Phase-encoded RF signal generation based on an integrated 49GHz micro-comb soliton crystal optical source

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Research Article

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Abstract

We demonstrate photonic RF phase encoding based on an integrated micro-comb source. By assembling single-cycle Gaussian pulse replicas using a transversal filtering structure, phase encoded waveforms can be generated by programming the weights of the wavelength channels. This approach eliminates the need for RF signal generators for RF carrier generation or arbitrary waveform generators for phase encoded signal generation. A large number of wavelengths—up to 60—were provided by the microcomb source, yielding a high pulse compression ratio of 30. Reconfigurable phase encoding rates ranging from 2 to 6 Gb/s were achieved by adjusting the length of each phase code. This work demonstrates the significant potentials of this microcomb-based approach to achieve high-speed RF photonic phase encoding with low cost and footprint.

Introduction

Phase encoded continuous wave (CW) radio frequency (RF) signals are widely employed in low probability of intercept (LPI) radar systems, since they feature low power density and employ random codes to avoid being cracked [1-2]. In such systems, targets are resolved within range when the reflected phase encoded signals are compressed at the receiver, and a large signal bandwidth is required to achieve a high resolution [3]. Photonic techniques have significant potential to overcome the limitations of their electronic counterparts [4] due to their intrinsically broad bandwidth, immunity from electromagnetic interference, and low propagation loss [5-11].

Significant effort has been devoted to realizing photonic-assisted RF phase encoding, including approaches based on polarization modulators [12, 13], Sagnac loops [14, 15], and dual parallel modulators [16, 17]. However, these approaches all face limitations of one form or another, such as the need for complicated modulation schemes to achieve the required π -phase shifts, and the need for both high-frequency RF signal generators and arbitrary waveform generators. The former increases the complexity and instability (such as the bias drift of the modulators) of the system, while the latter greatly increase the cost, size and power consumption.

An alternative method of generating RF phase encoded signals based on transversal filtering structures has been proposed [18]. In this method, RF high-order Gaussian pulses are broadcast onto 4 wavelength channels via an intensity modulator, and then progressively delayed through a dispersive medium such that the pulse segments are assembled (concatenated) in the time domain. By controlling the phase of each pulse segment, phase-encoded waveforms can be generated. This approach reduces the need for RF sources and complicated modulation schemes, and offers a high potential phase encoding speed by tailoring the delay step and pulse width. However, it is not without challenges. The use of discrete laser arrays significantly increases the complexity and cost for further integration and limits the number of wavelengths. This in turn leads to a limited sequence length and thus a small pulse compression ratio that would limit the performance of radar systems. Secondly, the employed high-order Gaussian pulses

require complicated generation schemes such as high-order differentiation, which will increase the cost and complexity of the system.

Integrated microcombs [19-24], generated through optical parametric oscillation in monolithic microring resonators (MRRs), are promising multi-wavelength sources that offer many advantages including a much higher number of wavelengths and greatly reduced footprint and complexity. Thus, a wide range of RF applications have been demonstrated based on micro-combs, such as transversal filters [25-27], differentiators [28], optical true time delays [29, 30] and channelizers [31, 32], Hilbert transformers [33-35], microwave mixers [36], microwave generation [37], and more.

In this paper, we demonstrate phase encoded CW RF signal generation using an integrated soliton crystal micro-comb source. The soliton crystal is a recently discovered coherent and stable solution of the Lugiato-Lefever equation [38, 39], which governs the nonlinear dynamics of the optical parametric oscillator. The soliton crystal stably forms through the background wave generated by a mode crossing, and features over thirty times higher intra-cavity power than traditional dissipative Kerr solitons. Thus, they can remove thermal effects and enable adiabatic pump sweeping for coherent comb generation [39, 40]. These properties, together with the broadband comb spectrum, make soliton crystals promising for demanding integrated RF photonic systems, such as the photonic RF phase-encoder introduced in this work.

Here, by multicasting an RF single-cycle pulse (instead of the high-order pulse used in [18]) onto a spectrally flattened micro-comb and progressively delaying the replicas with a dispersive medium, the RF pulse replicas are assembled arbitrarily in time according to the designed binary phase codes. The large number of wavelengths offered by the microcomb enabled 30 bits, representing an enhancement of over 4 times compared to previous work [18], for the phased encoded RF sequence, leading to a pulse compression ratio as high as 29.6. A reconfigurable phase encoding rate ranging from 1.98 to 5.95 Gb/s was also achieved by varying the length of each phase code. These results verify the strong potential of our approach for the realization of photonic RF phase encoding schemes and represent a solid step towards the miniaturization of fully integrated radar transmitters with greatly reduced cost and footprint.

Theory

Figure 1 illustrates the operation principle of a photonic phase encoder. First, an RF Gaussian pulse $f(t)$ with a duration of Δt is generated. Then a discrete convolution operation between the RF pulse and flattened microcomb spectrum (denoted by a discrete signal $g[n]$ with length N and binary values of 1 or -1) is performed with a delay step of Δt , and can be described as: **see formula 1 in the supplementary files.**

The discrete convolution operation between the RF pulse $f(t)$ and the flattened microcomb spectrum is achieved using the experimental setup in Figure 2. The RF pulse is first multi-cast onto the wavelength channels to yield replicas, which are then delayed with a progressive step that matches the pulse duration Δt . By flipping the sign of the delayed replicas according to designed phase codes $g[n]$, a phase-encoded

sequence can be assembled in the time domain. The sign reversal is accomplished by spatially separating the intended positive pulses from the negative ones using the programmable wavelength dependent spatial routing capability of a waveshaper, and then directing the two separate outputs to the positive and negative inputs of a differential photodetector, respectively. The total number of RF pulse replicas N is equal to the number of wavelength channels, which is 60 in our case—15 times that of the previous work [18]. Thus, the total time length of the phase-encoded sequence is $T = N \cdot \Delta t$. Here, the basic temporal element in the phase-encoded sequence is termed an “RF segment”, which is a single-cycle or multi-cycle sine wave assembled from the input RF pulse (i.e., two anti-phase RF pulses assemble a single-cycle sine wave). The centre frequency of the phase-encoded sequence is determined by the frequency of the assembled sine waves, thus is equivalently given by $1/2/\Delta t$. Assuming each RF segment constitutes m pulses, then the length of the phase-encoded sequence would be N/m , together with an equivalent phase encoding speed of $1/\Delta t/m$. We note that the generated phase-encoded sequence has a bandwidth similar to the input RF pulse, which is subject to the Nyquist bandwidth, equivalent to half of the comb spacing ($48.9 \text{ GHz}/2 = 24.45 \text{ GHz}$).

In a radar system, the phase encoded RF waveform is first amplified and then emitted by antennas, followed by reflection from the target, and finally collected and processed at the receiver. The range information of the target is carried on the delay of the received waveforms, which can be readily determined by calculating the autocorrelation function of the reflected phase-encoded RF signal given by

See formula 2 in the supplementary files section.

In practical systems this is calculated by performing a hardware autocorrelation extracted by an array of range gates. The range gates are composed of matched filters with their tap coefficients determined by the employed phase codes (Fig. 3). The function of the matched filters is to perform single-output autocorrelations for the received signal, and the range gate that has the highest output power denotes the resolved range of the target.

