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# RF and microwave photonic signal generation and processing using Kerr optical micro-combs

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## ABSTRACT

We demonstrate a radio frequency (RF) phase-encoded signal generator as well as a user-defined RF arbitrary waveform generator (AWG) based on a soliton crystal micro-comb generated by an integrated MRR with a free spectral range of ~49 GHz. Owing to the soliton crystal's robust and stable generation as well as the high intrinsic efficiency, RF phase-encoded signal generators and AWGs with simple operation and fast reconfiguration are realized. The soliton crystal micro-comb provides 60 wavelengths for RF phase-encoded signal generators, achieving a phase encoding speed of 5.95 Gb/s and a high pulse compression ratio of 29.6. Over 80 wavelengths are employed for the AWGs, achieving tunable square waveforms with a duty cycle ratio ranging from 10% to 90%, sawtooth waveforms with tunable slope ratios from 0.2 to 1, and symmetric concave quadratic chirp waveforms. Our system has great potential to achieve RF and microwave photonic signal generation and processing with low cost and footprint.

**Keywords:** microwave photonics, micro-ring resonators, RF phase-encoded signal generation, RF arbitrary waveform generation

## 1. INTRODUCTION

Phase-encoded signal generators are extensively exploited in low-probability-of-intercept radar (LPIR), since phase-encoded radio frequency (RF) signals feature low power density and employ random codes to avoid being cracked [1, 2]. Arbitrary waveform generators (AWGs) are another significant category of signal sources with wider applications, such as radar, measurements, and wireless communications [3-5]. RF signals with broad bandwidth have great potential in these applications, for example achieving high-resolution target recognition in LPIR systems [6]. However, most of the existing approaches for RF phase encoded signal generators and AWGs are based on electronic technologies, with large footprint, high cost, and limitations in bandwidth and speed [7, 8].

Photonic techniques have significant potential to overcome limitations of their electronic counterparts benefiting from their intrinsically broad bandwidth, immunity from electro-magnetic interference, and low propagation loss. Extensive approaches have been developed to achieve photonic-assisted RF phase encoding, such as methods based on polarization modulators [9, 10], dual parallel modulators [11, 12], and Sagnac loops [13, 14]. However, for these methods, there is a need for complicated modulation schemes, resulting in increased complexity and instability, and also a need for both high-frequency RF signal generators and AWGs, leading to increased cost, size, and power consumption. There are also limitations for approaches of achieving photonic-assisted RF arbitrary waveform generation. For spatial-to-time and wavelength-to-time mapping methods [8, 15-17], the synthesized waveforms are usually single-shot pulses. For Fourier synthesis method [18], the synthesized signal bandwidth is subject to the resolution of line-by-line spectral shaping.

An alternative method for photonic-assisted RF signal processing is based on transversal filter system, which offers high reconfigurability and accuracy attributing to the parallel scheme where each channel can be controlled independently. However, discrete laser arrays or electro-optical comb sources are employed to establish multiple wavelength channels. RF phase encoding based on transversal filter system has been proposed [19], where the need for complicated modulation schemes was reduced, but discrete laser arrays were used and high-order differentiation was implemented, which increased the complexity and cost of the system.

Integrated optical Kerr frequency combs, or 'micro-combs', have attracted significant interest for RF photonic systems as multi-wavelength sources. Micro-combs arise from optical parametric oscillation in ultra-high-Q monolithic micro-ring resonators (MRRs) and offer plenty of advantages compared with conventional multi-wavelength sources, such as larger wavelength number and greatly reduced system complexity and footprint. Extensive RF photonic applications have been demonstrated based on micro-combs [20], such as transversal filters [21, 22], temporal signal processors [23-27], frequency synthesizers [28], true time delay lines [29], and channelizers [30, 31] and many other applications [32-43].

