Microwave Repetition Rate Frequency Comb on a chip

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***Abstract*—A silicon-chip microcomb accessing the important microwave-rate FSR range is reported. The microcombs feature a few mW threshold level and comb heterodyne beat of several 100 Hertz. Microcombs with repetition rates ranging from 2.6GHz to 132GHz are demonstrated.**

Keywords-Frequency comb; Four-wave mixing; Integrated Optics; microcavities;

I. INTRODUCTION

There is currently intense interest in microcombs and there have been demonstrations using silica micro-toroids [1], CaF_2 diamond-milled rods [2,3], silicon-nitride rings on silicon [4], high-index silica rings on silicon [5], and in fiber Fabry-Perots [6]. One priority in this subject is the attainment of microwave-rate free-spectral-range (FSR) in a chip-based platform so as to enable self-referencing [7]. However, there are presently no on-chip micro-combs having repetition rate less than 80 GHz. Moreover, the following scaling of threshold power with FSR makes it challenging to reduce FSR without increasing threshold power.

$$P_{th} = \frac{(1+K)^3}{8K}\frac{n}{n_2}\frac{\omega}{\Delta\omega}\frac{A}{Q^2} \quad (1)$$

where K is the normalized external coupling rate, n_2 (n) is the nonlinear index (refractive index), $\Delta\omega$ (ω) is the free-spectral-range (optical frequency), A is the mode area, and Q is the resonator optical Q factor. In this work, we report a silicon-chip-based microcomb that accesses the important microwave-rate FSR range. At the same time, the device also achieves a low threshold turn-on power typically in the range of a few mW.

II. EXPERIMETNAL RESULTS

Improving the optical Q factor is an extremely effective way to offset the impact of reduced FSR ($\Delta\omega$) on threshold, as indicated in (1). Higher Q creates larger resonant build-up so that a given coupled power creates a greater Kerr-induced four-wave-mixing (FWM) of signal and idler waves. It also reduces oscillation threshold since optical loss is reduced. The microcomb of this work uses a new chip-based resonator that provides Q factors as high as 870 million [8,9]. Significantly, these devices do not require silica reflow [10], which becomes problematic at diameters approaching 1mm. Rather, only conventional semiconductor processing methods are necessary (lithography and wet etch) so that ultra-high-Q devices featuring FSR's of a few GHz to hundreds of GHz are possible.

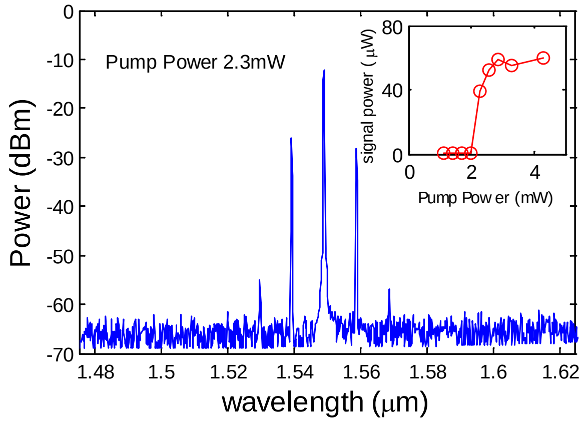

Fig. 1. Optical spectrum of the first generated lines just above threshold using a 2mm wedge disk. Inset: Power of first generated lines vs. coupled pump power.

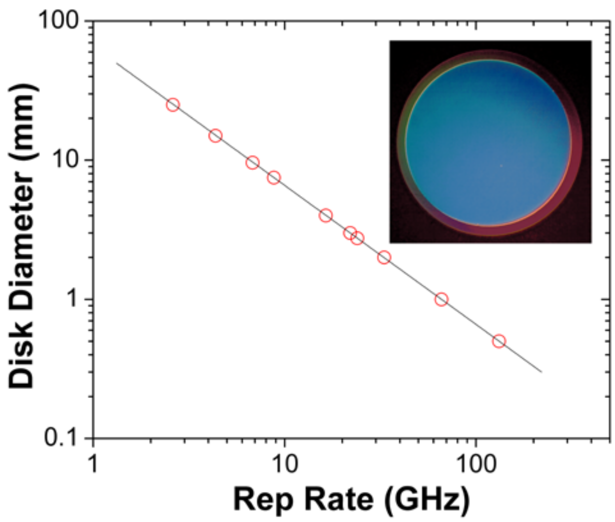

Fig. 2. Demonstrated microcomb rep rates from 2.6GHz to 132GHz plotted versus resonator diameter. Inset: A photomicrograph image of a 2mm disk.