Experimental Results

The experimental setup is shown in Figure 2. A CW laser is amplified and its polarization state adjusted to pump a nonlinear high Q factor (> 1.5 million) MRR, which featured a free spectral range of $\sim 0.4 \text{ nm}$, or 48.9 GHz . As the detuning between the pump laser and the MRR was changed, dynamic parametric oscillation states corresponding to distinctive solutions of the Lugiato-Lefever equation were initiated [38]. We thus generated soliton crystal microcombs [39, 40], which were tightly packaged solitons circulating in the MRR as a result of a mode crossing (at $\sim 1552 \text{ nm}$ in our case), and which resulted in the distinctive palm-like comb spectrum (Fig. 4).

Next, 60 lines of the microcomb were flattened ($N=60$ in our case), using two stages of WaveShapers (Finisar 4000S) to acquire a high link gain and signal-to-noise ratio. This was achieved by pre-flattening

the microcomb lines with the first WaveShaper such that the optical power distribution of the wavelength channels roughly matched with the desired channel weights. The second WaveShaper was employed for accurate comb shaping assisted by a feedback loop as well as to separate the wavelength channels into two parts (port 1 and port 2 of the Waveshaper) according to the polarity of the designed binary phase codes. The feedback loop was constructed by reading the optical spectrum with an optical spectrum analyser and comparing the power of the wavelengths with the designed weights to generate an error signal, which was then fed back into the second WaveShaper (WS2) to calibrate its loss until the error was below 0.2 dB.

Here, we used a Gaussian pulse with a duration of $\Delta t = 84$ ps, as the RF fragment $f[t]$. Although we used an arbitrary waveform generator (Keysight, 65 GSa/s) to generate the Gaussian pulse for the sake of simplicity, the arbitrary waveform generator is actually not a necessity and can be replaced with many other readily available approaches that are easier and cheaper [41, 42]. The input RF pulse was imprinted onto the comb lines, generating replicas across all the wavelength channels. The replicas then went through a ~ 13 km long spool of standard single mode fibre (with a dispersion of 17ps/nm/km) to progressively delay them, leading to a delay step of ~ 84 ps between the adjacent wavelength channels that matched with the duration of the RF pulse Δt . Finally, the wavelength channels were separated into two parts according to the designed phase codes and sent to a balanced photodetector (Finisar, 40 GHz) to achieve negative and positive replicas for the phase encoding.

Figure 5 shows the input Gaussian pulse and the flattened optical comb spectra measured at the output ports of the second Waveshaper (WS2). Each pair of wavelength channels from different ports can assemble a monocycle sine wave, thus with the 60 comb lines, 30 sine cycles can be achieved, with a total time length of $T = N\Delta t = 60 \times 84 \text{ ps} = 5.04$ ns.

By applying designed phase codes during the separation of the wavelength channels, the sine cycles could be π -phase shifted at desired times. The phase-encoded results are shown in Fig. 6. The number of Gaussian pulses for each RF segment (denoted by m) was reconfigured from 6 to 2, corresponding to reconfigurable sequence lengths (N/m) ranging from 10 to 30 and phase coding speeds ($1/\Delta t/m$) ranging from 1.98 to 5.95 Gb/s. The employed phase codes were denoted both by the shaded areas and the stair waveforms (black solid line). This result shows that our photonic phase coder can offer a reconfigurable sequence length to address the performance tradeoffs between range resolution and system complexity. To acquire a large pulse compression ratio for a high resolution, the sequence length should be maximized, where the number of Gaussian pulses for each RF segment (m) should be set as 2. While to reduce the complexity and cost of the RF system (such as the number of range gates at the receiver), the sequence length could be reduced by either employing fewer wavelength channels or by increasing m .

The corresponding optical spectra (Fig. 6 (a, c, e)) were measured at the output of Waveshaper to show the positive and negative phase codes realized by changing the wavelength channels' output ports at the Waveshaper. The encoded RF waveforms (Fig. 6 (b, d, f)) clearly show the flipped phase of the RF

segments at the time of negative phase codes, where the number of sine cycles was reconfigured as well, depending on the value of m . This result also shows that our approach is fully reconfigurable for different phase codes and encoding speeds. We note that higher encoding speeds can be achieved by reducing the duration of the RF fragment and the delay step Δt .

In this work we calculated the autocorrelation (Fig. 7) of the phase-encoded RF waveforms $s(t)$. As the sequence length varied from 10 to 30, the full width at half-maximum (FWHM) of the compressed pulses varied from 0.52 to 0.17 ns, which corresponds to a pulse suppression ratio ranging from 9.7 to 29.6. Meanwhile the peak-to-sidelobe ratio (PSR) also increased with the sequence length from 4.17 to 6.59 dB. These results confirm that the pulse compression ratio of an RF phase-encoded signal is linearly related to its sequence length [43], and that this can be significantly enhanced with our approach by employing a larger number of wavelength channels of the microcomb.

Figure 8 shows calculated examples of the estimated outputs of the range gates [43] with different distances. Considering an example with a sequence length $N/m = 30$, the delay of the matched filters would be $2\Delta t = 168$ ps. The tap coefficients for the l_{th} matched filter are $d[k-l]$, where $d[k]$, $k=1, 2, \dots, 30$, is the employed phase codes. The range resolution of the radar, which is the minimum distance between two resolvable targets, is determined by the delay step ($2\Delta t$) of the matched filters, which is given by $2\Delta t \cdot c = 5\text{cm}$, where $c = 3 \times 10^8 \text{m/s}$ is the speed of RF signals in air. If the distance between the target and radar is R , then the delay would be $2R/c$. The range gates would have a maximum output at the l_{th} range gate, $l = 2R/(c \cdot 2\Delta t)$. We note here that this calculation only shows the basic connections between our phase encoder and radar systems' performances - practical radar systems are subject to more complicated trade-offs involving capability versus performance.

We note that although random phase codes were used here as a proof of concept, the design of phase codes can be optimized to achieve a better detection performance of the radar system, which is an NP-hard problem and can be approximated and addressed with the methods in [44].

Further, the routes to further scale up the performance of our system are clear. The sequence length can be further increased by either employing microcombs that have a smaller FSR and thus more wavelength channels in the available optical band, or by introducing spatial-multiplexing techniques to boost the length of parallel channels. Moreover, the increasingly mature nonlinear platforms and recent advances in coherent soliton generation techniques (such as deterministic soliton generation [45] and battery-driven solitons [46]) enable microcombs to have an increasingly wide access and enhanced performance for engineering applications, including the phase-encoded signal generator reported here.

Finally, microcombs rely on parametric gain and FWM in MRRs which depend on many factors in terms of material properties, including the third-order nonlinearity, the linear and nonlinear loss, dispersion, etc. For GO-coated MRRs the extremely promising nonlinear optical properties of layered GO films will yield many new device properties that are difficult to achieve for typical integrated photonic devices. We

believe this could enable one to tailor the device performance for many applications to microcomb devices, quantum optics and nonlinear optical photonic chips in general [47-154].

