Ultra-high speed reconfigurable microwave and radio frequency photonic intensity differentiators using Kerr frequency optical microcombs

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Research Article

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Abstract

We propose and experimentally demonstrate a microwave photonic intensity differentiator based on a Kerr optical comb generated by a compact integrated micro-ring resonator (MRR). The on-chip Kerr optical comb, containing a large number of comb lines, serves as a high-performance multi-wavelength source for the transversal filter, which will greatly reduce the cost, size, and complexity of the system. Moreover, owing to the compactness of the integrated MRR, up to 200-GHz frequency spacing of the Kerr optical comb can be achieved, enabling a potential operation bandwidth of over 100 GHz. By programming and shaping individual comb lines according to the calculated tap weights, a reconfigurable intensity differentiator with variable differentiation orders can be realized. The operation principle is theoretically analyzed, and experimental demonstrations of first-order, second-order, and third-order differentiation functions based on the principle are presented. The radio frequency (RF) amplitude and phase responses of multi-order intensity differentiations are characterized, and system demonstrations of real-time differentiations for Gaussian input signal are also performed. The experimental results show good agreement with theory, confirming the effectiveness of our approach.

I. Introduction

With the ever-increasing demand for processing speed and throughput in modern communication systems, optical information processing technologies have attracted great interest due to their advantages in overcoming the intrinsic bandwidth bottleneck of electronic processing [1–6]. As one of the basic building blocks in optical signal processing and computing systems [7], photonic differentiators are a key requirement in high-speed signal analyzing, waveform shaping, pulse generation, and system control [8–10].

To implement photonic differentiators, a number of schemes have been proposed, which can be classified into two categories, namely, field differentiators and intensity differentiators [11]. Field differentiators based on apodized fibre Bragg gratings [8, 10, 12] and integrated silicon photonic devices [13–16] have been recently demonstrated. These types of differentiators yield the derivative of a complex optical field, having the ability to shape ultra-short optical pulses that could find applications in optical pulse generation and advanced coding [17–19]. On the other hand, some other applications such as ultra-wideband (UWB) frequency generation, radio frequency (RF) measurement, and RF filters, require intensity differentiators that could provide the derivative of the temporal intensity profiles associated with RF signals [20–22]. A photonic intensity differentiator based on a dual-drive Mach-Zehnder modulator (DDMZM) together with a RF delay line was reported in Ref. [11], but the processing speed was intrinsically limited by the operation bandwidth of the RF delay line. Photonic intensity differentiators based on semiconductor optical amplifiers (SOAs) and optical filters (OFs) have also been reported [23–24], featuring high processing speeds up to 40-Gb/s. This approach, however, works only for a fixed differentiation order and lacks reconfigurability, whereas processing systems with variable differentiation orders are desired in practical applications, in order to meet diverse computing requirements. To implement highly reconfigurable intensity differentiators, transversal filter schemes based on discrete

microwave photonic delay-lines have been investigated [9, 25]. However, these approaches had limitations of one form or another, such as the need of generating the taps using discrete laser arrays, thus significantly increasing the system cost and complexity.

In this paper, a reconfigurable microwave photonic intensity differentiator based on an integrated Kerr comb source is proposed and experimentally demonstrated. By employing an on-chip nonlinear MRR, we generate a broadband Kerr comb with a large number of comb lines and use it as a high-quality multi-wavelength source for the transversal filter. Moreover, the large frequency spacing of the integrated Kerr comb also yields an increased Nyquist zone, thus leading to a potential operation bandwidth of over 100 GHz, well beyond the processing bandwidth of electronic devices. By programming and shaping the power of individual comb lines according to corresponding tap weights [26–27], reconfigurable intensity differentiators with variable differentiation orders can be achieved. We present a detailed analysis of the operation principle, and perform experimental demonstrations of first-, second-, and third-order intensity differentiations using the proposed device. The RF amplitude and phase responses of the intensity differentiator are experimentally characterized, and system demonstrations of real-time differentiations for Gaussian input pulses are also carried out. The experimental results are consistent with theory, verifying the feasibility of our approach as a solution to high-speed reconfigurable microwave photonic intensity differentiators.

