Design and realization of octave-spanning, low f_{ceo} microcombs at sub-telecom wavelengths in silicon nitride

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Abstract: We present design and experimental characterization of microcombs with octave bandwidth, harmonic dispersive waves, and low carrier-envelope-offset frequency (f_{ceo}) for f-2f self-referencing. The method of tuning f_{ceo} is independent of changes in the spectral envelope.

Over the last two decades, developments in nonlinear optical microresonators have driven their emergence as compact, efficient, and reliable sources for optical frequency comb generation [1]. In particular, the realization of dissipative-Kerr-soliton (DKS) microresonator frequency combs (microcombs) [2], with their high coherence, broad spectral bandwidth, and smooth spectral envelopes, has greatly influenced the ascent of microcombs to the forefront of frequency comb research and application. To date, DKS microcombs have been utilized in a wide variety of applications including optical frequency synthesis [3], frequency metrology [4], and optical atomic clocks [5]. Central to all these applications is the requirement for precise control of the microcomb frequencies. Self-referencing via f-2f interferometry of octave-spanning solitons with dual dispersive waves (DWs) has proven a powerful technique in achieving the best-possible control through measurement and stabilization of the frequency comb carrier-envelope-offset frequency (f_{ceo}) [6]. Since fluctuations in comb repetition rate (f_{rep}), for example from resonator thermo-refractive noise, multiply coherently from the pumped mode to the ends of the spectrum, utilizing harmonic DWs often results in superior stability compared to close-to-pump locking schemes [7,8].

Here, we present the design and subsequent experimental characterization of microresonator frequency combs capable of f-2f stabilization for self-referencing. Our combs, designed to be pumped with near-1-micron laser light, span telecom (1550-1600 nm) to visible (780 nm) wavelengths and can take advantage of integrated photonics technology at both the pump and dispersive wave wavelengths. The octave bandwidth and dispersive waves at wavelengths of λ and 2*λ ("harmonic" DWs) are achieved through alteration of the waveguide horizontal dimension in the resonator (RW) for the deposited SiN film thickness (t). In addition, we demonstrate dispersion-independent control of the carrier-envelope-offset over 1 THz through resonator optical path length variation, allowing for simultaneous design of targeted DW positions while maintaining an electronically detectable f_{ceo} for self-referencing. Finally, we produce DKS spectra that span an octave and display dual dispersive waves.

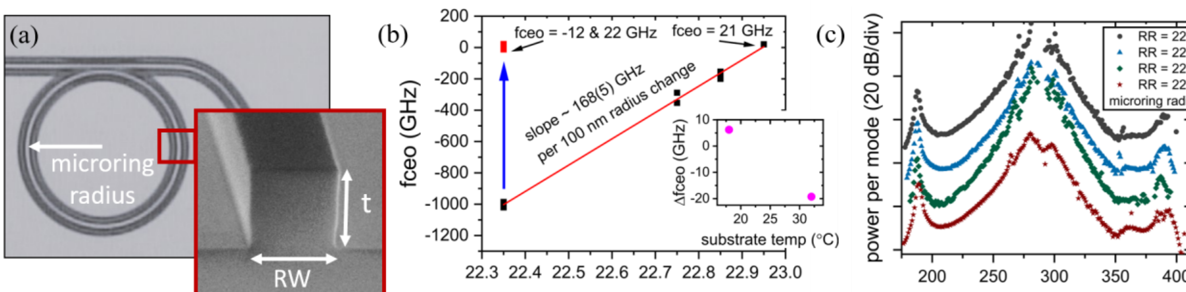

Fig 1. (a) Geometry of our microrings (inset: SiN waveguide cross section). (b) Tuning of f_{ceo} via resonator path length (main) and temperature (inset). (c) Fitted optical mode frequencies in combs corresponding to 1b (spectra offset for readability). Despite changing microring dimensions, the positioning of dispersive waves is relatively unaffected.

The microring resonators were fabricated at Ligentec, SA and were subtractively etched into a layer of stoichiometric silicon nitride (SiN) (Fig. 1a). In this work, we constrain ourselves to two design parameters. First, we vary the optical path length of the microcavity by changing the radius of the microring. Separately, we change the cross section of the resonator waveguide by its width (RW). The height of the resonator cross section is fixed by the silicon nitride layer thickness (t), which is fixed by the LPCVD deposition process and found to be 685–690 nm.

