Dual Pump Microresonator Frequency Comb Generation and Optical Buffer Memories

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Abstract: We analyse the dynamics and stability of Kerr frequency comb and soliton generation in a microresonator pumped by two cw lasers. The beating of the pumps leads to a temporal modulation which permits the stable holding of externally injected pulses into a practical, chip-scale optical data buffer for packed-switching networks based on microring resonators.

Optical microresonators are currently being actively investigated, as they may enable a new class of chip-scale frequency comb sources for spectroscopy and metrology applications[1]. Most research to date has focused on pumping the microresonator with a single cw laser. We analyse here an alternative configuration where the cavity is simultaneously pumped at two different frequencies. Dual pumping can be implemented either using two separate cw laser sources, or by modulating a single cw pump laser in order to simultaneously excite two modes separated by some multiple of the free-spectral-range. Such a configuration allows the generation of frequency combs without a pump intensity threshold in both the normal and the anomalous dispersion regime[2].

Moreover, dual pumped microresonator may also provide the necessary long-term stability of recirculating pulses in optical soliton memories[3]. Indeed, for enabling secure all-optical photonic transparent IP networks, one needs routing devices for the optical packets. However, packet switching based on header information is currently hampered by the lack of practical optical memories for buffering the data while the header bits are processed. Current optical memories are based on active re-circulating loops of silica fiber which are bulky and require optical amplification to compensate for the cavity loss, thus adding noise to the data. Such types of memories are thus power hungry and not cost-effective as they cannot be integrated on the chip of a photonic integrated circuit. A different type of optical memory can be based on a passive ring cavity pumped by a cw holding beam[4]. We show here that a dual pumped microresonator may potentially lead to a stable and fully integrable optical data buffer.

We model a bi-chromatically pumped microresonator by the mean-field approach: for two equal amplitude pumps with a common phase detuning, the intracavity field can be described by the driven and damped nonlinear Schrödinger equation

$$A_\tau + i\beta A_{tt} - i|A|^2 A = -(1+i\delta_0)A + f_0 \cos(\Omega t). \tag{1}$$

Here t is the ordinary (fast) time variable which describes the temporal profile of the field, and τ is the slow time-scale for the evolution of this profile over successive round-trips. The field A is periodic with the cavity round-trip time, i.e., $A(t+2\pi,\tau) = A(t,\tau)$[5]. Moreover, β is the second-order dispersion coefficient, δ_0 is the cavity detuning, f_0 is the external pump field and Ω is the pump modulation frequency.

To gain insight into the comb generation dynamics, we derived a truncated four-wave model involving the two strong pump modes and the dominant sideband pair, which allows us to capture much of the essential dynamics of Eq.(1). This allows us to predict the existence and stability of the stationary comb states of the dual pumped microresonator (see Fig.1, left).

Based on the four-wave model predictions, we numerically analyzed the different mechanisms for comb generation: Fig.1, right, demonstrates stable primary comb generation in the normal dispersion regime, with a comb line spacing given by the pump modulation frequency Ω. Fig.2, left, illustrates an example of secondary, background-free (i.e., with no dc component) comb which is generated in the anomalous dispersion regime and for negative cavity detuning. However, anomalous dispersion combs are generally unstable if they possess a dc component.

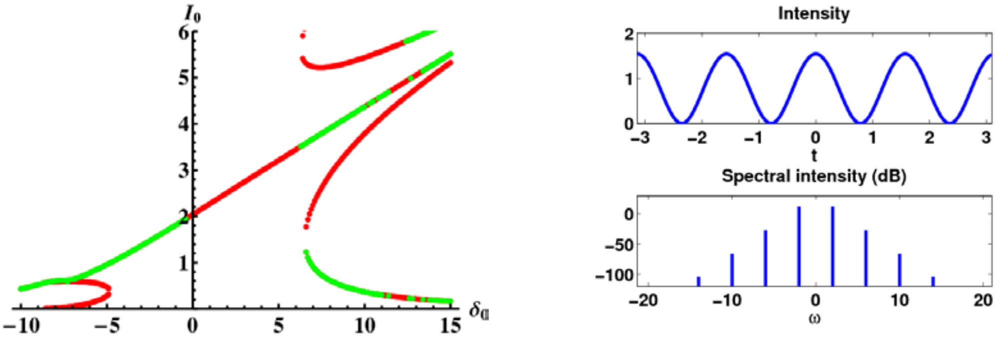

Fig.1: (left): Pump mode intensity I_0 vs. detuning δ_0, for $\kappa = \beta\Omega^2 = -1$ and $|f_0|=9$. Green (red) curves indicate stable (unstable) intensities; (right): normal dispersion, background-free primary frequency comb.