II. Operation Principle

Based on the classical theory of signals and systems [28], the spectral transfer function of an N -th order temporal differentiator can be expressed as

$$H(\omega) \propto (j\omega)^N, \quad (1)$$

where $j = \sqrt{-1}$, ω is the angular frequency, and N is the differentiation order. According to the above transfer function, the amplitude response of a temporal differentiator is proportional to $|\omega|^N$, while the phase response has a linear profile and a zero or π jump at zero frequency for N even and odd, respectively. The ideal RF amplitude and phase responses of first-order, second-order, and third-order microwave differentiators are shown in Figs. 1(a)–(c), respectively.

In this paper, we employ a versatile approach towards the implementation of microwave photonic differentiators based on transversal filters, where a finite set of delayed and weighted replicas of the input RF signal are produced in the optical domain and combined upon detection [29–31]. The transfer function of a typical transversal filter can be described as

$$H(\omega) = \sum_{n=0}^{M-1} a_n e^{-j\omega nT} \quad (2)$$

where M is the number of taps, a_n is the tap coefficient of the n -th tap, and T is the time delay between adjacent taps. It should be noted that the differentiator design based on Eq. (2) is an intensity differentiator, i.e., the output RF signal after being combined upon detection yields an exact differentiation of the input RF signal, in contrast to field differentiators that yield the derivative of a complex optical field [8, 10, 12–16].

To implement the temporal differentiator in Eq. (1), we calculate the tap coefficients in Eq. (2) based on the Remez algorithm [32]. The corresponding amplitude and phase responses of the first-, second-, and third-order differentiators as a function of the numbers of taps are plotted in Figs. 1(a)–(c). When the number of taps is increased, it is clear that the discrepancies between the amplitude responses of the transversal filters and the ideal differentiators are improved for all the three orders, whereas the phase response of the transversal filters is identical to that of the ideal differentiators regardless of the number of taps. To quantitatively analyze the discrepancies in the amplitude responses, we further calculate the root mean square errors (RMSEs) for the first-, second-, and third-order differentiators as a function of the number of taps, as shown in Fig. 1(d). One can see that the RMSE is inversely proportional to the number of taps, as reasonably expected. In particular, we note that when the number of taps increases, the RMSE decreases dramatically for a small number of taps, and then decreases more gradually as the number of taps becomes larger.

Figure 2 shows the schematic illustration of the reconfigurable microwave photonic intensity differentiator. It consists of two main blocks: one is a Kerr comb generation module based on a nonlinear MRR and the other is a transversal filter module for reconfigurable intensity differentiation. In the first module, the continuous-wave (CW) light from a tunable laser source (TLS) is amplified by an erbium-doped fibre amplifier (EDFA) followed by a tunable optical bandpass filter (BPF) to suppress the amplified spontaneous emission (ASE) noise. A polarization controller (PC) is inserted before the nonlinear MRR to make sure that the polarization state matches the desired coupled mode. When the wavelength of the CW light is tuned to a resonance of the nonlinear MRR and the light power is large enough for sufficient parametric gain, the optical parametric oscillation (OPO) process in the nonlinear MRR can be initiated, which generates a Kerr optical comb with nearly equal line spacing [33–34]. The nonlinear MRR is mounted on a highly precise temperature controlled stage (TCS) to avoid resonance drifts and maintain the wavelength alignment of the resonances to the CW light. Owing to the compact size and ultra-high quality factor of the nonlinear MRR, the generated Kerr comb provides a large number of wavelength channels with narrow linewidths for the subsequent transversal filter module. As compared with conventional intensity differentiators based on laser diode arrays, the cost, size and complexity can be greatly reduced. The generated Kerr comb then is directed to the second module. After being amplified by another EDFA, the Kerr comb is processed by a waveshaper to get weighted taps according to the coefficients calculated by means of the Remez algorithm. Considering that the generated Kerr comb is not flat, a real-time feedback control path is introduced to read and shape the comb lines' power accurately. A 2×2 balanced Mach-Zehnder modulator (MZM) is employed to generate replicas of the input RF signal. When the MZM is quadrature-biased, it could simultaneously modulate the input RF signal on both positive and negative slopes, thus yielding modulated signals with opposite phases and tap

coefficients with opposite algebraic signs. After being modulated, the tapped signals from one output of the MZM are delayed by a dispersive fibre. The time delay between adjacent taps is co-decided by the frequency spacing of the employed comb source and the dispersion accumulated in the fibre. Finally, the weighted and delayed taps are combined upon detection and converted back into RF signals to form the differentiation output.