In this paper, we demonstrate an RF phase-encoded signal generator and a user-defined RF AWG based on a soliton crystal micro-comb generated by an integrated MRR with a free spectral range (FSR) of  $\sim 49$  GHz [32, 33]. The soliton crystal micro-comb 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 (DKS) [20]. The input RF signal is multicast onto the flattened micro-comb lines and progressively delayed via dispersion. For phase-encoded signal generation, 60 wavelengths are used and phase flipping is realized via differential photodetection. A phase encoding speed of 5.95 Gb/s and a high pulse compression ratio of 29.6 are achieved. For arbitrary waveform generation, to enhance the speed and flexibility of the system, 81 wavelengths are used. Power of comb lines are tailored according to the designed weights. Tunable square waveforms with a duty cycle ratio ranging from 10% to 90%, sawtooth waveforms with tunable slope ratios from 0.2 to 1, and symmetric concave quadratic chirp waveforms with an instantaneous frequency reaching down to the sub-GHz range are achieved. These results verify the potential of our approaches as being an effective way to achieve RF phase-encoded signal generators and RF AWGs with low cost and footprint.

## 2. THEORY

Figure 1(a) illustrate the operation principle of the photonic RF phase-encoded signal generator and AWG. First, an RF Gaussian pulse  $f(t)$  with a duration of  $\Delta t$  was generated. A soliton crystal micro-comb source, whose optical spectrum is shown in Figure 1(b), was generated by a Hydrex MRR. Then a discrete convolution operation between the RF pulse and flattened micro-comb spectrum (denoted by a discrete signal  $g[n]$  with length  $N$  and binary values of 1 or  $-1$ ) was performed with a delay step of  $\Delta t$ , and can be described as:

$$(f * g)[n] = \sum_{i=1}^N f[n - i \cdot \Delta t] \cdot g[i] \quad (1)$$

The discrete convolution operation between the RF pulse  $f(t)$  and the flattened micro-comb spectrum was achieved using the experimental setup in Figure 1(c). The RF pulse was first broadcast onto the wavelength channels (comb lines flattened by a WaveShaper) to yield replicas, which were then delayed with a progressive step that matched with the pulse duration  $\Delta t$ .

For phase-encoded signal generation, by flipping the phase of the different delayed replicas via differential photodetection, according to designed phase codes  $g[n]$ , a phase-encoded sequence could be assembled in the time domain. The total number of RF pulse replicas  $N$  is equal to the number of wavelength channels, which is 60 here—15 times that of previous work [19] — thus the total time length of the phase-encoded sequence is  $T = N \cdot \Delta t$ . Here, the basic temporal elements in the phase-encoded sequence are termed “RF segments”, which are single-cycle or multi-cycle sine waves assembled from the input RF pulse. The center frequency of the phase-encoded sequence is determined by the frequency of the assembled sine waves, and 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  $1/(m\Delta t)$ . We note that the generated phase-encoded sequence has a bandwidth similar to the input RF pulse, which is subject to the Nyquist bandwidth that is half of the comb spacing ( $48.9 \text{ GHz}/2 = 24.45 \text{ GHz}$ ).

