On-chip optical frequency comb generation for RF photonic applications

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Abstract: We review several key problems in microresonator frequency comb generation for RF photonic applications, including comb intensity noise and power conversion efficiency, and show some preliminary demonstrations based on mode-locked and low-noise Kerr combs including programmable complex-tap signal processing and true-time-delay beamforming.

Optical frequency combs can find important applications in radiofrequency (RF) and microwave photonics [1, 2]. Traditional choices for comb sources include mode-locked lasers and electro-optic (EO) combs. Microresonator based Kerr comb (microcomb) generation is an emerging technique that shows many outstanding features including high repetition rate, compact volume, and broad bandwidth [3]. Moreover, some microresonator platforms can be integrated with a CMOS-compatible technique [4, 5], thus are highly promising for integrated RF photonics. One representative is silicon nitride (SiN) microring resonator. Figure 1 shows several SiN microrings that have been used for comb generation. Microheaters can be fabricated to achieve flexible thermal tuning and control. In incoherent RF photonic applications, the microcomb is used as a multi-wavelength carrier to duplicate the RF signals with electro-optic modulation. The RF photonic replicas can then be time delayed, tailored, filtered, and summed to accomplish complex signal processing functions. One attractive advantage of microcombs is their high repetition rate (line spacing) which can be up to hundreds of GHz. The high repetition rate corresponds to a large Nyquist zone, which greatly improves the interference-free RF frequency range. However, it should be noted that the number of comb lines decreases with larger line spacing for a given spectral range. The number of comb lines is usually related to the Q factor and time-bandwidth product of the RF photonic system. Therefore, a trade-off between the comb line spacing and the usable line number should be carefully considered in practical applications.

Similar to traditional analog fiber optic links, metrics such as noise figure, spurious-free dynamic range, and conversion loss, are very important for microcomb based RF photonic systems. These questions have not been fully investigated to date. But some conclusions have already become clear. It has been found that mode-locking and intensity noise are generally correlated especially for broadband combs [6, 7]. Incoherent comb states usually show intensity noise significantly higher than that of the pump laser. See Fig. 1(b) for examples of a high-noise incoherent comb state and a mode-locked low-noise comb state. Low-noise mode-locking transitions can be achieved with temporal soliton formation in the cavity [8, 9]. Another important metric is the power conversion efficiency, i.e. ratio of the pump power converted to the comb lines. The efficiency of soliton combs is related to the soliton duty cycle [10]. Dark soliton combs in the normal dispersion region usually show superior efficiency than bright solitons in the anomalous dispersion region. Figure 1(c) shows an example of dark soliton comb with an efficiency of 31.8%.

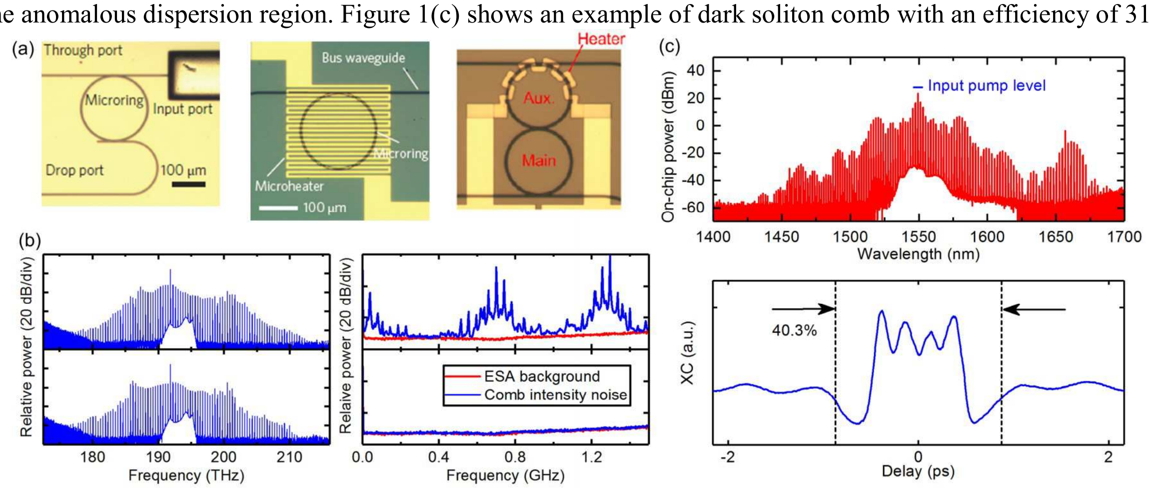

Fig. 1. On-chip microresonator based optical frequency comb generation. (a) Silicon nitride microring resonators. (b) Left: comb spectra; right: intensity noise. (c) Top: a dark soliton comb with conversion efficiency of 31.8%; bottom: time-domain waveform in the bus waveguide.

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Figure 2(a) shows the experimental setup of a complex-tap RF photonic filter based on a mode-locked dark pulse microcomb [11]. The comb line spacing is ~231 GHz corresponding to a Nyquist zone of 115.5 GHz. Twenty-one comb lines in the lightwave C band are selected to construct twenty one taps. Generally, the frequency response of a discrete-delay-line filter is periodic, imposing another limitation on the maximum RF frequency that can be processed. In Fig. 2(a), a 1.8-km single mode fiber is used to introduce a differential time delay of 5.7 ps between the comb lines, corresponding to a RF free spectral range of ~18 GHz. A method was proposed in [11] to break this limitation. By using an optical spectral shaper which has a resolution of 10 GHz, the optical sidebands contributing to the periodic RF passbands can be effectively suppressed. A real single-bandpass RF photonic filter can thus be achieved. Figure 2(b) shows the demonstrated Gaussian and rectangular filter functions which can be freely tuned in a range only limited by the modulator and photodetector.