It is worth mentioning that due to the intrinsic advantages of transversal filters, our scheme features a high degree of reconfigurability in terms of processing functions and operation bandwidth, thus offering a reconfigurable platform for diverse microwave photonic computing functions. By simply programming the waveshaper to shape the comb lines according to the corresponding tap coefficients, our scheme can also apply to other computing functions such as Hilbert transforms and differential equation solving [35–36]. The operation bandwidth can also be changed by adjusting the time delay between adjacent taps or employing specific tap coefficients. An increased operation bandwidth can be achieved by simply employing a dispersive fibre with shorter length. The operation bandwidth is fundamentally limited by the Nyquist zone, which is determined by the comb spacing. In our case, the frequency spacing of the Kerr comb generated by the nonlinear MRR reaches 200 GHz, thus leading to a potential operation bandwidth of over 100 GHz.

iii. Experimental Results

In our experiment, as Fig. 3 (a) shows, the nonlinear MRR used to generate the Kerr comb was fabricated on a high-index doped silica glass (Hydex) platform using CMOS compatible fabrication processes [33]. First, high-index ($n = 1.7$) doped silica glass films were deposited using standard plasma enhanced chemical vapour deposition (PECVD), then photolithography and reactive ion etching (RIE) were employed to form waveguides with exceptionally low surface roughness. Finally, the waveguides were buried in a lower index overcladding. The radius of the Hydex MRR is $\sim 135 \mu\text{m}$. The compact integrated MRR has a large free spectral range (FSR) of $\sim 1.6 \text{ nm}$, i.e., $\sim 200 \text{ GHz}$. Such a large FSR enables an increased Nyquist zone of $\sim 100 \text{ GHz}$, which is challenging for mode-locked lasers and externally-modulated comb sources [37–38]. The advantages of the Hydex platform for nonlinear OPO include ultra-low linear loss ($\sim 0.06 \text{ dB/cm}$), a moderate nonlinearity parameter ($\sim 233 \text{ W}^{-1}\text{km}^{-1}$), and in particular a negligible nonlinear loss up to extremely high intensities ($\sim 25 \text{ GW/cm}^2$) [33–34]. After packaging the input and output ports of the device with fibre pigtails, the total insertion loss is $\sim 3.5 \text{ dB}$. A scanning electron microscope (SEM) image of the cross-section of the Hydex MRR before depositing the SiO_2 upper cladding is shown in Fig. 3 (b). By boosting the power of the CW light from the TLS via an EDFA and adjusting the polarization state, multiple mode-spaced combs were first generated, in which the primary spacing was determined by the parametric gain. When the parametric gain lobes became broad enough, secondary comb lines with a spacing equal to the FSR of the Hydex MRR were generated via either degenerate or non-degenerate four wave mixing (FWM). In our experiment, the power threshold for the generation of secondary comb lines was $\sim 500 \text{ mW}$.

The resulting Type II Kerr optical comb [39] as shown in Fig. 4(a) is over 200-nm wide, and flat over ~ 32 nm. Since the generated comb only served as a multi-wavelength source for the subsequent transversal filter in which the optical power from different taps was detected incoherently by the photodiode, the coherence of the comb was not crucial and the proposed differentiator was able to work under relatively incoherent conditions. In the experiment, the numbers of taps used for first-, second-, and third-order differentiation demonstrations were 8, 6, and 6, respectively. The choice of these numbers was made mainly by considering the power dynamic range of the comb lines, i.e., the difference between the maximum power of the generated comb lines and the power associated with the noise floor. The power dynamic range was determined by the EDFA before waveshaping, and in our case, it was ~ 30 dB. An increased number of taps requires a broader power dynamic range, which can be achieved by using a further EDFA with a lower noise floor. As analysed in section 4, more taps are needed when the differentiation order increases, and for a fixed number of taps, increasing the order of differentiation also increases the required power dynamic range. In order to get better performance with a limited number of taps, we decreased the operation bandwidth of the second- and third-order differentiators to half of the transversal filter's Nyquist frequency when designing the response function with the Remez algorithm. It should be noted that the actual bandwidth of the differentiator is not limited by this design since the FSR of the transversal filter can be enlarged. The calculated tap coefficients for first-, second-, and third-order differentiation are listed in Table I. The selected comb lines of the generated optical comb were processed by the waveshaper based on these coefficients. Considering that the generated Kerr comb was not flat, we adopted a real-time feedback control path to increase the accuracy of comb shaping. The comb lines' power was first detected by an optical spectrum analyzer (OSA) and compared with the ideal tap weights, and then an error signal was generated and fed back into the waveshaper to calibrate the system and achieve accurate comb processing. The shaped optical combs are shown in Figs. 4(b)–(d). A good match between the measured comb lines' power (red solid line) and the calculated ideal tap weights (green cross) was achieved, indicating that the comb lines were successfully shaped. They were then divided into two parts according to the algebraic sign of the tap coefficients and fed into the 2×2 balanced MZM biased at quadrature. The modulated signal after the MZM was propagated through ~ 2.122 -km single mode (dispersive) fibre (SMF). The dispersion of the SMF is ~ 17.4 ps/(nm·km), which corresponds to a time delay of ~ 59 ps between adjacent taps and yields an effective FSR of ~ 16.9 GHz in the RF response spectrum.

