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Power-Efficient Microcombs beyond Octave Spectral Span using Photonic Molecules

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Abstract: We utilize photonic molecules for power-efficient soliton microcomb generation on an integrated silicon nitride chip. Single soliton with a spectral span of up to two octaves is demonstrated.

Stabilized optical frequency combs (OFCs) play an important role in high-precision metrology applications, such as optical atomic clock [1], optical frequency synthesis [2], and astronomical spectrograph calibration [3]. Full stabilization of OFCs typically requires an octave spectral span for f-2f self-referencing, enabling detection and stabilization of the carrier envelope offset (CEO) frequency. OFCs generated on integrated photonic chips (i.e. microcombs) can achieve an octave span with strong comb line power for f-2f process due to their small mode volume [4]. The deployment of OFC-based advanced applications is also pushing forward the employment of microcomb sources. However, coherent microcombs (i.e. solitons) generated from a single cavity with anomalous dispersion exhibit low conversion efficiency, since the pump is positioned at the red-detuned region, as illustrated in Fig. 1(a-c), and hence a strong pump power is required. This not only limits the reduction of repetition rate down from ~ 1 THz while maintaining strong comb line powers at the f-2f frequencies, but also challenges the integration with pump lasers compatible with photonic integration that typically have a maximum power level of about 100 mW.

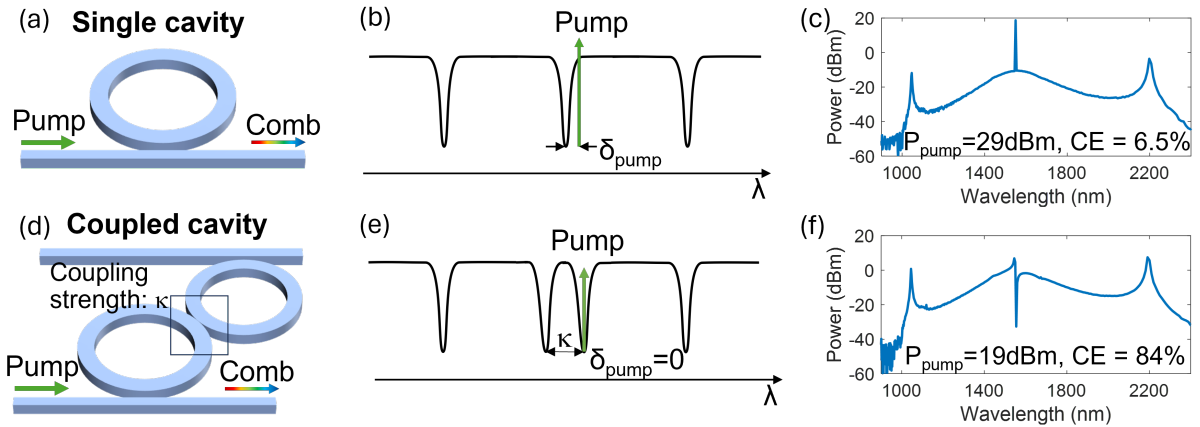


Fig. 1. (a) Schematic of a single cavity structure for microcomb generation. (b) Illustration of cavity resonances and pump position upon soliton generation. The pump is largely red-detuned, denoted by δ_{pump} . (c) An example soliton spectrum generating from single cavity with high pump power and low conversion efficiency (CE). (d) Schematic of a coupled cavity structure [5] for microcomb generation. (e) Illustration of cavity resonances and pump position upon soliton generation. The mode coupling introduced by the auxiliary cavity shifts the resonance to accommodate for δ_{pump} . (f) An example soliton spectrum generating from a coupled cavity at a reduced pump power and high CE.

In this work, we employ a photonic molecule for soliton generation with improved power efficiency. As illustrated in Fig. 1(b), by introducing mode coupling to red-shift the cavity resonance to be closer to the pump laser, such a coupled cavity structure can greatly enhance the utility of the power, resulting in a reduced pump power and higher conversion efficiency (CE) [5]. Our

~ 750 GHz repetition rate microcomb achieves an octave span with high power efficiency, along with strong dispersive wave emission at both f - $2f$ frequencies. Furthermore, the first order Kelly sideband [6] is excited in a microcomb with 600 GHz repetition rate due to the strong nonlinear conversion, extending the spectral span to two octaves.