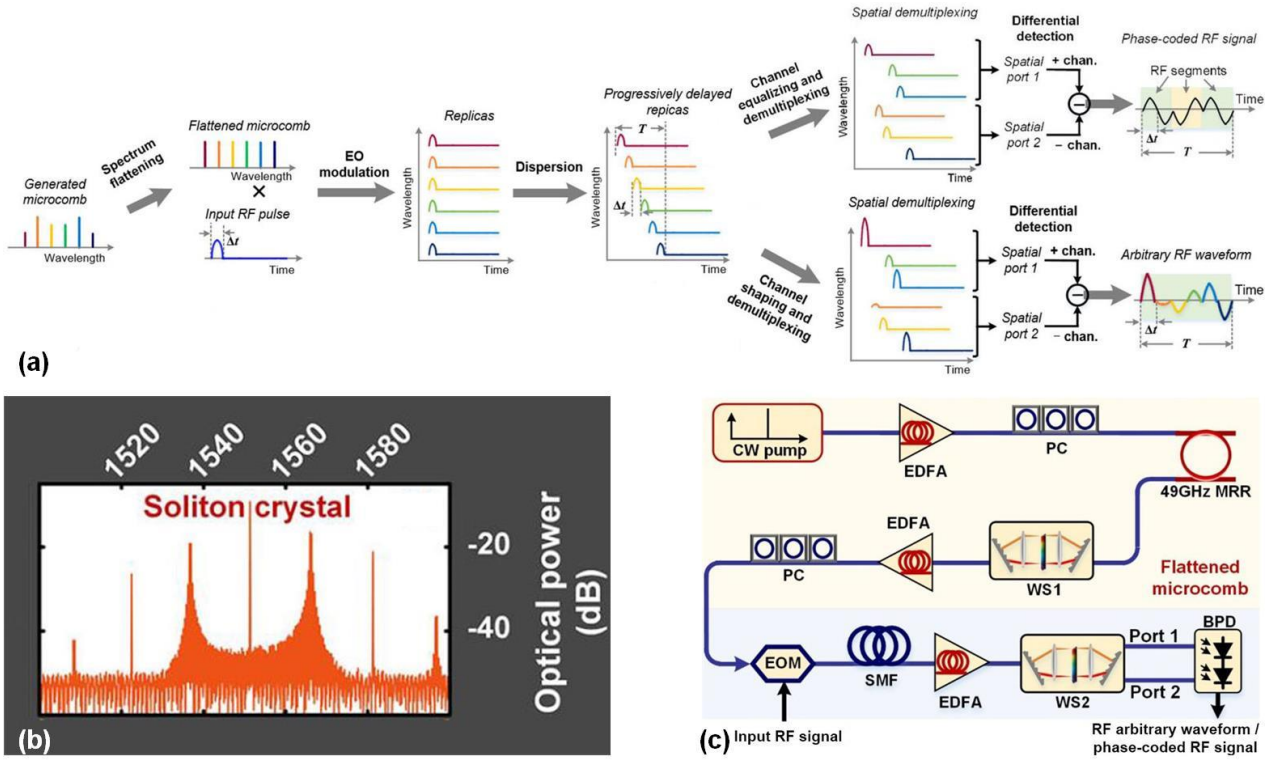


Figure 1. (a) Illustration of the operation of photonic RF phase-encoded signal generator and RF arbitrary waveform generator (AWG). (b) Optical spectrum of soliton crystal micro-comb. (c) Schematic of photonic RF phase-encoded signal generation and arbitrary waveform generation based on an integrated 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.

For arbitrary RF waveform generation, the soliton crystal micro-comb was flattened and modulated with the RF input pulse in order to multicast the RF waveform onto all of the wavelength channels to yield 81 replicas. The second WaveShaper accurately shaped the comb power according to the designed weights. The wavelength channels for positive and negative taps were separately measured by an optical spectrum analyzer. Finally, the delayed replicas were combined and then summed upon photodetection. By tailoring the comb lines' power according to the tap weights, arbitrary waveform generation could be achieved.

### 3. EXPERIMENTAL RESULTS

The experimental setup is shown in Fig. 1(c). A CW laser is amplified and with its polarization state adjusted to pump a nonlinear high Q factor Hydex MRR, which featured a Q factor of over 1.5 million and a free spectral range of  $\sim 0.4$  nm, or 48.9 GHz. As the detuning between the pump laser and the MRR changed, dynamic parametric oscillation states corresponding to distinctive solutions of the Lugiato-Lefever equation were initiated [44]. We generated soliton crystal micro-combs [45], which were tightly packed solitons circulating in the MRR as a result of a mode crossing (at  $\sim 1552$  nm in our case), and manifested by the generated distinctive palm-like comb spectrum (Figure 1(b)).