Figure 2(c) shows the scheme of a microcomb based RF photonic true-time-delay beamformer [12]. The synthesis of the beam patterns is quite similar to the synthesis of the filter transfer functions in Fig. 2(b). Both are Fourier transform of the tap coefficients related to the comb lines. However, in RF beamforming, the differential time delay between the comb lines needs to be controlled for beam scanning. Such tunable differential delay can be introduced by using a binary dispersion matrix which is constructed of highly dispersive delay lines and fast optical switches. In [12], a beamforming network was demonstrated with twenty one comb lines and a four-bit dispersion matrix built with single mode fibers and MEMs optical switches. A method incorporating phase modulation and spectral shaping was proposed to achieve arbitrary RF beam pattern control. The RF frequency range is 8~20 GHz. The beam can be scanned between ±60.2°. Figure 2(d) shows the simulated Gaussian and rectangular beam patterns based on measured RF amplitudes and phases.

In summary, microcombs have shown great potentials for RF photonics. Several preliminary systems including complex-tap signal processing and true-time-delay beamforming have been demonstrated. Microcomb generation with extraordinarily low noise and high efficiency will be worth pursuing in future for RF photonic applications.

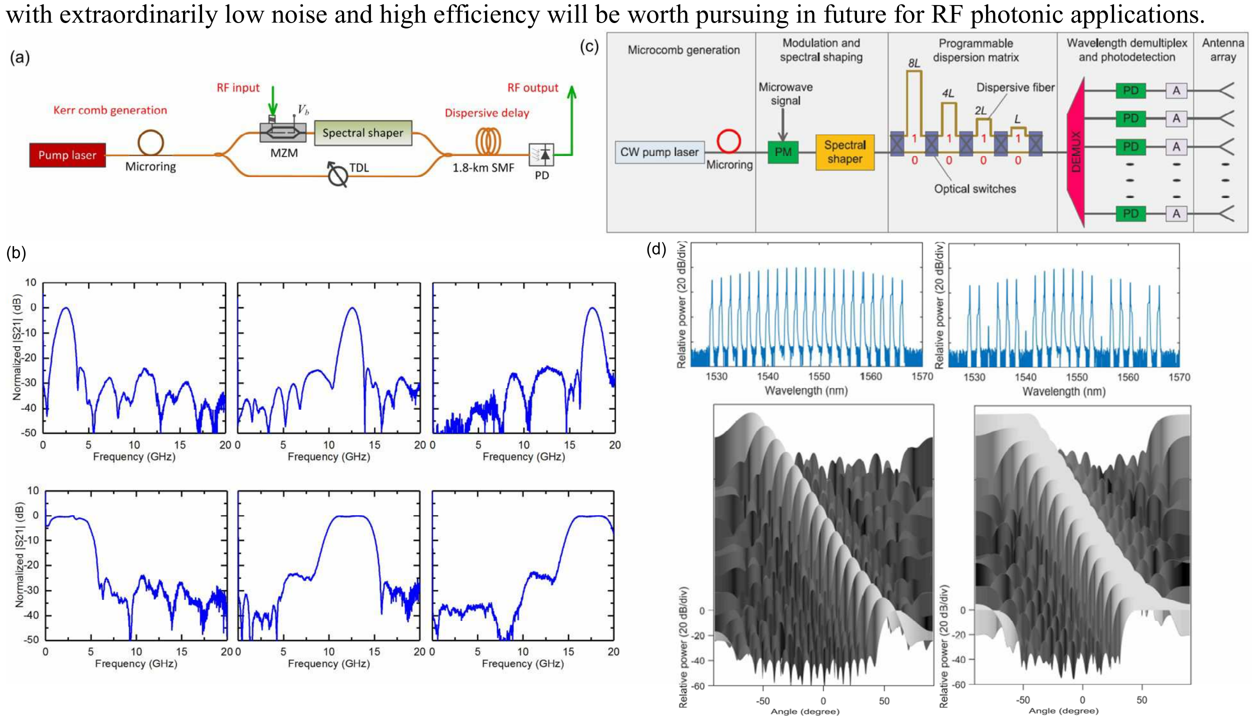

Fig. 2. (a) Experimental setup of a complex-tap microwave photonic signal processor. (b) Frequency responses of real single-bandpass filtering. Top: Gaussian shape; bottom: rectangular shape. (c) Scheme of a microcomb based microwave beamformer with arbitrary beam pattern control. (d) Top: comb spectra; bottom: calculated beam patterns; left: Gaussian beamforming; right: rectangular beamforming.

Funding: National Natural Science Foundation of China (6169190011, 6169190012, 61420106003); Beijing Natural Science Foundation (4172029). Air Force Office of Scientific Research (FA9550-15-1-0211); DARPA PULSE program (W31P40-13-1-0018); National Science Foundation (ECCS-1509578).

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