Frequency Synthesis with Chip-Scale Microresonators

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Abstract: We describe the generation of low-noise optical and microwave signals via Kerr and Brillouin nonlinearities in high-quality-factor optical microresonators. Applications to clocks, timing, communications and sensing are discussed.

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Nonlinear-wave mixing inside optical microresonators gives rise to the generation of both optical and microwave signals with spectral and temporal properties that are attractive to a wide range of applications. We have been exploring several microresonator platforms (see Figure 1) in which Kerr and Brillouin nonlinearities are used for the generation of broad bandwidth optical frequency combs as well as exceedingly low-noise, continuous-wave lasers. In this talk, we will provide an overview of the microresonator devices and their nonlinear properties, the spectral and temporal characteristics of the generated signals, and some applications that we have been pursuing with these devices.

The Kerr nonlinearity mediates parametric frequency-comb generation when a high-Q microresonator is pumped with a single-frequency continuous-wave laser [1,2]. Beginning at minimum with quantum fluctuations, degenerate and non-degenerate four-wave mixing transfer energy from a pump to frequency sidebands spaced by the free-spectral range of the cavity (typically 10-1000 GHz). While simple in concept, this system is rich in nonlinear dynamics, and in some cases an array of phase-locked and equidistant comb modes can be generated (Fig. 1(e)). We have studied the phase-locking mechanisms and intrinsic noise processes, and have developed techniques to further expand and stabilize the comb spectrum with precision at the femtosecond level [3-6]. Significantly, we have recently employed such a microresonator frequency comb in a self-referencing scheme and thereby used it to form a phase-coherent link between optical and microwave domains. Some microresonator comb devices are compatible with semiconductor processing and could be further integrated with other photonic and electronic components on a

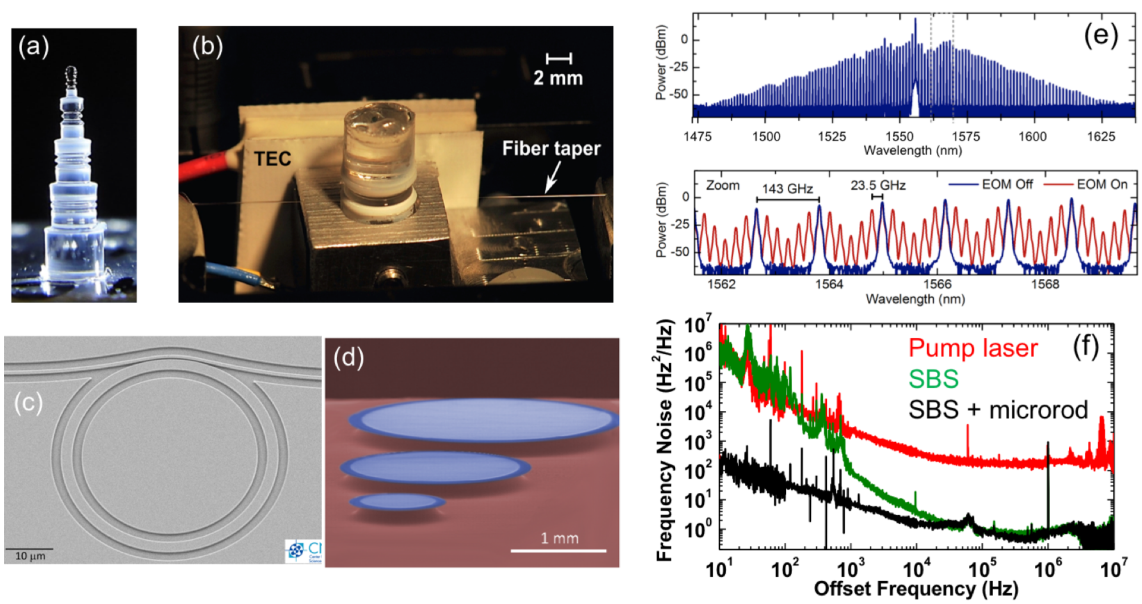

Figure 1: Microresonator devices: (a) silica microrod with multiple whispering gallery modes laser-machined at diameters ranging from 1.6 mm at the bottom to 0.37 mm at the top, (b) 6 mm silica microrod showing tapered fiber coupling and temperature control (TEC), (c) Silicon nitride ring resonator with free spectral range of 1 THz and integrated coupling waveguide, (d) lithographically patterned and etched silica disk resonators. (e) 143 GHz microresonator frequency comb produced in a silica microrod. The lower frame is a zoomed in scan showing the comb lines in blue that are augmented by 23.5 GHz modes produced with an electro-optic modulator to enable measurement and control of the 143 GHz parametric comb. (f) Frequency noise spectrum of a low noise SBS laser (green) that is stabilized to the microrod of image (b). The frequency noise of the SBS pump laser is also shown in red.

silicon chip. In the future, such technology may bring the precision, flexibility, and measurement power of optical frequency combs to a wide range of new and emerging applications in spectroscopic sensing, communications and precision timing beyond the confines of the research laboratory.

In a second microresonator system, we take advantage of stimulated Brillouin scattering (SBS) in a silica microresonator to generate a compact laser with linewidth of ~200 Hz and white frequency-noise floor as low as 0.1 Hz^2/Hz [7-9]. This low noise laser can be chip-integrated and operate at any wavelength in the transparency window of silica. We have specifically demonstrated tunability across the telecom C band. Our measurements have shown that the laser noise is limited by fundamental thermal fluctuations in the microresonator, and thereby highlight the expansion of the optical mode volume as a means to further improve the performance [9]. Based on this principle, we have further reduced the SBS laser linewidth to below 100 Hz, when it is stabilized to a second, passive microresonator [8].

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