After the weighted and delayed taps were combined upon detection, the RF responses for different differentiation orders were characterized by a vector network analyser (VNA, Anritsu 37369A). Figures. 5(a-i), (b-i), and (c-i) show the measured and simulated amplitude responses of the first-, second-, and third-order intensity differentiators, respectively. The corresponding phase responses are depicted in Figs. 5(a-ii), (b-ii), and (c-ii). It can be seen that all the three differentiators feature the responses expected from ideal differentiation. The FSR of the RF response spectra is ~ 16.9 GHz, which is consistent with the time delay between adjacent taps, as calculated before measurement. Note that by adjusting the FSR of the proposed transversal filter through the dispersive fibre or by programming the tap coefficients, a variable

operation bandwidth for the intensity differentiator can be achieved, which is advantageous for meeting diverse requirements in operation bandwidth.

We also performed system demonstrations of real-time signal differentiation for Gaussian input pulses with a full-width at half maximum (FWHM) of ~ 0.12 ns, generated by an arbitrary waveform generator (AWG, KEYSIGHT M9505A), as shown in Fig. 6(a). The waveform of the output signals after differentiation are shown in Figs. 6 (b)–(d) (blue solid curves). They were recorded by means of a high-speed real-time oscilloscope (KEYSIGHT DSOZ504A Infiniium). For comparison, we also depict the ideal differentiation results, as shown in Figs. 6 (b)–(d) (red dashed curves). The practical Gaussian pulse in Fig. 6(a) is used as the input RF signal for the simulation. One can see that the measured curves closely match their theoretical counterparts, indicating good agreement between experimental results and theory. Unlike the field differentiators in Refs. [8, 10, 12–16], temporal derivatives of intensity profiles can be observed, indicating that intensity differentiation was successfully achieved. For the first-, second-, and third-order differentiators, the calculated RMSE between the measured and the theoretical curves are $\sim 4.15\%$, $\sim 6.38\%$, and $\sim 7.24\%$, respectively.

To further investigate the imperfections associated with the experimental results, we employed commercial software (VPI Photonics) to simulate the RF amplitude and phase responses of the various differentiators by considering the tap weight error during the comb shaping, the chirp induced by the MZM, and the third-order dispersion (TOD) of the fibre. Based on the measured error signal from the feedback control path and the empirical chirp value in previous experiments [35], the tap weight error, chirp coefficient, and TOD in our simulation were set to be 0.5 dB, 0.5, and 0.083 ps/(nm²·km), respectively. The simulated amplitude and phase responses are plotted in Figs. 5 (a)–(c). One can see that after incorporating these two effects, the simulated RF responses fit more closely to the experimental results, thus confirming that the degradation of the RF responses can be attributed to both of these effects. By employing a low-chirped MZM, further increasing the resolution of the feedback control path, and compensating the TOD, we can anticipate improved performance of the differentiators.

IV. Discussion

All-optical signal processing based on nonlinear optics has proven to be extremely powerful, particularly when implemented in photonic integrated circuits based on highly nonlinear materials such as silicon [40–43]. All optical signal processing functions include all-optical logic [44], demultiplexing at ultra-high bit rates from 160Gb/s [45] to over 1Tb/s [46], optical performance monitoring (OPM) using slow light [47, 48], all-optical regeneration [49, 50], and others [51–56]. Complementary metal oxide semiconductor (CMOS) compatible platforms are centrosymmetric and so the 2nd order nonlinear response is zero. Hence, nonlinear devices in these platforms have been based on the 3rd order nonlinear susceptibility including third harmonic generation [51, 57–61] and the Kerr nonlinearity (n_2) [40–42]. The efficiency of Kerr nonlinearity based all-optical devices depends on the waveguide nonlinear parameter (γ). Although silicon-on-insulator nanowire devices can achieve extremely high nonlinearities (γ), they suffer from high nonlinear optical losses due to two-photon absorption (TPA) and the resulting generated free carriers [42].