Conclusion

We demonstrate photonic RF phase encoding using an integrated micro-comb source. A single-cycle Gaussian pulse was multicast onto the comb wavelengths to assemble the desired phase-encoded RF waveform. A high pulse compression ratio of 29.6 and phase encoding speed of 5.95 Gb/s were achieved, enabled by the use of 60 wavelengths generated by the microcomb. The sequence length was reconfigured by adjusting the length of each phase code, which led to a reconfigurable encoding speed. These results verify that our approach to high-speed RF phase encoding is competitive in terms of performance, with potentially lower cost and footprint.

References

1. P. Ghelfi, F. Laghezza, F. Scotti, G. Serafino, A. Capria, S. Pinna, D. Onori, C. Porzi, M. Scaffardi, A. Malacarne, V. Vercesi, E. Lazzeri, F. Berizzi, and A. Bogoni, "A fully photonics-based coherent radar system," *Nature*, vol. 507, pp. 341, Mar. 2014.
2. M. Skolnik, "Role of radar in microwaves," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 3, pp. 625-632. 2002.
3. P. Ghelfi, F. Scotti, F. Laghezza, and A. Bogoni, "Photonic Generation of Phase-Modulated RF Signals for Pulse Compression Techniques in Coherent Radars," *Journal of Lightwave Technology*, vol. 30, no. 11, pp. 1638-1644, Jun. 2012.
4. J. Capmany, and D. Novak, "Microwave photonics combines two worlds," *Nat. Photonics*, vol. 1, no. 6, pp. 319-330, Jun. 2007.
5. J. P. Yao, "Microwave Photonics," *J. Lightwave Technol.*, vol. 27, no. 1-4, pp. 314-335, Jan-Feb. 2009.
6. D. Marpaung, J. Yao, and J. Capmany, "Integrated microwave photonics," *Nature Photonics*, vol. 13, no. 2, pp. 80-90, Feb. 2019.
7. V. R. Supradeepa, C. M. Long, R. Wu, F. Ferdous, E. Hamidi, D. E. Leaird, and A. M. Weiner, "Comb-based radiofrequency photonic filters with rapid tunability and high selectivity," *Nat. Photonics*, vol. 6, no. 3, pp. 186-194, Mar. 2012.
8. J. Wu, X. Xu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "RF Photonics: An Optical Microcombs' Perspective," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 4, pp. 1-20. 2018.
9. J. Azaña, "Ultrafast Analog All-Optical Signal Processors Based on Fiber-Grating Devices," *IEEE Photonics Journal*, vol. 2, no. 3, pp. 359-386. 2010.
10. Z. Jiang, C.-B. Huang, D. E. Leaird, and A. M. Weiner, "Optical arbitrary waveform processing of more than 100 spectral comb lines," *Nature Photonics*, vol. 1, pp. 463, Aug. 2007.

11. S. T. Cundiff, and A. M. Weiner, "Optical arbitrary waveform generation," *Nature Photonics*, vol. 4, pp. 760, Oct. 2010.
12. H. Chi, and J. Yao, "Photonic Generation of Phase-Coded Millimeter-Wave Signal Using a Polarization Modulator," *IEEE Microwave and Wireless Components Letters*, vol. 18, no. 5, pp. 371-373. 2008.
13. Y. Zhang, and S. Pan, "Generation of phase-coded microwave signals using a polarization-modulator-based photonic microwave phase shifter," *Optics Letters*, vol. 38, no. 5, pp. 766-768, Mar. 2013.
14. Z. Li, W. Li, H. Chi, X. Zhang, and J. Yao, "Photonic Generation of Phase-Coded Microwave Signal With Large Frequency Tunability," *IEEE Photonics Technology Letters*, vol. 23, no. 11, pp. 712-714. 2011.
15. W. Liu, and J. Yao, "Photonic Generation of Microwave Waveforms Based on a Polarization Modulator in a Sagnac Loop," *Journal of Lightwave Technology*, vol. 32, no. 20, pp. 3637-3644, Oct. 2014.
16. S. Zhu, Z. Shi, M. Li, N. H. Zhu, and W. Li, "Simultaneous frequency upconversion and phase coding of a radio-frequency signal for photonic radars," *Optics Letters*, vol. 43, no. 3, pp. 583-586, Feb. 2018.
17. S. Zhu, M. Li, X. Wang, N. H. Zhu, Z. Z. Cao, and W. Li, "Photonic generation of background-free binary phase-coded microwave pulses," *Optics Letters*, vol. 44, no. 1, pp. 94-97, Jan. 2019.
18. Y. Dai, and J. Yao, "Microwave pulse phase encoding using a photonic microwave delay-line filter," *Optics Letters*, vol. 32, no. 24, pp. 3486-3488, Dec. 2007.
19. T. J. Kippenberg, A. L. Gaeta, M. Lipson, and M. L. Gorodetsky, "Dissipative Kerr solitons in optical microresonators," *Science*, vol. 361, no. 6402, pp. 8083. 2018.
20. D. J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, "New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics," *Nat. Photonics*, vol. 7, no. 8, pp. 597-607, Aug. 2013.
21. A. L. Gaeta, M. Lipson, and T. J. Kippenberg, "Photonic-chip-based frequency combs," *Nature Photonics*, vol. 13, no. 3, pp. 158-169, Mar. 2019.
22. M.-G. Suh, and K. J. Vahala, "Soliton microcomb range measurement," *Science*, vol. 359, no. 6378, pp. 884-887. 2018.
23. W. Liang, D. Eliyahu, V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, D. Seidel, and L. Maleki, "High spectral purity Kerr frequency comb radio frequency photonic oscillator," *Nature communications*, vol. 6, pp. 7957. 2015.
24. D. T. Spencer, T. Drake, T. C. Briles, J. Stone, L. C. Sinclair, C. Fredrick, Q. Li, D. Westly, B. R. Ilic, and A. Bluestone, "An optical-frequency synthesizer using integrated photonics," *Nature*, vol. 557, no. 7703, pp. 81-85. 2018.
25. X. Xu, J. Wu, T. G. Nguyen, M. Shoeiby, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Advanced RF and microwave functions based on an integrated optical frequency comb source," *Opt. Express*, vol. 26, no. 3, pp. 2569-2583, Feb 5. 2018.
26. X. Xu, M. Tan, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Advanced Adaptive Photonic RF Filters with 80 Taps Based on an Integrated Optical Micro-Comb

