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Dark-pulse Kerr combs in linearly coupled microring structures

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Abstract: We demonstrate mode-locked dark-pulse Kerr comb formation in linearly coupled microresonators. The comb states are coherent and reproducible, and feature 36% conversion when pumped with 2.5 mW power.

1. Introduction

The generation of dissipative Kerr solitons in microresonators became a milestone in the quest towards a chip-scale frequency comb source. Although successful demonstrations in diverse fields have been made [1], one outstanding issue with dissipative Kerr solitons is their poor power conversion efficiency [2]. This has a fundamental origin in the need to operate the soliton microcomb at a large frequency detuning. The limited conversion efficiency is a crucial aspect when considering co-integration with chip-scale laser sources or applications that demand higher power per line, such as optical communications.

In contrast, mode-locked dark-pulse Kerr combs [3] operate in the normal dispersion regime and can attain much higher conversion efficiency [4]. Unfortunately, they rely on the linear coupling between two transverse modes in the cavity in order to achieve phase matching. These interactions can be engineered in a suitable arrangement of linearly coupled cavities [5,6], employing thermal heaters to tune the interaction between the two modes. However, it remains unclear whether the reported combs in these structures correspond to mode-locked dark-pulses. Here, we demonstrate dark-pulse Kerr combs in a suitable arrangement of linearly coupled cavities. Our experimental results can be accurately modeled based on the measured parameters of the cold cavities. As a result, we achieve a combination of reproducibility, low-power operation (2.5 mW), high conversion efficiency ($\approx$ 36%) and spectral flatness (power distribution among lines) that is unprecedented among coherent microcombs.

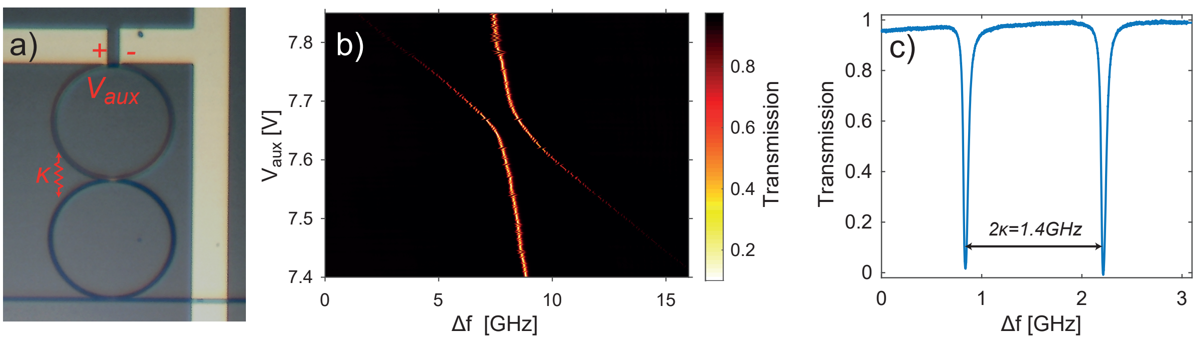

Fig. 1. a) Photograph of the two-ring structure in this experiment. Applying a voltage, V_{aux}, to the micro-heater on the auxiliary ring red shifts the longitudinal mode spectrum of the auxiliary cavity modes. b) An engineered mode-crossing at 1566.8 nm. c) The supermodes in b) when the voltage is 7.65V and keeps a minimal separation between them.

2. Microcomb demonstration

The two-ring structure in our demonstrations (see Fig. 1a) was fabricated in silicon nitride using a novel subtractive processing method [7], with a microheater placed on the auxiliary ring. The microring waveguides had a width of 1850 nm and a height of 600 nm. The transmission spectrum of the linearly coupled cavities was measured with a continuously swept laser, with an interferometer for frequency reference. The main ring has a measured intrinsic Q of about 7 million and the power coupling between bus waveguide and main ring was 0.0014. The measured free spectral range (FSR) and group velocity dispersion were 224.8 GHz and $66\,\mathrm{ps}^2/\mathrm{km}$ with a third order dispersion of $-0.9\mathrm{ps}^3/\mathrm{km}$. The auxiliary mode had an FSR of 234.5 GHz. Fig. 1b shows the separation between the hybridized resonances in the mode crossing as voltage was applied to the microheater. Fig. 1c shows the minimum separation between the two resonances, from which the coupling rate was observed as $\kappa = 0.7\,\mathrm{GHz}$.