Even if the free carriers are swept out by p-i-n junctions, silicon's relatively poor intrinsic nonlinear figure of merit ($FOM = n^2 / (\beta \lambda)$, where β is the TPA and λ the wavelength) of around 0.3 in the telecom band is too low to achieve good performance. While TPA can be turned to advantage for some all-optical functions [62–64], for the most part, silicon's low FOM in the telecom band is a limitation. This has motivated research on a range of alternate nonlinear platforms including chalcogenide glasses [65–74]. However, while offering many advantages, these platforms are not compatible with CMOS processing – the basis of the silicon computer chip industry.

In 2007/8 new CMOS compatible platforms for nonlinear optics were reported that exhibited extremely low two-photon absorption in the telecommunications wavelength band. These included silicon nitride [75, 76] as well as high-index doped silica glass (Hydex) [77–87], similar in its optical properties to silicon oxynitride. In addition to negligible nonlinear absorption, these platforms displayed a moderate Kerr nonlinearity, resulting in an extremely high nonlinear figure of merit as well as a nonlinear parameter that was high enough to support substantial parametric gain. Following the first report of micro-ring resonator (MRR) based frequency comb source driven by the Kerr optical nonlinearity in 2007 [88], the first fully integrated optical parametric oscillators were reported in 2010 [76, 77] that were also CMOS compatible. Since then the field of integrated micro-combs, or “Kerr combs” has become one of the largest fields in optics and photonics [87]. Integrated optical Kerr frequency comb sources, or “micro-combs” are a fundamentally new and powerful tool to accomplish many new functions on an integrated chip, due to their ability to provide highly coherent combs of multiple wavelength channels, at the same time offering a very high degree of wavelength spacing control. Optical micro-combs are produced via optical parametric oscillation driven by modulational instability gain in monolithic MRRs. They offer significant advantages over more traditional multi-wavelength sources. Many innovative applications have been reported based on integrated Kerr micro-combs, from filter-driven mode-locked lasers [89–92] to quantum optical photonic chips [93–101], ultrahigh bandwidth optical fiber data transmission [102–104], optical neural networks [105–107], integrated optical frequency synthesizers [108]. We refer the reader to extensive reviews of micro-combs have been presented recently [87, 109–116]. The success of the new CMOS platforms silicon nitride and Hydex motivated the search for even higher performing CMOS compatible platforms such as amorphous silicon [117] and silicon rich silicon nitride [118] that display a combination of low linear loss, high nonlinearity and very low nonlinear loss.

All-optical signal processing based on nonlinear optics has attracted significant interest over the years for its ability to achieve ultrahigh bandwidth without needing optical to electronic (or visa versa) conversion. It has been particularly important for a wide range of signal processing functions for both telecommunications and RF/microwave applications. RF photonic applications range from radar systems to signal generation and processing, [119–168] and are attractive because of the ultra-high bandwidths that can be achieved as well as low transmission loss and strong electromagnetic interference immunity. There is a very wide range photonic RF approaches including techniques that map the optical filter response in the optical domain onto the RF domain. This is perhaps best represented by integrated devices based on stimulated Brillouin scattering [128–135], which has resulted in extremely high performance for RF resolution – being able to resolve features as fine as 32 MHz, at the same time

achieving a stopband rejection > 55 dB. A key approach to achieving reconfigurable transfer functions for adaptive signal processing has been based on the transversal filter method [136–140] that operate by generating weighted, progressively delayed replicas of an RF signal imprinted on an optical carrier and then summing them via photo-detection. Transverse filters can realize a wide range of RF signal processing functions by only adjusting the tap weights, and so this method is very attractive to realize advanced RF filters that need to be dynamically adaptive. Both discrete laser diode arrays [141, 142] as well as integrated and fibre Bragg grating arrays and sampled gratings [143] have been successful at supplying the required taps. However, while offering many advantages, these approaches suffer from significantly increased complexity as well as reduced performance due to limitations in the available number of taps. Alternative approaches, such as employing optical frequency comb sources achieved by electro-optic (EO) or acousto-optic (AO) modulation [142, 144, 145], can help overcome this problem, but they require multiple high frequency modulators that rely on high-frequency RF sources. Of these approaches, EO combs have been used the longest and have achieved significant success at realizing many powerful functions.