- Source," *Journal of Lightwave Technology*, vol. 37, no. 4, pp. 1288-1295, Feb. 2019.
27. X. X. Xue, Y. Xuan, H. J. Kim, J. Wang, D. E. Leaird, M. H. Qi, and A. M. Weiner, "Programmable Single-Bandpass Photonic RF Filter Based on Kerr Comb from a Microring," *J. Lightwave Technol.*, vol. 32, no. 20, pp. 3557-3565, Oct 15. 2014.
 28. X. Xu, J. Wu, M. Shoeiby, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Reconfigurable broadband microwave photonic intensity differentiator based on an integrated optical frequency comb source," *APL Photonics*, vol. 2, no. 9, 096104 Sep. 2017.
 29. X. Xu, J. Wu, T. G. Nguyen, T. Moein, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Photonic microwave true time delays for phased array antennas using a 49 GHz FSR integrated optical micro-comb source," *Photonics Res*, vol. 6, no. 5, pp. B30-B36, May 1. 2018.
 30. X. Xue, Y. Xuan, C. Bao, S. Li, X. Zheng, B. Zhou, M. Qi, and A. M. Weiner, "Microcomb-Based True-Time-Delay Network for Microwave Beamforming with Arbitrary Beam Pattern Control," *Journal of Lightwave Technology*, vol. 36, no. 12, pp. 2312-2321, Jun. 2018.
 31. X. Xu, M. Tan, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "High performance RF filters via bandwidth scaling with Kerr micro-combs," *APL Photonics*, vol. 4, no. 2, pp. 026102. 2019.
 32. X. Xu, J. Wu, T. G. Nguyen, S. Chu, B. Little, A. Mitchell, R. Morandotti, and D. J. Moss, "Broadband RF Channelizer based on an Integrated Optical Frequency Kerr Comb Source," *Journal of Lightwave Technology*, vol. 36, no. 19, pp. 7, 2018.
 33. M. Tan, X. Xu, B. Corcoran, J. Wu, A. Boes, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Broadband microwave and RF photonic fractional Hilbert transformer based on a 50GHz integrated Kerr micro-comb", Vol. 37 2019. IEEE Journal of Lightwave Technology. DOI:10.1109/JLT.2019.2946606
 34. T. G. Nguyen, M. Shoeiby, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Integrated frequency comb source based Hilbert transformer for wideband microwave photonic phase analysis", *Optics Express* Vol. 23, no. 17, 22087 (2015). DOI:10.1364/OE.23.022087
 35. X. Xu, M. Tan, J. Wu, R. Morandotti, A. Mitchell, and D. J. Moss, "Microcomb-based photonic RF signal processing", *IEEE Photonics Technology Letters* Vol. 31 (2019). DOI: 10.1109/LPT.2019.2940497
 36. X. Xu, J. Wu, Mengxi Tan, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, "Broadband microwave frequency conversion based on an integrated optical micro-comb source", *IEEE Journal of Lightwave Technology* Vol. 37 (2019). DOI: 10.1109/JLT.2019.2930466
 37. A. Pasquazi; M. Peccianti; B. Little; S. T. Chu; D. J. Moss; R. Morandotti, "Stable, dual mode, high repetition rate mode-locked laser based on a microring resonator", *Optics Express* vol. 20, no. 24, 27355 – 27362, 2012. DOI: 10.1364/OE.20.027355
 38. A. Pasquazi, M. Peccianti, L. Razzari, D. J. Moss, S. Coen, M. Erkintalo, Y. K. Chembo, T. Hansson, S. Wabnitz, P. Del'Haye, X. X. Xue, A. M. Weiner, and R. Morandotti, "Micro-combs: A novel generation of optical sources," *Physics Reports, Review Section of Physics Letters*, vol. 729, pp. 1-81, Jan 27. 2018.

39. D. C. Cole, E. S. Lamb, P. Del'Haye, S. A. Diddams, and S. B. Papp, "Soliton crystals in Kerr resonators," *Nat. Photonics*, vol. 11, no. 10, pp. 671-676, Oct. 2017.
40. W. Q. Wang, Z. Z. Lu, W. F. Zhang, S. T. Chu, B. E. Little, L. R. Wang, X. P. Xie, M. L. Liu, Q. H. Yang, L. Wang, J. G. Zhao, G. X. Wang, Q. B. Sun, Y. S. Liu, Y. S. Wang, and W. Zhao, "Robust soliton crystals in a thermally controlled microresonator," *Opt. Lett.*, vol. 43, no. 9, pp. 2002-2005, May 1. 2018.
41. W. Chiming, and N. K. Dutta, "High-repetition-rate optical pulse generation using a rational harmonic mode-locked fiber laser," *IEEE Journal of Quantum Electronics*, vol. 36, no. 2, pp. 145-150. 2000.
42. H. Jeongwoo, and N. Cam, "A new ultra-wideband, ultra-short monocycle pulse generator with reduced ringing," *IEEE Microwave and Wireless Components Letters*, vol. 12, no. 6, pp. 206-208. 2002.
43. N. Levanon, and B. Getz, "Comparison between linear FM and phase-coded CW radars," *IEE Proceedings - Radar, Sonar and Navigation*, vol. 141, no. 4, pp. 230-240. 1994.
44. A. D. Maio, S. D. Nicola, Y. Huang, Z. Luo, and S. Zhang, "Design of Phase Codes for Radar Performance Optimization with a Similarity Constraint," *IEEE Transactions on Signal Processing*, vol. 57, no. 2, pp. 610-621. 2009.
45. H. Zhou, Y. Geng, W. Cui, S.-W. Huang, Q. Zhou, K. Qiu, and C. Wei Wong, "Soliton bursts and deterministic dissipative Kerr soliton generation in auxiliary-assisted microcavities," *Light: Science & Applications*, vol. 8, no. 1, pp. 50, 2019.
46. B. Stern, X. Ji, Y. Okawachi, A. L. Gaeta, and M. Lipson, "Battery-operated integrated frequency comb generator," *Nature*, vol. 562, no. 7727, pp. 401. 2018.
47. L. Razzari, D. Duchesne, M. Ferrera, R. Morandotti, S. Chu, B. E. Little, and D. J. Moss, "CMOS-compatible integrated optical hyper-parametric oscillator," *Nat. Photonics*, vol. 4, no. 1, pp. 41-45, Jan. 2010.
48. D.J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, "New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics," *Nat. Photonics*, vol. 7, no. 8, pp. 597-607, Aug. 2013.
49. Pasquazi, M. Peccianti, L. Razzari, D. J. Moss, S. Coen, M. Erkintalo, Y. K. Chembo, T. Hansson, S. Wabnitz, P. Del Haye, X. X. Xue, A. M. Weiner, and R. Morandotti, "Micro-Combs: A Novel Generation of Optical Sources", *Physics Reports*, vol. 729, pp. 1-81, Jan. 2018.
50. M. Ferrera, L. Razzari, D. Duchesne, R. Morandotti, Z. Yang, M. Liscidini, J. E. Sipe, S. Chu, B. E. Little, and D. J. Moss, "Low-power continuous-wave nonlinear optics in doped silica glass integrated waveguide structures," *Nat. Photonics*, vol. 2, no. 12, pp. 737-740, 2008.
51. M. Kues, C. Reimer, P. Roztock, L. R. Cortes, S. Sciara, B. Wetz, Y. B. Zhang, A. Cino, S. T. Chu, B. E. Little, D. J. Moss, L. Caspani, J. Azana, and R. Morandotti, "On-chip generation of high-dimensional entangled quantum states and their coherent control," *Nature*, vol. 546, no. 7660, pp. 622-626, Jun. 2017.
52. L. Caspani, C. Xiong, B. Eggleton, D. Bajoni, M. Liscidini, M. Galli, R. Morandotti, David J. Moss, "On-chip sources of quantum correlated and entangled photons", *Nature: Light Science and Applications*, vol. 6, e17100 (2017); doi: 10.1038/lsa.2017.100.

