Reconfigurable Radiofrequency Photonic Filters Based on Soliton Microcombs

Jianqi Hu[1], Jijun He[2], Arslan S. Raja[2], Junqiu Liu[2], Tobias J. Kippenberg[2], Camille-Sophie Brès[1,*]
[1]*Ecole Polytechnique Fédérale de Lausanne, Photonic Systems Laboratory (PHOSL), STI-IEL, Station 11, CH-1015 Lausanne, Switzerland*
[2]*École Polytechnique Fédérale de Lausanne, Laboratory of Photonics and Quantum Measurements (LPQM), SB-IPHYS, Station 3, CH-1015 Lausanne, Switzerland*
[*]*camille.bres@epfl.ch*

Abstract: We demonstrate soliton based radiofrequency filters using a 104 GHz Si_3N_4 microresonator. The filter passband frequencies are widely reconfigured via inherent soliton states of perfect soliton crystals and two-soliton microcombs, without any external pulse shaping.
OCIS codes: (060.5625) Radio frequency photonics; (250.4390) Nonlinear optics, integrated optics.

1. Introduction

Microwave photonics is ubiquitous in the generation, processing, and delivery of radiofrequency (RF) signals [1]. Among others, RF filters based on optical frequency combs and dispersive propagation are key enabling functions with high selectivity and broadband tunability, unparalleled by their electrical counterparts [2]. To minimize the form factor and the cost while improving the performances of comb based RF filters, the integrated microcombs have been used [3-4], in the place of traditional electro-optic combs or mode-locked lasers. Meanwhile, the large comb spacing of microcombs also enhances the RF filters with broader Nyquist zone (spur-free range), lower latency, and less dispersion induced fading. However, all these microcomb based RF filters are implemented on either dark pulses [3] or complex soliton crystal states [4]. Thus, external programmable pulse shaping modules are demanded to equalize or smooth the overall comb spectral shape, which inevitably undermines the merits using integrated comb sources. Leveraging the smooth spectral shape of single soliton or regulated dissipative Kerr soliton (DKS) [5] for RF filters is yet to be explored.

In this paper, we demonstrate for the first time, to our knowledge, single soliton based RF photonic filters using a 104 GHz ultrahigh Q Si_3N_4 microresonator. The microresonator is fabricated using photonic Damascene reflow process [6,7]. In addition, we harness the inherent rich soliton states of microresonator to all-optically reconfigure the RF filters, without requiring any external pulse shaping. Specifically, perfect soliton crystals (PSCs) are utilized to multiply the comb spacing [8], thereby dividing the RF passband frequencies. Moreover, we reconfigure the RF filters through the versatile yet deterministic two-soliton microcombs, in the presence of avoided mode crossings [9]. The spectral interference of two solitons is functionally similar to the interferometric setup, which intrinsically bypasses the need of another pulse shaper for RF filter tuning [3-4]. Thus, the proposed scheme dramatically reduces the system complexity and form factor of microcomb based RF filters, and can find applications in the current radar systems, 5G wireless, and satellite communications.

2. Principle and experimental setup

Fig. 1(a) shows the experimental setup. A tunable continuous-wave (CW) laser is first amplified, polarization managed, and directed to a Si_3N_4 microresonator for soliton microcomb generation [7]. The generated comb is then pump filtered, amplified and polarization managed again before sending to a Mach-Zehnder modulator (MZM) biased at quadrature. The RF signals from a vector network analyzer (VNA) are upconverted to the optical domain, propagate through a spool of 4.583 km standard single mode fiber (SMF) to acquire incremental dispersive delays, and finally beat at an 18 GHz bandwidth photodetector (PD) to retrieve the RF signals. This exactly corresponds to a tapped delay line (TDL) filter, where the power of each comb line is the tap weight, and the delay is determined by the comb spacing and the amount of dispersion.