There are two main considerations in the design of microresonators for self-referencing. The primary consideration is achieving an f_{ceo} that is within the ability of conventional photodetectors and electronics to detect and control. In principle, f_{ceo} can range from $-f_{rep}/2$ to $f_{rep}/2$; for octave-spanning microcombs which typically achieve this bandwidth by increasing the FSR to 1 THz, achieving an f_{ceo} less than 40 GHz is a challenge.

We adopt the technique of changing the optical path length of the resonator by increasing the radius of the microring (RR) without changing the waveguide cross section (Fig. 1b). Experimentally, we measure a coefficient of 168(5) GHz change in f_{ceo} for 0.10 micron change in microring radius. Substrate temperature can also control f_{ceo}, to a lesser extent, via the thermo-optic effect (Fig. 1b inset). We see in both simulation and experiment that changing the radius by the fraction necessary to bring f_{ceo} from 0 to f_{rep} has no appreciable effect on the waveguide dispersion, allowing tuning of the f_{ceo} independent of tuning of dispersive wave position (Fig. 1c).

Secondly, in the absence of external broadening, the microcomb must have an octave bandwidth within the resonator to allow f-2f interferometry. This is typically achieved through careful dispersion engineering and use of dual dispersive waves [6,9]. Although dispersive wave placement at harmonic optical frequencies (i.e. ν_m and ν_{2m}) is the most desirable, the main purpose of the dispersive waves is to enable an octave span by shifting power towards the revival in phase matching where the integrated dispersion crosses zero [6]. Indeed, microcombs with dispersive waves that overshoot the harmonic relationship to give a more-than octave spectrum have been successfully self-referenced and used for both optical and microwave frequency synthesis [7,3,5].

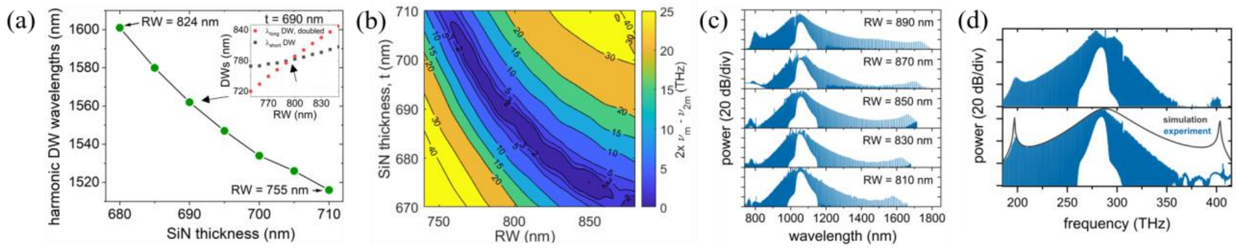

Fig 2. Design of microcomb spectral envelope and experimental results.

Figure 2a shows the simulated DW wavelengths for harmonic DW designs (main) and for a fixed thickness (inset). Figure 2b shows the full design space of dual dispersive wave combs, with the dark blue island in the center corresponding to combs with a spectral envelope containing harmonic DWs. The horizontal width of this central island tells us how fine our fabricated RW variation must be to ensure the desired comb spectrum. Note that simulating the relationship of the DWs to closer than 1-2 THz is not useful, as the dispersion only gives the spectral envelope of the comb. The actual frequencies involved in f-2f interferometry will be determined by f_{rep} and f_{ceo}. Figure 2c shows the experimental results of a scan of RW with resulting spectra spanning 1-1.3 octaves.

Unlike changing the optical path length of the resonator, dispersion engineering of the spectral envelope via waveguide cross section will change both f_{ceo} and dispersive wave placement [6,9]; this is one of the main challenges of designing microcombs for self-referencing. However, as seen in Fig. 1b, a series of twelve rings with radii varying by 50 nm is sufficient to ensure one resonator within the 40 GHz window for measurable f_{ceo}. As more than 400 microrings can be patterned on a 3x10 mm chiplet, this provides an adequately high yield per chiplet.

There is discrepancy between optical power in the measured vs. simulated combs at short wavelengths, which persists for simulations of various geometries, powers, and detunings (Fig. 2d). We attribute this, in part, to the Raman self-frequency shift, which is not captured by the simulation, and, to a greater extent, to the bus waveguide-resonator coupling. The bus waveguide is straight instead of curved along the ring (point coupler) and is optimized for coupling the pump at 1030 nm. We expect shorter wavelengths to be far from critically coupled in such a geometry. Coupler optimization is a necessary next step for stabilizing these spectra [10].

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