One of the most interesting properties of the dual pumped configuration is that is also capable of supporting cavity solitons, i.e., isolated pulses that exists on a background, and that have smooth spectral profile that involves all cavity modes with the fundamental mode spacing of a single free-spectral-range. Cavity solitons can be created by injecting a similar writing pulse into the cavity, which forms an optical soliton buffer[4]. The advantage of using a dual pump scheme is to suppress interactions between individual solitons[3]. In fact, the pumping of two modes that are separated by multiples of the free-spectral-range introduces a low intensity pattern of non interacting clock pulses whose number can be controlled by the modulation frequency in order to determine the number of bits in the cavity. These clock pulses provide a fixed background onto which the cavity solitons can be written, and the modulation frequency can be selected so that only a single cavity soliton will fit onto each clock pulse. The clock pulses could also be used to provide a re-timing feature in order to synchronize detection. The same pulses that are used to write the cavity solitons can also be used to erase an optical bit for a proper choice of amplitude and width, thus allowing the cavity to function as a logical XOR gate. The entire pattern can moreover by erased by lower the pump amplitude below the threshold for cavity solitons. An example of stable storage of the 16 bit word 0100100001010111 where ones are represented by cavity soliton pulses is shown in Fig.2, right.

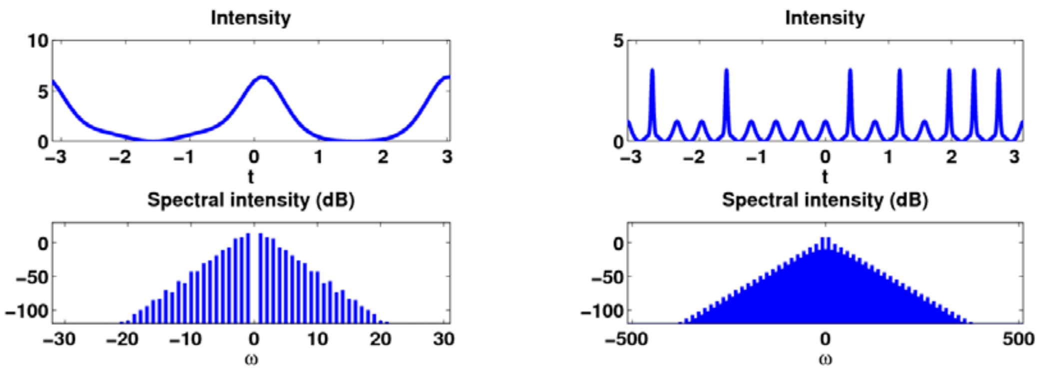

Fig.2: (left): Stable anomalous dispersion frequency comb without a background component but with even modes filled in due to secondary comb generation; (right): Coexistence of multiple injected cavity solitons on top of a stationary 16 bit pattern of low-intensity clock pulses.

In summary, we have shown that a dual pumped microresonator is capable of generating background-free frequency combs both in the anomalous and in the normal dispersion regime. Additionally, we proposed a long term stable optical buffer memory with suppressed pulse interactions. This research was funded by Fondazione Cariplo (grant no. 2011-0395).

References

1. T. J. Kippenberg *et al., Science* **332**, 555-559 (2011).
2. D. Strekalov and N. Yu, *Physical Review A* **79**, 041805(R) (2009).
3. S. Wabnitz, *Optics Letters* **18**, 601-603 (1993).
4. F. Leo *et al., Nature Photonics* **4**, 471-476 (2010).
5. T. Hansson *et al., Phys. Rev. A* **88**, 023819 (2013).