Fig. 1(b) illustrates the integrated group velocity dispersion (GVD) of the Si_3N_4 microresonator, with respect to the central mode of 1555.12 nm [7]. Based on the fitting of measured integrated GVD, the free spectral range (FSR) $D_1/2\pi \sim 104$ GHz, and dispersion parameters $D_2/2\pi \sim 128$ MHz, $D_3/2\pi \sim O(1)$ kHz can be estimated. Several mode crossings can be clearly seen in Fig. 1(b), which will result in a modulation on the intracavity CW background and will lead to the ordering and regulation of the DKS pulses [8,9]. By scanning the laser over the resonance, step formations in the transmission power are observed, indicating the initiation of solitons (Fig. 1(c)). Under moderate laser scanning power (~ 20 mW at input), the PSC step with different soliton numbers can be obtained in different resonances (blue curve in Fig. 1(c)) [8]. When the power of laser increases (~ 100 mW at input), multiple soliton steps (red curve in Fig. 1(c)) are formed. This enables two-soliton microcomb generation, by either directly falling to the state or backward tuning from higher number of solitons [8]. The inherent versatile soliton states consequently allow for the reconfiguration of their corresponding RF filters.

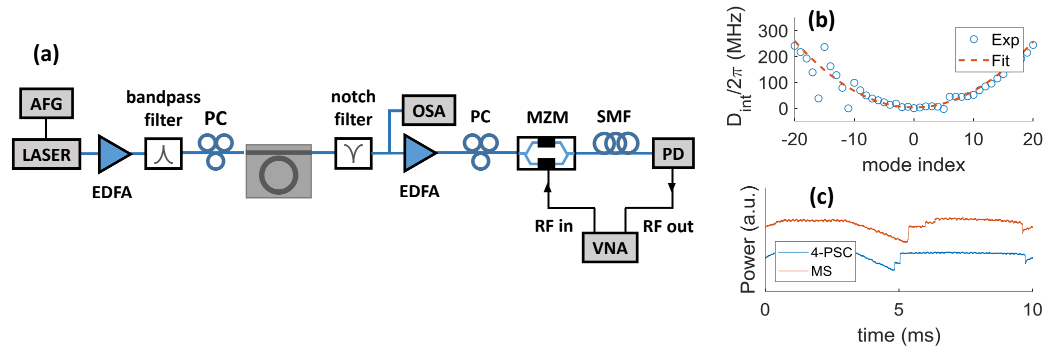

Fig. 1. (a) Experimental setup. (AFG: arbitrary function generator, EDFA: erbium-doped fiber amplifier, PC: polarization controller, OSA: optical spectrum analyzer, MZM: Mach-Zehnder modulator, SMF: single mode fiber, PD: photodetector, VNA: vector network analyzer). (b) Measured (circle) and fitted (dashed line) dispersion properties of the TE_{00} mode family in a 104 GHz Si_3N_4 microresonator. (c) Transmissions observed when scanning a laser over a resonance of the microresonator: 4-PSC (blue) and multiple-soliton (MS - red) step formations.

3. Results and discussion

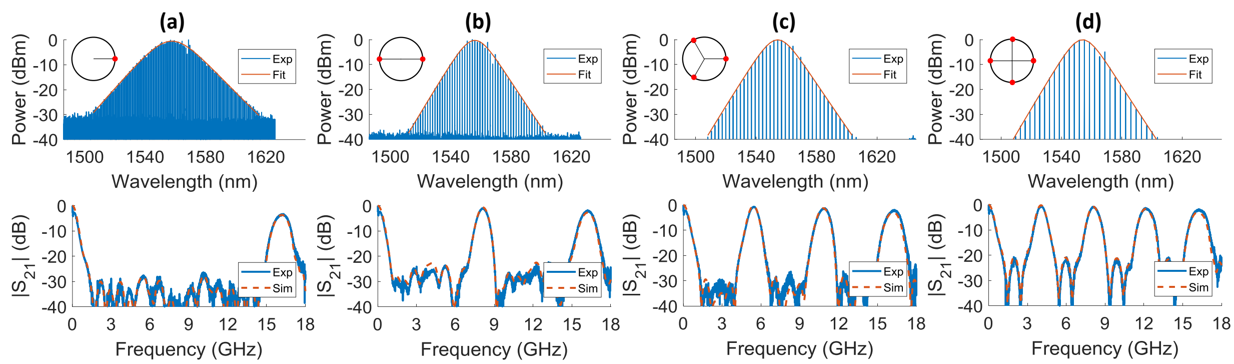

Fig. 2. (a) Single soliton (b-d) 2-, 3-, 4- PSC microcombs and their corresponding RF photonic filters. Upper row: experimental (blue) and $sech^2$ fitted (red) comb spectra; Bottom row: experimental (blue) and simulated (red) power responses of RF filters. The insets show the soliton distributions in azimuthal angle. The passband frequencies of corresponding RF filters are at 16.24 GHz, 8.12 GHz, 5.42 GHz, and 4.06 GHz, pumped at 1555.96 nm, 1555.96 nm, 1554.29 nm, and 1555.12 nm, respectively.