For phase-encoded signal generation, 60 lines of the micro-comb were flattened, 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 micro-comb lines with the first WaveShaper (WS1) 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 analyzer and comparing with designed weights to generate an error signal, which was fed back into the second WaveShaper (WS2) to calibrate its loss until the error was below 0.2 dB. Here, we use a Gaussian pulse with a duration of  $\Delta t = 84$  ps, as the RF fragment  $f[t]$ . The input RF pulse was imprinted onto the comb lines, generating replicas

across all the wavelength channels. The replicas then went through a  $\sim 13$  km long spool of standard single mode fiber to progressively delay them, leading to a delay step of  $\sim 84$  ps between the adjacent wavelength channels that matched with the duration of the RF pulse  $\Delta t$ . Finally, the wavelength channels were separated into two parts according to designed phase codes and sent to a balanced photodetector (Finisar, 40 GHz) to achieve negative and positive replicas for the phase encoding.

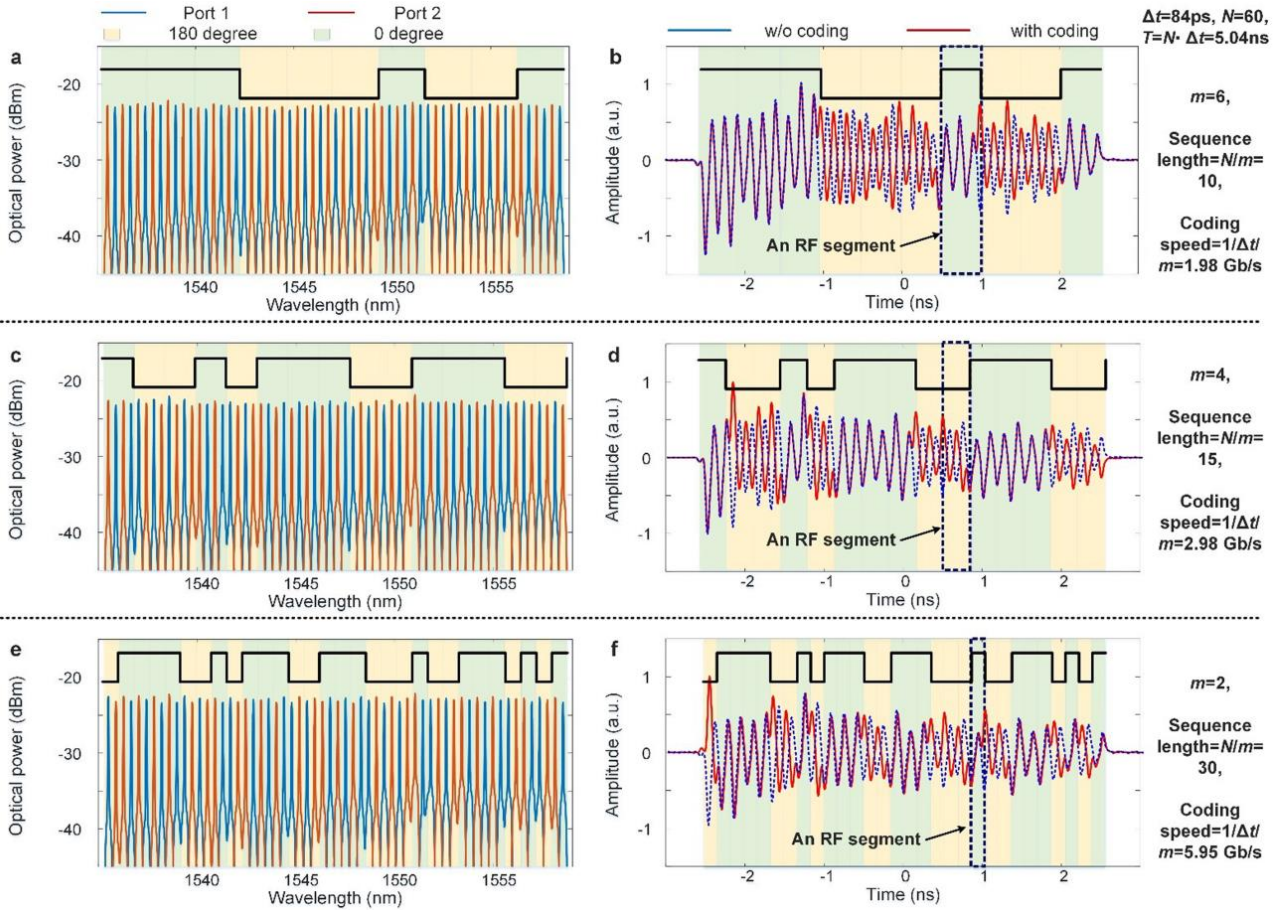


Figure 2. (a),(c),(e) The optical spectra of the flattened micro-comb at different ports of the WaveShaper with different phase codes and sequence length. (b),(d),(f) The assembled phase-encoded RF waveform.

By applying designed phase codes during the separation of the wavelength channels, the sine cycles could be  $\pi$ -phase shifted at desired times. The phase-encoded results are shown in Figure 2. 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  $1/(m\Delta t)$  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 reconfigurable sequence lengths 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 to 2. Further, 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 (Figure 2(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 (Figure 2(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 according to  $m$ . 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  $\Delta t$ .