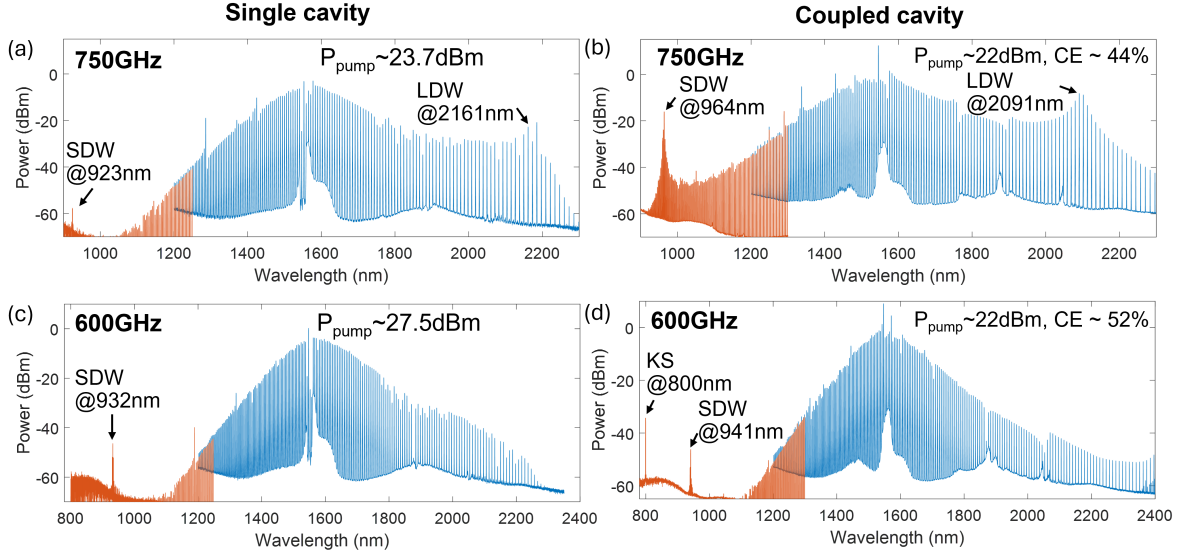


Fig. 2. Experimental soliton spectra generated from (a) a 750GHz single cavity, (b) a 750GHz coupled cavity, (c) a 600GHz single cavity, (d) a 600GHz coupled cavity. For measuring soliton generated in single cavity, a coarse wavelength division multiplexer is used to suppress the pump and measure the comb lines. SDW: short-wavelength dispersive wave. LDW: long-wavelength dispersive wave. KS: Kelly sideband.

The nonlinear dynamics for soliton generation in a coupled cavity is studied using Ikeda map [5,7]. This numerical simulation not only shows the feasibility of generating single soliton with the existence of mode coupling, but also give guidance for the design parameters. The final design parameters are obtained by simulating the three coupling regions with Ansys Lumerical FDTD. First, we adopt a pulley coupler structure for the bus waveguide coupling to the main ring. The pulley design, with a smaller waveguide width for the bus, can increase the coupling strength at the lower wavelength region, while targeting a heavily over-coupled pump. Second, the coupling strength between the main and auxiliary rings is designed to be similar as δ_{pump} , so that the shifted pump resonance mode can align with the pump laser to achieve the highest power efficiency, as illustrated in Fig. 1(e). Third, we introduce a bus waveguide for the auxiliary ring to avoid nonlinear oscillation resulting from the strong field enhancement inside the ring.

We use high-quality (Q) factor silicon nitride microrings fabricated in house using a subtractive fabrication process on 4-inch wafers [8]. The SiN film thickness is ~ 740 nm to target anomalous dispersion. We design the widths of the ring waveguides to engineer the dispersion, in order to obtain dispersive waves at both f - $2f$ frequencies, which are around $1 \mu\text{m}$ and $2 \mu\text{m}$ with a $1.55 \mu\text{m}$ pump. The ring width for the 750GHz (600GHz) comb is 1740 nm (1950 nm). The photonic molecule consists of a coupled cavity, where the repetition rate of the auxiliary ring is slightly different from that of the main ring. For 750GHz comb, the repetition rates are ~ 755.8 GHz (~ 749 GHz) for the main (auxiliary) rings. Whereas for 600GHz comb, the repetition rates are ~ 597.5 GHz (~ 601.7 GHz) for the main (auxiliary) rings. An ultra-high intrinsic Q factor of $1 \sim 2 \times 10^7$ is achieved for these devices.

We characterize single soliton generating from both single and coupled cavity for comparing the improved performance. Generating a soliton in single cavity is achieved by applying a sawtooth-like burst pulse (one tooth at a time) to the microheater. In sharp contrast, the coupled cavity enables easy soliton generation without any rapid wavelength tuning mechanism, as described in [5]. Fig. 2 shows the optical spectra for 750GHz and 600GHz combs. The pump powers are estimated on-chip powers, considering 2 dB insertion loss per facet. For the 750 GHz comb in

Fig. 2(a)(b), the comb line powers are greatly enhanced using coupled cavity, with -16 dBm short wavelength dispersive wave (SDW) and -9 dBm long wavelength dispersive wave (LDW). A high nonlinear CE of $\sim 44\%$ is achieved for an octave-spanning soliton microcomb. The 600 GHz soliton microcomb also achieve a high CE of $\sim 52\%$. The dispersive wave emission appears at a large spectral separate beyond an octave span, where the SDW appears at 941 nm while the LDW is beyond the optical spectrum analyzer measurement limit of 2400 nm (Fig. 2(d)). Notably, the first order Kelly sideband at ~ 800 nm is being excited under such strong conversion, extending the spectral span to two octaves. This indicates that with proper dispersion engineering, a broadband spectrum beyond an octave can be achieved, which can enable performing f-2f self-referencing at the pump wavelength to make use of the strong pump power.

In conclusion, we have demonstrated octave-spanning microcombs with improved power-efficiency by employing photonic molecule structures. This shows the potential for achieving high performance octave-spanning microcombs with reduced repetition rates, enabling their photonic integration with pump laser chips.

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