53. M. Kues, C. Reimer, B. Wetzel, P. Roztock, B. E. Little, S. T. Chu, T. Hansson, E. A. Viktorov, D. J. Moss, and R. Morandotti, "Passively mode-locked laser with an ultra-narrow spectral width," *Nat. Photonics*, vol. 11, no. 9, pp. 608-608, Sep. 2017.
54. C. Reimer, M. Kues, P. Roztock, B. Wetzel, F. Grazioso, B. E. Little, S. T. Chu, T. Johnston, Y. Bromberg, L. Caspani, D. J. Moss, and R. Morandotti, "Generation of multiphoton entangled quantum states by means of integrated frequency combs," *Science*, vol. 351, no. 6278, pp. 1176-1180, Mar. 2016.
55. M. Ferrera, Y. Park, L. Razzari, B. E. Little, S. T. Chu, R. Morandotti, D. J. Moss, and J. Azana, "On-chip CMOS-compatible all-optical integrator," *Nat. Commun.*, vol. 1, Article 29. 1 Jun. 2010.
doi:10.1038/ncomms1028
56. F. Da Ros, E. P. da Silva, D. Zibar, S. T. Chu, B. E. Little, R. Morandotti, M. Galili, D. J. Moss, and L. K. Oxenlowe, "Wavelength conversion of QAM signals in a low loss CMOS compatible spiral waveguide," *APL Photonics*, vol. 2, no. 4, 046105. Apr. 2017.
57. Pasquazi, L. Caspani, M. Peccianti, M. Clerici, M. Ferrera, L. Razzari, D. Duchesne, B. E. Little, S. T. Chu, D. J. Moss, and R. Morandotti, "Self-locked optical parametric oscillation in a CMOS compatible microring resonator: a route to robust optical frequency comb generation on a chip," *Opt. Express*, vol. 21, no. 11, pp. 13333-13341, Jun. 2013.
58. Reimer, M. Kues, L. Caspani, B. Wetzel, P. Roztock, M. Clerici, Y. Jestin, M. Ferrera, M. Peccianti, A. Pasquazi, B. E. Little, S. T. Chu, D. J. Moss, and R. Morandotti, "Cross-polarized photon-pair generation and bi-chromatically pumped optical parametric oscillation on a chip," *Nat. Commun.*, vol. 6, Article 8236. Sep. 2015.
59. J. Wu, X. Xu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "RF Photonics: An Optical Microcombs' Perspective," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 4, pp. 1-20. 2018.
60. X. Xu, M. Tan, J. Wu, R. Morandotti, A. Mitchell, and D. J. Moss, "Microcomb-based photonic RF signal processing," *IEEE Photonics Technology Letters*, vol. 31, no. 23, pp. 1854-1857. 2019.
61. X. Xu, J. Wu, T. G. Nguyen, T. Moein, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Photonic microwave true time delays for phased array antennas using a 49 GHz FSR integrated optical micro-comb source [Invited]," *Photonics Research*, vol. 6, no. 5, pp. B30-B36, May 1. 2018.
62. X. Xue, Y. Xuan, C. Bao, S. Li, X. Zheng, B. Zhou, M. Qi, and A. M. Weiner, "Microcomb-Based True-Time-Delay Network for Microwave Beamforming With Arbitrary Beam Pattern Control," *Journal of Lightwave Technology*, vol. 36, no. 12, pp. 2312-2321, Jun. 2018.
63. X. Xu, J. Wu, T. G. Nguyen, M. Shoeiby, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Advanced RF and microwave functions based on an integrated optical frequency comb source," *Optics Express*, vol. 26, no. 3, pp. 2569-2583, Feb 5. 2018.
64. X. Xu, M. Tan, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Advanced Adaptive Photonic RF Filters with 80 Taps based on an integrated optical micro-comb," *Journal of Lightwave Technology*, vol. 37, no. 4, pp. 1288-1295, 2019.

65. X. X. Xue, Y. Xuan, H. J. Kim, J. Wang, D. E. Leaird, M. H. Qi, and A. M. Weiner, "Programmable Single-Bandpass Photonic RF Filter Based on Kerr Comb from a Microring," *Journal of Lightwave Technology*, vol. 32, no. 20, pp. 3557-3565, Oct 15. 2014.
66. X. Xu, J. Wu, M. Shoeiby, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Reconfigurable broadband microwave photonic intensity differentiator based on an integrated optical frequency comb source," *APL Photonics*, vol. 2, no. 9, 096104. Sept. 2017.
67. M. Tan, X. Xu, B. Corcoran, J. Wu, A. Boes, T. G. Nguyen, S.T. Chu, B.E. Little, R. Morandotti, A. Mitchell, and D.J. Moss, "Microwave and RF photonic fractional Hilbert transformer based on a 50 GHz Kerr microcomb," *J. of Lightwave Technology*, vol. 37, no. 24, p 6097, 2019.
68. M. Tan, X. Xu, B. Corcoran, J. Wu, A. Boes, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "RF and microwave fractional differentiator based on photonics," *IEEE Transactions on Circuits and Systems II: Express Briefs*, Early Access. 2020. DOI: [10.1109/TCSII.2020.2965158](https://doi.org/10.1109/TCSII.2020.2965158)
69. X. Xu, J. Wu, M. Tan, T. G. Nguyen, S. Chu, B. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "Micro-comb based photonic local oscillator for broadband microwave frequency conversion," *Journal of Lightwave Technology*, vol. 38, no. 2, pp. 332-338. 2020.
70. X. Xu, M. Tan, J. Wu, A. Boes, B. Corcoran, T. G. Nguyen, S. T. Chu, B. Little, R. Morandotti, A. Mitchell and D. J. Moss, "Photonic RF phase-encoded signal generation with a microcomb source," *Journal of Lightwave Technology*, vol. 38, no.7, pp1722-1727. 2020.
71. DOI: [10.1109/JLT.2019.2958564](https://doi.org/10.1109/JLT.2019.2958564)
72. X. Xu, M. Tan, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. J. Moss, "High performance RF filters via bandwidth scaling with Kerr micro-combs," *APL Photonics*, vol. 4, no. 2, pp. 026102. 2019.
73. X. Xu, J. Wu, T. G. Nguyen, S. Chu, B. Little, A. Mitchell, R. Morandotti, and D. J. Moss, "Broadband RF Channelizer based on an Integrated Optical Frequency Kerr Comb Source," *Journal of Lightwave Technology*, vol. 36, no. 19, pp. 4519-4526. 2018.
74. X.Xu, J.Wu, T.G. Nguyen, S.T. Chu, B.E. Little, R.Morandotti, A.Mitchell, and D. J. Moss, "Continuously tunable orthogonally polarized optical RF single sideband generator and equalizer based on an integrated microring resonator", *IOP Journal of Optics*, vol. 20 no.11, p115701, 2018.
75. X.Xu, J.Wu, T.G.Nguyen, S.T.Chu, B.E.Little, R.Morandotti, A.Mitchell, and D.J. Moss, "Orthogonally polarized optical RF single sideband generator and equalizer based on an integrated micro-ring resonator", *IEEE Journal of Lightwave Technology* Vol. 36, No. 20, pp4808-4818 (2018).
76. X.Xu, J.Wu, T.G. Nguyen, S.T. Chu, B.E. Little, R.Morandotti, A.Mitchell, and D. J. Moss, "Continuously tunable orthogonally polarized optical RF single sideband generator and equalizer based on an integrated microring resonator", *IOP Journal of Optics*, vol. 20 no.11, p115701, 2018.
77. X.Xu, J.Wu, T.G.Nguyen, S.T.Chu, B.E.Little, R.Morandotti, A.Mitchell, and D.J. Moss, "Orthogonally polarized optical RF single sideband generator and equalizer based on an integrated micro-ring resonator", *IEEE Journal of Lightwave Technology* Vol. 36, No. 20, pp4808-4818 (2018).