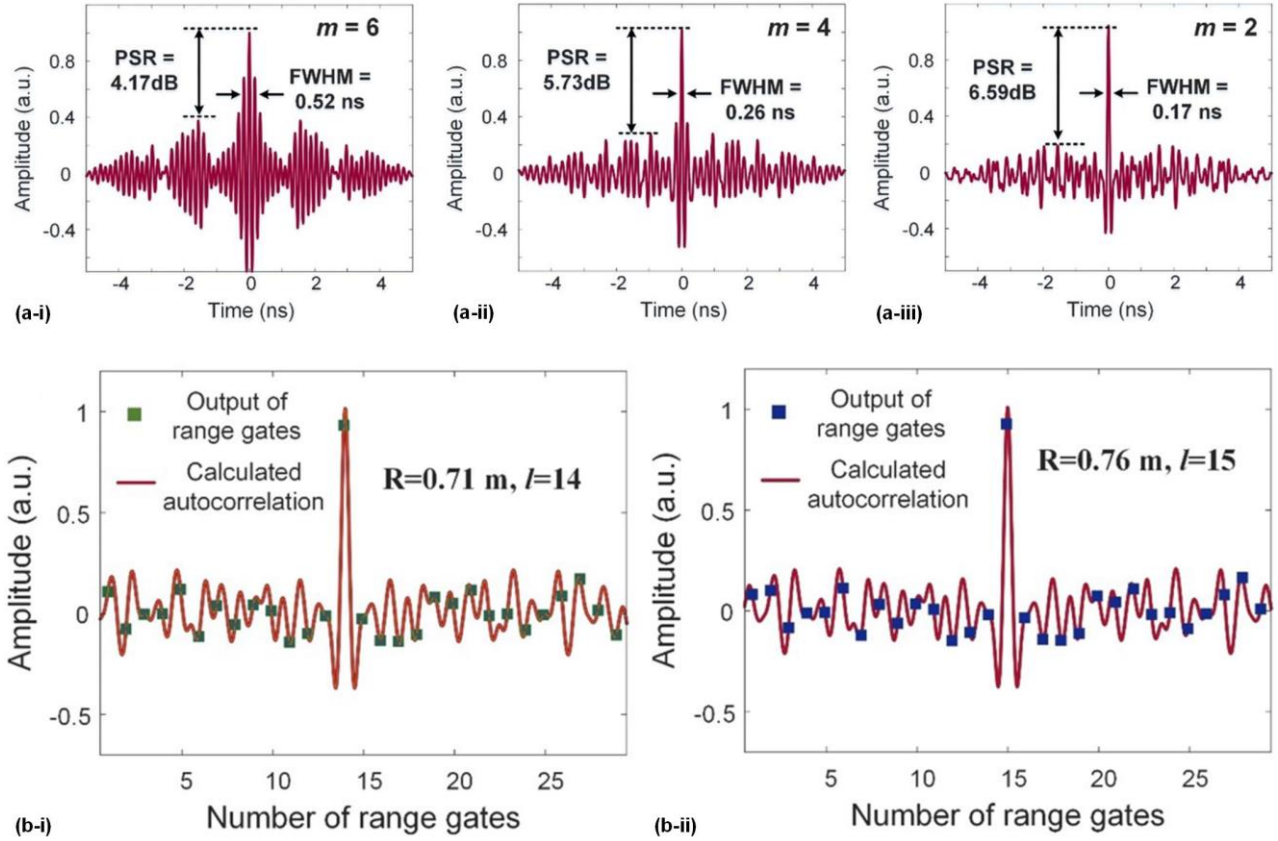


Figure 3. (a) The calculated autocorrelation of the phase-encoded RF waveforms for the number of pulses in each RF segment (i)  $m = 6$ , (ii)  $m = 4$ , and (iii)  $m = 2$ . (b) Calculated outputs of the range gates for the distance between the target and radar (i)  $R = 0.71$  m, and (b)  $R = 0.76$  m.

We also calculated the autocorrelation (Figure 3(a)) of the phase-encoded RF waveforms. 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 [46], and that this can be significantly enhanced with our approach by using a larger number of wavelength channels of the microcomb. Figure 3(b) shows calculated examples of the estimated outputs of the range gates, 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  $c[k-l]$ , where  $c[k]$ ,  $k = 1, 2, \dots, 30$ , 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  $2\Delta t \cdot c = 5$  cm, where  $c = 3 \times 10^8$  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 relations between our phase encoder and the radar systems' performance. Practical radar systems are subject to more complicated trade-offs involving capability versus performance.

For arbitrary waveform generation, 81 lines of the micro-comb were flattened. On the basis of phase encoding, by tailoring the comb lines' power according to the tap weights arbitrary waveform generation could be achieved. To demonstrate the flexibility of our photonic RF signal generation approach, we designed square waveforms (Figure 4(a-i)) with a tunable duty cycle ratio ranging from 10% to 90%. Similarly, sawtooth waveforms (Fig. 4(a-ii)) with a tunable slope ranging from 0.2 to 1 were generated. The received signals were digitally sampled by an 80 GSa/s real-time oscilloscope, with the measured waveforms normalized to the peak intensity. We then demonstrated the frequency-modulated waveform, as shown in Figure 4(b), for which the sign of the frequency modulation (or 'chirp') can be programmed to sweep from high to low and then from low to high frequency, which is very difficult to achieve with electronic techniques. We compared

the experimental results obtained with the corresponding calculated instantaneous frequency of the designed symmetric concave quadratic chirp, both of which are shown in Figure 4(b-iii,iv).