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In a typical experimental setup, the amplified pump laser is coupled to the disk resonator using a tapered fiber [11] and is thermally locked within the cavity resonance [12]. When the coupled, pump power exceeds threshold, FWM lines turn-on very abruptly (see Fig. 1. inset). A threshold less than 2.3mW is measured for a 2mm, wedge disk having an intrinsic Q of 300 million. An optical micrograph of this disk resonator is provided in Fig. 2. Fig. 1 shows that the first generated FWM lines are typically multiple cavity FSR away from the pump, where the dispersion is compensated by nonlinear phase shift and the parametric gain is maximized. Interestingly, only modest pumping above threshold is required to generate densely-spaced, comb lines with repetition rate equal to one cavity FSR. Fig. 3 shows about 200 comb lines with 33.2GHz spacing generated with coupled pump power of only 7.5mW. At even higher power levels, a comb bandwidth of 68THz for 33.2 GHz rep rate (>2000 comb lines) is observed. Using these devices, chip-based microcombs with repetition rates covering the entire microwave spectrum have been demonstrated (see Fig. 2 main panel). The 2.6GHz repetition rate is the smallest demonstrated so far for any microcomb.

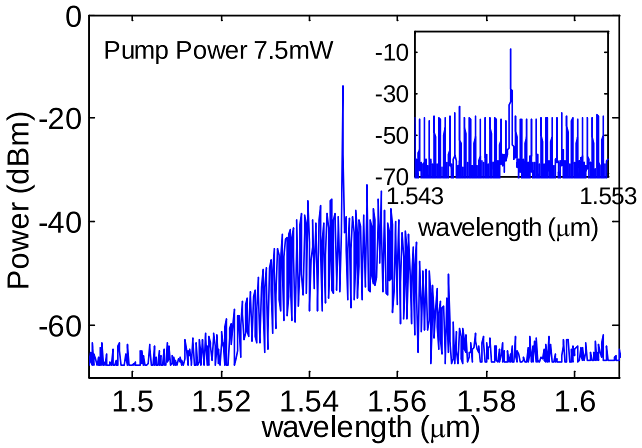

Fig. 3. Optical spectrum of the Kerr comb with 200 comb lines and with comb spacing 33.2GHz at pump power 7.5mW. Inset: zoom-in measurement of the Kerr comb with 10nm span and RBW 20pm.

In order to characterize the coherence of this microwave rate Kerr-comb, we directly demodulate the optical comb by detection on a fast photo-receiver with bandwidth 25GHz. The detected electrical spectrum using a 3mm disk (FSR=21.9 GHz) is shown in Fig. 4. Without any external locking, the free-running, mode-locked Kerr comb features a 3dB repetition rate linewidth in the 100s Hertz level, which illustrates the high coherence of the Kerr comb.

In conclusion, a chip-based microcomb at microwave rates from 132GHz to 2.6GHz has been demonstrated for the first time. The Kerr comb beat note is easily detected and is highly coherent with a typical free-running beat linewidth at the 100s of Hertz level. The devices also feature milliWatt level threshold.

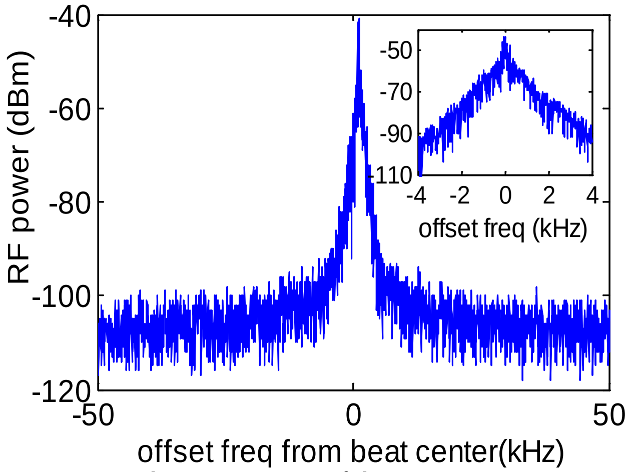

Fig. 4. Microwave beat note spectrum of the 21.9GHz repetition rate Kerr comb (RBW 300Hz, span 100kHz). Inset: zoom in measurement of the beat note, span 8kHz, RBW100Hz.

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