78. T.Ido, H.Sano, D.J.Moss, S.Tanaka, and A.Takai, "Strained InGaAs/InAlAs MQW electroabsorption modulators with large bandwidth and low driving voltage", *Photonics Technology Letters*, Vol. 6, 1207 (1994). DOI: 10.1109/68.329640.
79. D. Moss, "Temporal RF photonic signal processing with Kerr micro-combs: Hilbert transforms, integration and fractional differentiation", *OSF Preprints*, 18 Feb. (2021). DOI: 10.31219/osf.io/hx9gb.
80. D. Moss, "RF and microwave photonic high bandwidth signal processing based on Kerr micro-comb sources", *TechRxiv. Preprint* (2020). DOI:10.36227/techrxiv.12665609.v3.
81. D. Moss, "RF and microwave photonic signal processing with Kerr micro-combs", *Research Square* (2021). DOI: 10.21203/rs.3.rs-473364/v1.
82. M.Tan, X. Xu, J. Wu, D.J. Moss, "RF Photonic Signal Processing with Kerr Micro-Combs: Integration, Fractional Differentiation and Hilbert Transforms", *Preprints* (2020). 2020090597. doi:10.20944/preprints202009.0597.v1.
83. Mengxi Tan, Xingyuan Xu, Jiayang Wu, Thach G. Nguyen, Sai T. Chu, Brent E. Little, Roberto Morandotti, Arnan Mitchell, and David J. Moss, "Photonic Radio Frequency Channelizers based on Kerr Micro-combs and Integrated Micro-ring Resonators", *JOSarXiv.202010.0002*.
84. Mengxi Tan, Xingyuan Xu, David Moss "Tunable Broadband RF Photonic Fractional Hilbert Transformer Based on a Soliton Crystal Microcomb", *Preprints*, DOI: 10.20944/preprints202104.0162.v1
85. Mengxi Tan, X. Xu, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, "Orthogonally polarized Photonic Radio Frequency single sideband generation with integrated micro-ring resonators", *Journal of Semiconductors* vol. 42, No.4, 041305 (2021). DOI: 10.1088/1674-4926/42/4/041305.
86. Mengxi Tan, X. Xu, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, "Photonic Radio Frequency Channelizers based on Kerr Optical Micro-combs", *Journal of Semiconductors* 42 (4), 041302 (2021). (ISSN 1674-4926). DOI:10.1088/1674-4926/42/4/041302.
87. Mengxi Tan, Xingyuan Xu, David Moss "Tunable Broadband RF Photonic Fractional Hilbert Transformer Based on a Soliton Crystal Microcomb", *Preprints*, DOI: 10.20944/preprints202104.0162.v1
88. B. Corcoran, et al., "Ultra-dense optical data transmission over standard fiber with a single chip source", *Nature Communications*, vol. 11, Article:2568, 2020. DOI:10.1038/s41467-020-16265-x.
89. X. Xu, et al., "Photonic perceptron based on a Kerr microcomb for scalable high speed optical neural networks", *Laser and Photonics Reviews*, vol. 14, no. 8, 2000070, 2020. DOI:10.1002/lpor.202000070.
90. X. Xu, et al., "11 TOPs photonic convolutional accelerator for optical neural networks", *Nature*, vol.589 (7840) 44-51 (2021). DOI: 10.1038/s41586-020-03063-0.
91. X Xu et al., "11 TeraFLOPs per second photonic convolutional accelerator for deep learning optical neural networks", *arXiv preprint arXiv:2011.07393* (2020).

92. D. Moss, "11 Tera-FLOP/s photonic convolutional accelerator and deep learning optical neural networks", Research Square (2021). DOI: <https://doi.org/10.21203/rs.3.rs-493347/v1>.
93. D.Moss, "11.0 Tera-FLOP/second photonic convolutional accelerator for deep learning optical neural networks", TechRxiv. Preprint (2020). <https://doi.org/10.36227/techrxiv.13238423.v1>.
94. Moss, David. "11 Tera-flop/s Photonic Convolutional Accelerator for Optical Neural Networks." OSF Preprints, 23 Feb. (2021). DOI: 10.31219/osf.io/vqt4s.
95. Mengxi Tan, X. Xu, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, "Photonic Radio Frequency Channelizers based on Kerr Optical Micro-combs", Journal of Semiconductors, Vol. 42, No. 4, 041302 (2021). (ISSN 1674-4926). DOI:10.1088/1674-4926/42/4/041302.
96. H. Bao, L.Olivieri, M.Rowley, S.T. Chu, B.E. Little, R.Morandotti, D.J. Moss, J.S.T. Gongora, M.Peccianti and A. Pasquazi, "Laser Cavity Solitons and Turing Patterns in Microresonator Filtered Lasers: properties and perspectives", Paper No. LA203-5, Paper No. 11672-5, SPIE LASE, SPIE Photonics West, San Francisco CA March 6-11 (2021). DOI:10.1117/12.2576645
97. Mengxi Tan, X. Xu, J. Wu, A. Boes, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, "Advanced microwave signal generation and processing with soliton crystal microcombs", or "Photonic convolutional accelerator and neural network in the Tera-OPs regime based on Kerr microcombs", Paper No. 11689-38, PW210-OE201-67, Integrated Optics: Devices, Materials, and Technologies XXV, SPIE Photonics West, San Francisco CA March 6-11 (2021). DOI: 10.1117/12.2584017
98. Mengxi Tan, Bill Corcoran, Xingyuan Xu, Andrew Boes, Jiayang Wu, Thach Nguyen, Sai T. Chu, Brent E. Little, Roberto Morandotti, Arnan Mitchell, and David J. Moss, "Optical data transmission at 40 Terabits/s with a Kerr soliton crystal microcomb", Paper No.11713-8, PW210-OE803-23, Next-Generation Optical Communication: Components, Sub-Systems, and Systems X, SPIE Photonics West, San Francisco CA March 6-11 (2021). DOI:10.1117/12.2584014
99. Mengxi Tan, X. Xu, J. Wu, A. Boes, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, "RF and microwave photonic, fractional differentiation, integration, and Hilbert transforms based on Kerr micro-combs", Paper No. 11713-16, PW210-OE803-24, Next-Generation Optical Communication: Components, Sub-Systems, and Systems X, SPIE Photonics West, San Francisco CA March 6-11 (2021). DOI:10.1117/12.2584018
100. Mengxi Tan, X. Xu, J. Wu, A. Boes, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, "Broadband photonic RF channelizer with 90 channels based on a soliton crystal microcomb", or "Photonic microwave and RF channelizers based on Kerr micro-combs", Paper No. 11685-22, PW210-OE106-49, Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XIV, SPIE Photonics West, San Francisco CA March 6-11 (2021). DOI:10.1117/12.2584015
101. X. Xu, M. Tan, J. Wu, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, B. Corcoran, D. Hicks, and D. J. Moss, "Photonic perceptron based on a Kerr microcomb for scalable high speed optical neural