Fig. 2 shows the spectra of single soliton (Fig. 2(a)) and 2-, 3-, 4- PSCs (Fig. 2(b-d)), as well as their corresponding normalized RF filter power responses. The passband frequencies of these filters are respectively at 16.24 GHz, 8.12 GHz, 5.42 GHz, and 4.06 GHz, with main-to-sidelobe suppression ratio (MSMR) of 23.2 dB, 22.6 dB, 25.6 dB, and 20.4 dB (all exceeding 20 dB without spectral shaping). The reconfiguration of PSC based RF filters can be simply seen as multiplying the initial 104 GHz comb spacing, leading to the RF passband frequency division. The current setup corresponds to a TDL filter with all positive taps, thus gives rise to the baseband response [2]. For all the RF filter simulations, the second- and third-order dispersion of the SMF are estimated as -20.2 ps^2/km and 0.12 ps^3/km, while the power of each comb line is extracted from the spectrum after the second EDFA. All the experimental results are in excellent agreement with simulations.

Fig. 3 illustrates the spectra of two-soliton microcombs and their corresponding RF filters, pumped at resonance 1555.96 nm. The two solitons residing in one period induces sinusoid interference of $sech^2$ spectral shape, which is equivalent to the modulation of TDL filter tap weights. Therefore, new RF passbands of halved amplitude would occur, which are shifted to both sides from the initial response by the relative angle between two solitons. Two-soliton microcombs with relative angles of 19.7°, 43.0°, 68.1° 94.6°, 117.0°, 142.5°, and 169.2° (extracted from spectral envelop fitting) are experimentally obtained. Correspondingly, the RF filters are centered at 0.85 GHz, 1.96 GHz, 3.05 GHz, 4.24 GHz, 5.26 GHz, 6.40 GHz, and 7.51 GHz, which approximates linearly with the soliton angle. Note that the possible angle between two solitons is determined by the overall mode crossing profile, and is rather robust to both laser power and frequency detuning, thereby deterministically dictates the filter passband frequencies to be either one of those shown in Fig. 3(h). The synthesized RF filters are widely reconfigurable from DC to 8.1 GHz (2-PSC frequency) with at most 1.2 GHz grid, as well as preserving the bandwidth within 490 MHz to 620 MHz. Continuous tuning of the RF passband frequency might be achieved via controlled mode interaction [10].