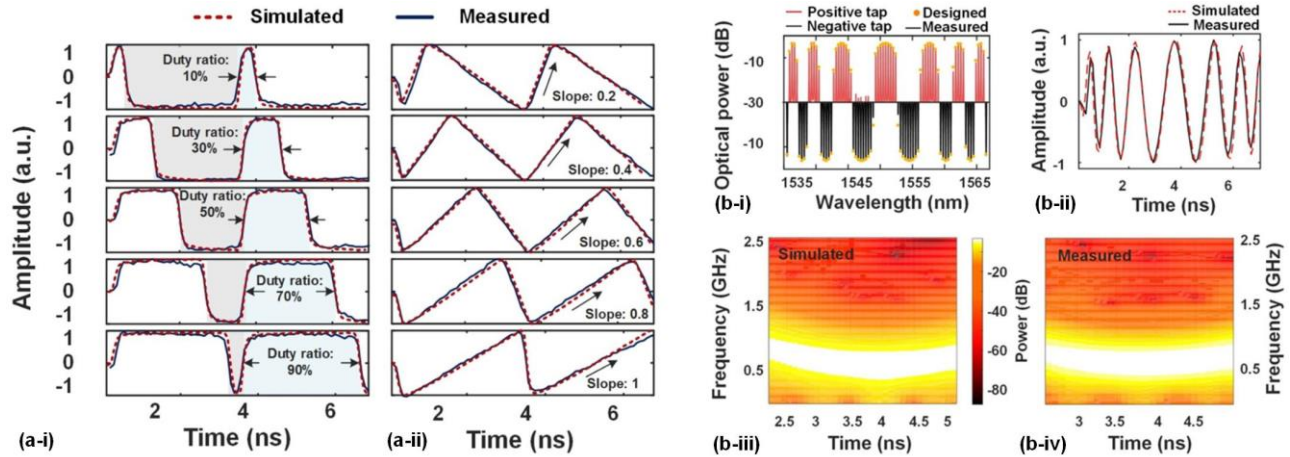


Figure 4. (a) Simulated and measured tunable RF waveforms. (i) Square waveforms. (ii) Sawtooth waveforms. (b) Experimental results of the generated chirped waveform. (i) Designed and measured optical spectra. (ii) Simulated and measured RF waveforms. The extracted corresponding instantaneous frequency (iii) simulated and (iv) experimental results.

Compared to electronic means of arbitrary waveform generation, our scheme makes possible RF waveforms with much higher instantaneous bandwidth by simply shortening the time delay and the corresponding optical pulse width. Note that we used a commercial arbitrary waveform generator (Keysight, 65 GSa/s) here to generate the pulse for this proof of principle demonstration. This allowed us to investigate the device performance by, for example, readily changing the pulse width to test the capability of our system to span different frequency ranges for the RF waveform. In practice, however, electronic AWGs are not necessary and can easily be replaced with many other readily available approaches that are simpler, easier and cheaper [47].

The quality and stability of the soliton crystal comb was more than good enough for our experiments. Indeed, the soliton crystal combs have been shown to be stable and reliable enough to support ultrahigh bandwidth communications at 44Terabits/s [48], with extremely high stability over many 10's of hours. The energy efficiency and noise of our system would be increased further by reducing the loss through the system, for example by achieving higher levels of integration.

There is significant potential for substantially higher levels of integration than the discrete devices used here – ultimately achieving fully monolithically integrated embodiments of our system. The central component of our system, the optical frequency comb source, is already integrated. Further, all of the other components have been demonstrated in integrated form, including on-chip InP spectral shapers [49], highspeed integrated lithium niobate modulators [50], integrated dispersive elements [51], and photodetectors [52]. Finally, many recent advances have been made in reducing the power-consumption of Kerr combs [53] that would greatly reduce the system energy requirements. These results will have a significant impact on the field of microwave photonics, [54-92] particularly that based on micro-combs [93-209] with potential applications even to the mid IR [210-216]

#### 4. CONCLUSION

We demonstrate photonic RF phase-encoded signal generation and RF arbitrary waveform generator 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 and RF arbitrary waveform. For RF phase encoding, a high pulse compression ratio of 29.6 and phase encoding speed of 5.95 Gb/s was 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. For RF arbitrary waveform generation, the comb source provides over 80 channels, that we use to successfully achieve arbitrary waveform shapes including square waveforms with a tunable duty ratio ranging from 10% to 90%, sawtooth waveforms with a tunable slope ratio of 0.2 to 1, and a symmetric concave quadratic chirp waveform with an instantaneous frequency of sub-GHz. These results verify that our approach to high-speed RF phase encoding and user-defined AWG is competitive in terms of performance, with potentially lower cost and footprint.

Competing interests: The authors declare no competing interests.

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