- networks”, IEEE Topical Meeting on Microwave Photonics (MPW), pp. 220-224, Matsue, Japan, November 24-26, 2020. Electronic ISBN:978-4-88552-331-1. DOI: 10.23919/MWP48676.2020.9314409
102. Mengxi Tan, Bill Corcoran, Xingyuan Xu, Andrew Boes, Jiayang Wu, Thach Nguyen, S.T. Chu, B. E. Little, Roberto Morandotti, Arnan Mitchell, and David J. Moss, “Ultra-high bandwidth optical data transmission with a microcomb”, IEEE Topical Meeting on Microwave Photonics (MPW), pp. 78-82. Virtual Conf., Matsue, Japan, November 24-26, 2020. Electronic ISBN:978-4-88552-331-1. DOI: 10.23919/MWP48676.2020.9314476
 103. M. Tan, X. Xu, J. Wu, R. Morandotti, A. Mitchell, and D. J. Moss, “RF and microwave high bandwidth signal processing based on Kerr Micro-combs”, *Advances in Physics X*, VOL. 6, NO. 1, 1838946 (2020). DOI:10.1080/23746149.2020.1838946.
 104. M Tan, X Xu, J Wu, DJ Moss, “High bandwidth temporal RF photonic signal processing with Kerr micro-combs: integration, fractional differentiation and Hilbert transforms”, arXiv preprint arXiv:2103.03674 (2021).
 105. Mengxi Tan, X. Xu, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and David J. Moss, “Orthogonally polarized Photonic Radio Frequency single sideband generation with integrated micro-ring resonators”, *Journal of Semiconductors* 42 (4), 041305 (2021). DOI: 10.1088/1674-4926/42/4/041305.
 106. L. Razzari, D. Duchesne, M. Ferrera, et al., “CMOS-compatible integrated optical hyper-parametric oscillator,” *Nature Photonics*, vol. 4, no. 1, pp. 41-45 (2010).
 107. M. Ferrera, L. Razzari, D. Duchesne, et al., “Low-power continuous-wave nonlinear optics in doped silica glass integrated waveguide structures,” *Nature Photonics*, vol. 2, no. 12, pp. 737-740 (2008).
 108. Pasquazi, et al., “Sub-picosecond phase-sensitive optical pulse characterization on a chip”, *Nature Photonics*, vol. 5, no. 10, pp. 618-623 (2011). DOI: 10.1038/nphoton.2011.199.
 109. D. Duchesne, M. Peccianti, M. R. E. Lamont, et al., “Supercontinuum generation in a high index doped silica glass spiral waveguide,” *Optics Express*, vol. 18, no. 2, pp. 923-930 (2010).
 110. M. Ferrera, et al., “On-chip CMOS-compatible all-optical integrator”, *Nature Communications*, vol. 1, Article 29 (2010).
 111. H. Bao et al., “Turing patterns in a fibre laser with a nested micro-resonator: robust and controllable micro-comb generation”, *Physical Review Research*, vol. 2, pp. 023395 (2020).
 112. L. D. Lauro, J. Li, D. J. Moss, R. Morandotti, S. T. Chu, M. Peccianti, and A. Pasquazi, “Parametric control of thermal self-pulsation in micro-cavities,” *Opt. Lett.* vol. 42, no. 17, pp. 3407-3410, Aug. 2017.
 113. H. Bao et al., “Type-II micro-comb generation in a filter-driven four wave mixing laser,” *Photonics Research*, vol. 6, no. 5, pp. B67-B73 (2018).
 114. Pasquazi, et al., “All-optical wavelength conversion in an integrated ring resonator,” *Optics Express*, vol. 18, no. 4, pp. 3858-3863 (2010).

115. Pasquazi, Y. Park, J. Azana, et al., "Efficient wavelength conversion and net parametric gain via Four Wave Mixing in a high index doped silica waveguide," *Optics Express*, vol. 18, no. 8, pp. 7634-7641 (2010).
116. M. Peccianti, M. Ferrera, L. Razzari, et al., "Subpicosecond optical pulse compression via an integrated nonlinear chirper," *Optics Express*, vol. 18, no. 8, pp. 7625-7633 (2010).
117. D. Duchesne, M. Ferrera, L. Razzari, et al., "Efficient self-phase modulation in low loss, high index doped silica glass integrated waveguides," *Optics Express*, vol. 17, no. 3, pp. 1865-1870 (2009).
118. M. Peccianti, et al., "Demonstration of an ultrafast nonlinear microcavity modelocked laser", *Nature Communications*, vol. 3, pp. 765 (2012).
119. M. Kues, et al., "Passively modelocked laser with an ultra-narrow spectral width", *Nature Photonics*, vol. 11, no. 3, pp. 159 (2017). DOI:10.1038/nphoton.2016.271
120. Pasquazi, L. Caspani, M. Peccianti, et al., "Self-locked optical parametric oscillation in a CMOS compatible microring resonator: a route to robust optical frequency comb generation on a chip," *Optics Express*, vol. 21, no. 11, pp. 13333-13341 (2013).
121. Pasquazi, M. Peccianti, B. E. Little, et al., "Stable, dual mode, high repetition rate mode-locked laser based on a microring resonator," *Optics Express*, vol. 20, no. 24, pp. 27355-27362 (2012).
122. Reimer, L. Caspani, M. Clerici, et al., "Integrated frequency comb source of heralded single photons," *Optics Express*, vol. 22, no. 6, pp. 6535-6546 (2014).
123. Reimer, et al., "Cross-polarized photon-pair generation and bi-chromatically pumped optical parametric oscillation on a chip", *Nature Communications*, vol. 6, Article 8236 (2015). DOI: 10.1038/ncomms9236
124. L. Caspani, et al., "Multifrequency sources of quantum correlated photon pairs on-chip: a path toward integrated Quantum Frequency Combs," *Nanophotonics*, vol. 5, no. 2, pp. 351-362 (2016).
125. Reimer, M. Kues, P. Roztock, B. Wetz, F. Grazioso, B. E. Little, S. T. Chu, T. Johnston, Y. Bromberg, L. Caspani, D. J. Moss, and R. Morandotti, "Generation of multiphoton entangled quantum states by means of integrated frequency combs," *Science*, vol. 351, no. 6278, pp. 1176-1180 (2016).
126. P. Roztock, M. Kues, C. Reimer, B. Wetz, S. Sciara, Y. Zhang, A. Cino, B. E. Little, S. T. Chu, D. J. Moss, and R. Morandotti, "Practical system for the generation of pulsed quantum frequency combs," *Optics Express*, vol. 25, no. 16, pp. 18940-18949 (2017).
127. Y. Zhang, et al., "Induced photon correlations through superposition of two four-wave mixing processes in integrated cavities", *Laser and Photonics Reviews*, vol. 14, no. 7, 2000128 (2020). DOI: 10.1002/lpor.202000128
128. M. Kues, C. Reimer, A. Weiner, J. Lukens, W. Munro, D. J. Moss, and R. Morandotti, "Quantum Optical Micro-combs", *Nature Photonics*, vol. 13, no.3, pp. 170-179 (2019).
129. Reimer, et al., "High-dimensional one-way quantum processing implemented on d-level cluster states", *Nature Physics*, vol. 15, no.2, pp. 148–153 (2019).