For microcomb generation the two ring structure was pumped with a CW laser, which was tuned towards longer wavelengths starting from the blue side of the set of supermodes (see Fig. 2). The auxiliary voltage was

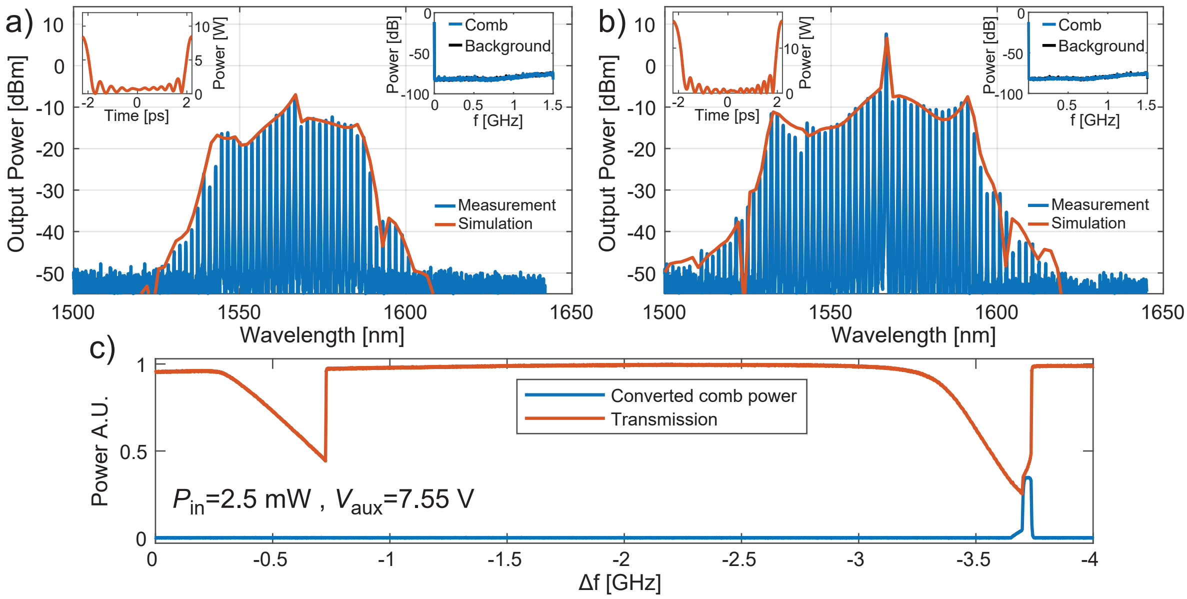

Fig. 2. a), b) microcombs generated with pump power 2.5 mW and 10 mW respectively (blue experiment, red simulation). Inset upper left: temporal pulse envelope of the simulated comb. Inset upper right: ESA trace of the output comb (30 kHz resolution bandwidth). c) Transmission scan (red) and converted comb power (blue) vs the relative frequency change, as the pump laser is tuned towards higher wavelengths.

set to 7.55 V and 7.6 V for input pump powers 2.5 mW and 10 mW, respectively. Using this method, microcombs were deterministically generated with a conversion efficiency of 36% and 25% for 2.5 mW and 10 mW (see Fig. 2a-b). These are much lower power levels than previously displayed in normal dispersive microrings. Providing 24 tones with $> -19\,\text{dBm}$ power and $12\,\text{dB}$ flatness, the comb in Fig. 2a is attractive for optical communications. We measured the amplitude noise of the output comb with an electrical spectrum analyzer (ESA), showing no excess noise, indicating a mode-locked state. In Fig. 2c, we show the evolution of the converted comb power and transmission as the laser was tuned towards the red side. The laser first pushes through the blue shifted resonance of the supermode to generate a comb in the red shifted resonance. This behaviour resembles the dynamics of two-mode normal dispersion microresonators [8].

A numerical verification of our comb states was conducted using the measured parameters mentioned above, and a nonlinear coefficient $\gamma = 1.1\,(\text{W}\cdot\text{m})^{-1}$. Instead of the method in [9], we used Runge-Kutta in the interaction picture method [10] for the Ikeda map, expanded to include the auxiliary ring. The offset between the two modes was set to 3 GHz and 2.2 GHz for 2.5 mW and 10 mW input powers, but the effect of this parameter on the simulation is relatively small. Fig. 2a-b show the resulting comb envelope, in excellent agreement with the experimentally measured microcomb. The inset shows the calculated intracavity waveform, indicating that the comb corresponds to a mode-locked dark-pulse state.

In summary, we have demonstrated reproducible microcombs that combine high conversion efficiency with low pump powers in linearly coupled microcavities. We numerically showed that these waveforms correspond to mode-locked dark-pulse Kerr combs. These results are important towards developing chip-scale microcombs with power levels compatible with heterogeneously integrated lasers. From a fundamental point of view, the arrangement of coupled cavities allow the dynamics of dark-pulse Kerr combs to be explored in a controllable manner.

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