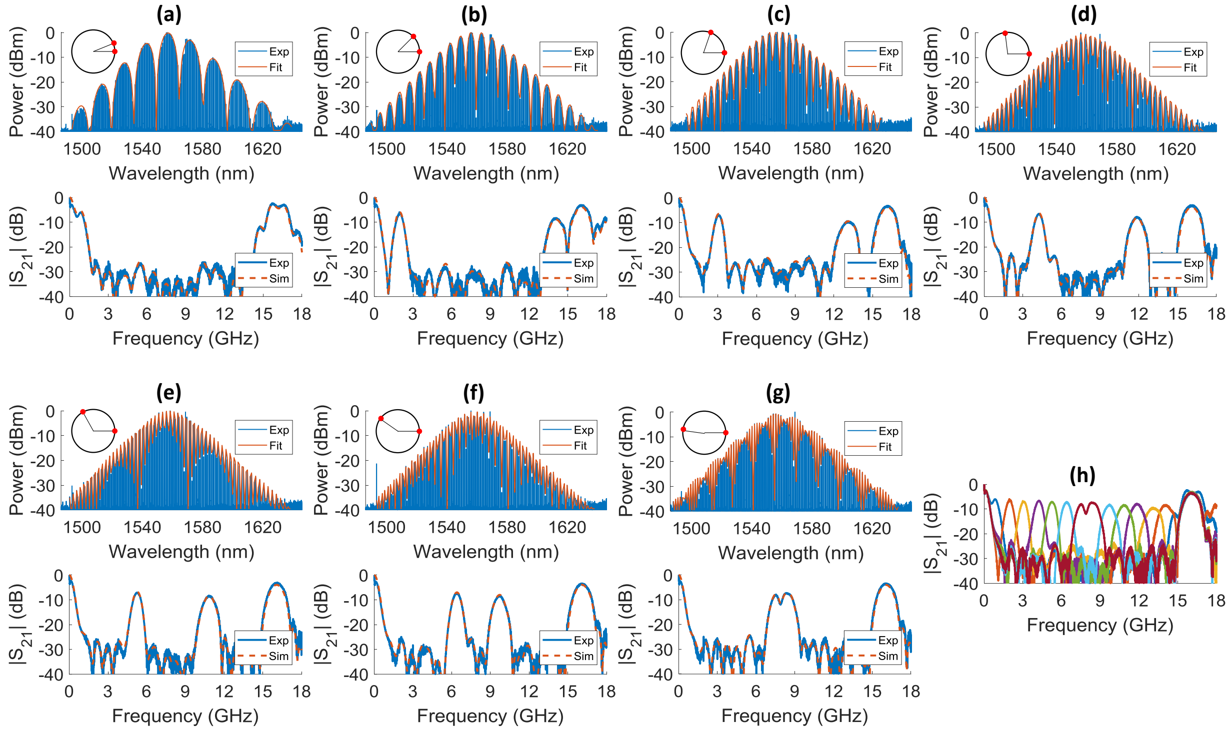

Fig. 3. (a-g) Two-soliton microcombs pumped at resonance 1555.96 nm and their corresponding RF photonic filters. Upper row: experimental (blue) and fitted (red) comb spectra; Bottom row: experimental (blue) and simulated (red) power responses of RF filters. The insets show the relative azimuthal angles between two solitons at (a-g) 19.7°, 43.0°, 68.1° 94.6°, 117.0°, 142.5°, and 169.2°, respectively. The passband frequencies of RF filters are correspondingly at 0.85 GHz, 1.96 GHz, 3.05 GHz, 4.24 GHz, 5.26 GHz, 6.40 GHz, and 7.51 GHz. (h) summary of all the obtained RF filters in (a-g).

4. Conclusion

In conclusion, we demonstrate for the first time soliton based RF photonic filters without any additional pulse shaping. Moreover, we utilize the intrinsic PSCs and two-soliton states of microresonator for the reconfiguration of RF filters. The proposed scheme significantly decreases the system complexity and cost, serving as a crucial step towards fully integrated, widely reconfigurable microcomb based RF photonic filters.

This work was supported by Contract HR0011-15-C-0055 (DODOS) from the Defense Advanced Research Projects Agency (DARPA), Microsystems Technology Office (MTO), and by the Air Force Office of Scientific Research, Air Force Material Command, USAF under Award No. FA9550-15-1-0099, and by Swiss National Science Foundation under grant agreement No. 176563 (BRIDGE) and No. 159897.

References

[1] D. Marpaung et al., “Integrated microwave photonics,” Nat. Photonics **13**(2), 80-90 (2019).
[2] V. R. Supradeepa et al., “Comb-based radiofrequency photonic filters with rapid tunability and high selectivity,” Nat. Photonics **6**(3), 186–194 (2012).
[3] X. Xue et al., “Programmable single-bandpass photonic RF filter based on Kerr comb from a microring,” J. Lightwave Technol. **32**(20), 3557–3565 (2014).
[4] X. Xu et al., “Advanced adaptive photonic RF filters with 80 taps based on an integrated optical micro-Comb source,” J. Lightwave Technol., **37**(4), 1288-1295 (2019).
[5] T. Herr et al., “Temporal solitons in optical microresonators,” Nat. Photonics **8**(2), 145–152 (2013).
[6] M. H. P. Pfeiffer et al., “Ultra-smooth silicon nitride waveguides based on the Damascene reflow process: fabrication and loss origins”, Optica **5**, 884–892 (2018).
[7] J. Liu et al., “Ultralow-power chip-based soliton microcombs for photonic integration,” Optica **5**, 1347–1353 (2018).
[8] M. Karpov et al., “Dynamics of soliton crystals in optical microresonators,” Nat. Phys. **15**, 1071–1077 (2019).
[9] Y. Wang et al., “Universal mechanism for the binding of temporal cavity solitons,” Optica **4**(8), 855–863 (2017).
[10] Y. Liu et al., “Investigation of mode coupling in normal-dispersion silicon nitride microresonators for Kerr frequency comb generation,” Optica **1**(3), 137–144 (2014).