130. H. Arianfard et al., "Three waveguide coupled sagnac loop reflectors for advanced spectral engineering," *J. Lightwave Technol.*, doi: 10.1109/JLT.2021.3066256.
131. J. Wu et al., "Nested configuration of silicon microring resonator with multiple coupling regimes," *IEEE Photon. Technol. Lett.*, vol. 25, no. 6, pp. 580-583, Mar. 2013.
132. J. Wu, T. Moein, X. Xu, and D. J. Moss, "Advanced photonic filters based on cascaded Sagnac loop reflector resonators in silicon-on-insulator nanowires," *APL Photonics*, vol. 3, 046102 (2018). DOI:/10.1063/1.5025833Apr. 2018.
133. J Wu, T Moein, X Xu, DJ Moss, "Silicon photonic filters based on cascaded Sagnac loop resonators", *arXiv:1805.05405a* (2018).
134. J. Wu, T. Moein, X. Xu, G. H. Ren, A. Mitchell, and D. J. Moss, "Micro-ring resonator quality factor enhancement via an integrated Fabry-Perot cavity," *APL Photonics*, vol. 2, 056103 (2017).
135. H. Arianfard, J. Wu, S. Juodkazis, and D. J. Moss, "Advanced Multi-Functional Integrated Photonic Filters Based on Coupled Sagnac Loop Reflectors", *Journal of Lightwave Technology*, Vol. 39, No.5, pp.1400-1408 (2021). DOI: 10.1109/JLT.2020.3037559.
136. David J. Moss, "Optimization of Optical Filters based on Integrated Coupled Sagnac Loop Reflectors", *Research Square* (2021). DOI: <https://doi.org/10.21203/rs.3.rs-478204/v1>
137. H. Arianfard, J. Wu, S. Juodkazis, D. J. Moss, "Spectral Shaping Based on Integrated Coupled Sagnac Loop Reflectors Formed by a Self-Coupled Wire Waveguide", submitted, *IEEE Photonics Technology Letters*, vol. 33 (2021).
138. J. Wu et al., "Graphene oxide waveguide and micro-ring resonator polarizers," *Laser Photonics Rev.*, vol. 13, no. 9, pp. 1900056, Aug. 2019.
139. Y. Zhang et al., "Optimizing the Kerr nonlinear optical performance of silicon waveguides integrated with 2D graphene oxide films," *J. Lightwave Technol.*, doi: 10.1109/JLT.2021.3069733.
140. Y. Qu et al., "Analysis of four-wave mixing in silicon nitride waveguides integrated with 2D layered graphene oxide films," *J. Lightwave Technol.*, vol. 39, no. 9, pp. 2902-2910, May. 2021.
141. Y. Qu et al., "Enhanced four-wave mixing in silicon nitride waveguides integrated with 2D layered graphene oxide films," *Adv. Opt. Mater.*, vol. 8, no. 20, pp. 2001048, Oct. 2020.
142. J. Wu et al., "2D layered graphene oxide films integrated with micro-ring resonators for enhanced nonlinear optics," *Small*, vol. 16, no. 16, pp. 1906563, Mar. 2020.
143. Moss, David; Wu, Jiayang; xu, xingyuan; Yang, Yunyi; jia, linnan; Zhang, Yuning; et al. (2020): Enhanced optical four-wave-mixing in integrated ring resonators with graphene oxide films. *TechRxiv*. Preprint. <https://doi.org/10.36227/techrxiv.11859429.v1>.
144. Wu, J.; Yang, Y.; Qu, Y.; Jia, L.; Zhang, Y.; Xu, X.; Chu, S.T.; Little, B.E.; Morandotti, R.; Jia, B.; Moss, D.J. Enhancing Third Order Nonlinear Optics in Integrated Ring Resonators with 2D Material Films. *Preprints 2020*, 2020030107
145. Wu, J.; Yang, Y.; Qu, Y.; Jia, L.; Zhang, Y.; Xu, X.; Chu, S.T.; Little, B.E.; Morandotti, R.; Jia, B.; Moss, D.J. Enhancing Third Order Nonlinear Optics in Integrated Ring Resonators with 2D Material Films.

146. J Wu et al., "Enhanced four-wave-mixing with 2D layered graphene oxide films integrated with CMOS compatible micro-ring resonators", arXiv preprint, arXiv:2002.04158 (2020).
147. Y. Zhang et al., "Enhanced Kerr nonlinearity and nonlinear figure of merit in silicon nanowires integrated with 2D graphene oxide films," ACS Appl. Mater. Interfaces, vol. 12, no. 29, pp. 33094-33103, Jun. (2020).
148. TD Vo et al., "Silicon-chip-based real-time dispersion monitoring for 640 Gbit/s DPSK signals", Journal of Lightwave Technology, vol. 29, no. 12, 1790-1796 (2011).
149. C Grillet, C Smith, D Freeman, S Madden, B Luther-Davies, EC Magi, "Efficient coupling to chalcogenide glass photonic crystal waveguides via silica optical fiber nanowires", Optics Express, vol. 14, no. 3, pp.1070-1078 (2006).
150. Y Zhang et al., "Enhanced nonlinear optical figure-of-merit at 1550nm for silicon nanowires integrated with graphene oxide layered films", arXiv preprint arXiv:2004.08043 (2020).
151. Moss et al., "Transforming silicon into a high performing integrated nonlinear photonics platform by integration with 2D graphene oxide films", TechRxiv. Preprint. (2020).
<https://doi.org/10.36227/techrxiv.12061809.v1>.
152. Moss, "Elevating silicon into a high performance nonlinear optical platform through the integration of 2D graphene oxide thin films", Research Square (2021). DOI: <https://doi.org/10.21203/rs.3.rs-511259/v1>.
153. Moss, D.; Wu, J.; Jia, B.; Yang, Y.; Qu, Y.; Jia, L.; Zhang, Y. "Improved Nonlinear Optics in Silicon-on-insulator Nanowires Integrated with 2D Graphene Oxide Films", Preprints (2020), 2020040033.
154. Y. Yang et al., "Invited article: enhanced four-wave mixing in waveguides integrated with graphene oxide," APL Photonics, vol. 3, no. 12, pp. 120803, Oct. 2018.

Declarations

Competing interests: The authors declare no competing interests.

Figures

Figure 1

Illustration of the operation of the photonic RF phase encoder.

Figure 2

Schematic diagram of photonic RF phase encoding based on an integrated optical micro-comb source. EDFA: erbium-doped fibre amplifier. PC: polarization controller. MRR: micro-ring resonator. WS: WaveShaper. EOM: Mach-Zehnder modulator. SMF: Single mode fibre. BPD: balanced photodetector.

Figure 3

Structure of the range gates at the radar systems' receiver.

Figure 4

Soliton crystal microcomb.

Figure 5

(a) The input Gaussian pulse. (b) The optical spectra of the flattened microcomb at different ports of the Waveshaper. (c) Assembled RF signal with 30 cosine cycles.

Figure 6

(a, c, e) The optical spectra of the flattened microcomb at different ports of the Waveshaper with different phase codes and sequence length. (b, d, f) The assembled phase-encoded RF waveform.

Figure 7

The calculated autocorrelation of the phase-encoded RF waveforms for (a) $m=6$, (b) $m=4$, and (c) $m=2$.

Figure 8

Calculated outputs of the range gates for (a) $R=0.71$ m and (b) $R=0.76$ m.

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