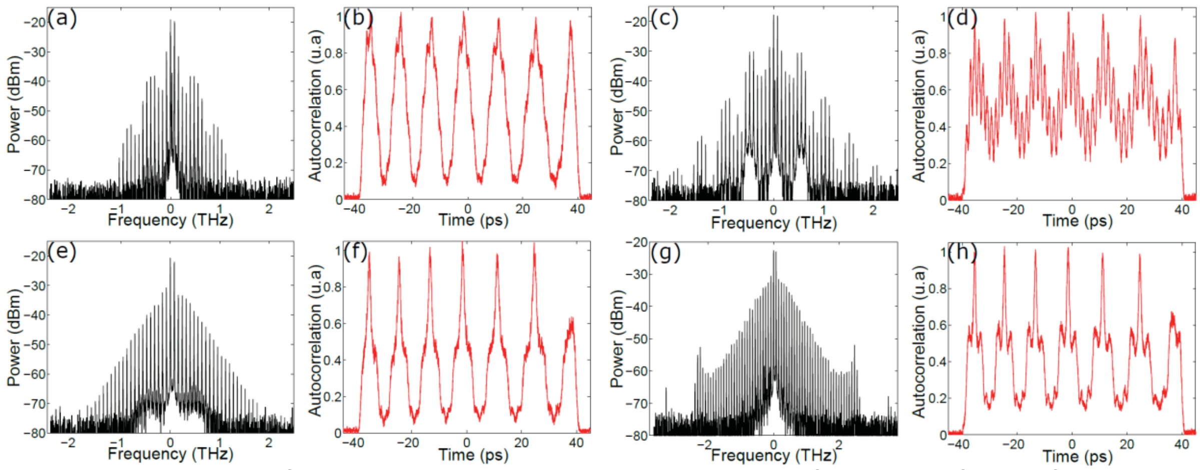

Fig. 3: Experimental results of various comb states, obtained in the dual pumping configuration, as a function of input power and cavity detuning. (a,b) $\Delta = 1.1$, $P_0 = 0.16$ W; (c,d) $\Delta = 1.1$, $P_0 = 0.26$ W; (e,f) $\Delta = 1.6$, $P_0 = 0.23$ W; (g,h) $\Delta = 2.15$, $P_0 = 0.54$ W. Note that the temporal window of our autocorrelator is limited to 80 ps.

fiber (HNLF) ($\gamma = 10\ W^{-1}\cdot km^{-1}$) with a low anomalous group-velocity dispersion ($\beta_2 = -0.9\ ps^2\cdot km^{-1}$). A 90/10 coupler is used to form the fiber loop cavity and the resulting cavity finesse was estimated to be nearly 19. Before injection into the cavity, a strong cw pump (@1552.5 nm, linewidth <1 KHz) is intensity modulated (at the null transmission point of the electro-optic modulator) to generate two pump lines of equal power, which are separated by a multiple of the fiber cavity free spectral range. A PID controller feeds back the laser frequency to maintain the resonance condition of the cavity. Both temporal and spectral characterizations of the comb states are provided by means of an autocorrelator and a high-resolution optical spectrum analyzer.

Figure 3 reports some of the comb states obtained when the frequency spacing between the two pumps was fixed to 80 GHz. Similar dynamics were also obtained for 40 GHz frequency spacing. Here the measurements were performed for the same detunings used in the simulations, and the experimental results are found to be in good qualitative agreement with the numerics. The autocorrelation traces confirm the formation of trains of single and multi-pulse temporal structures. From Fig 3(g,h), we can also infer the formation of a train of soliton-like pulses that generate resonant waves.

Conclusions

We have reported important and distinct aspects of the nonlinear dynamics of Kerr frequency comb generation in a bichromatically pumped fiber ring cavity. In particular, the frequency spacing between the two pumps provides an additional degree of freedom that allows us to observe a large range of both stable and unstable comb states, including periodic trains of background free cavity soliton-like pulses sitting on low power wings.

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