Integrated optical Kerr micro-combs are a relatively recent innovation and have been very successful - offering many advantages over other approaches that use multi-wavelength sources for RF applications. They have been demonstrated to be capable of achieving extremely high bit rate telecommunications systems as well as a very wide range of RF signal processing functions [147–168]. They can generate frequency combs with a much larger spacing than electro-optic combs. EO combs and micro-combs are in fact complementary in many ways – EO combs focuses on finer wavelength spacings from 10's of MHz to 10 - 20 GHz, while integrated micro-combs typically have much wider spacings from 10's to 100's of GHz and even into the THz regime. Larger comb spacings yield much wider Nyquist zones that are needed to achieve large RF bandwidths, whereas finer spacings provide much larger numbers of wavelengths or RF “taps”, but at the cost of a much smaller Nyquist zone, or RF bandwidth. Micro-combs can provide higher numbers of wavelengths together with still being able to provide a large FSR, in a compact footprint. For RF transversal filters the number of taps, or wavelengths, dictates the available number of channels for, for example, RF true time delays as well as determining the performance of RF filters [125, 161]. Other systems such as beamforming devices [152] can also be greatly improved in terms of their quality factor and angular resolution. Other innovative approaches to filtering include techniques such as RF bandwidth scaling [165] that provide a certain bandwidth for each wavelength channel, and so the total operation bandwidth (maximum RF signal bandwidth that can be processed) will depend on the number of wavelengths, and will therefore be significantly enhanced by the use of micro-combs.

We have reported [147–168] a wide range of microwave and RF signal processing based on transversal filtering and bandwidth scaling methods based on Kerr micro-combs applied to RF and microwave spectral filters. We have achieved both integral and fractional order Hilbert transformers and differentiators, as well as RF integrators. We have examined the trade-offs involved between using wide spaced micro-combs with an FSR of 200GHz [149–151] with record low FSR spaced micro-combs at 49 GHz, based on soliton crystals [162–179]. While 200GHz Kerr micro-combs have proven to be a powerful

source for RF transversal filters, enabling high versatility as well as dynamic reconfigurability, the relatively large comb spacing FSR of ~ 1.6 nm restricts the number of taps to typically less than 21 wavelengths within the 30nm wide C-band. This is important since transversal filters require optical amplifiers and spectral shapers that are typically only available in the telecommunications bands (1530–1620nm). This limitation in the tap number has restricted the performance of micro-comb based transversal RF filters in frequency selectivity, bandwidth, and dynamic versatility. To improve on this, we reported micro-comb-based photonic RF transversal filters operating with a record high number of taps – up to 80 wavelengths over the C-band [157]. This is the highest number reported for micro-comb RF transversal filters, and has been enabled by a record low 49GHz FSR integrated Kerr micro-comb source. For filter applications [161] this enabled QRF factors for RF bandpass filters 4 times higher than that achievable with 200GHz combs. For temporal signal processing, this yields dramatic improvements in both bandwidth and reconfigurability. This photonics platform has been highly successful at a wide range of linear and nonlinear optical devices [77–92, 180–183] as well as quantum optical chips [93–101, 184–191]. Our results confirm the feasibility of achieving high performance advanced as well as adaptive RF transversal filters for use in high bandwidth RF signal processing systems, at the same time providing reduced cost, footprint, and complexity. Note that many of the functions that we implement with fiber components, such as the delay lines, can equally well be implemented with compact tunable dispersion compensators [192–195] as well as integrated detectors and modulators [196].

V. Conclusion

Here, we propose and demonstrate a reconfigurable microwave photonic intensity differentiator based on an integrated Kerr comb source. The Kerr optical comb was achieved via a CMOS-compatible nonlinear MRR, which greatly increased the processing bandwidth and has the potential for a low cost, size, and complexity processing system. By programming and shaping the individual comb lines' power according to the calculated tap weights, we successfully demonstrate the first, second, and third-order intensity differentiation of the RF signal. The RF amplitude and phase responses of the proposed differentiator are characterized, and system demonstrations of real-time differentiations are performed for Gaussian input pulses. We achieve good agreement between theory and experimental, thus verifying the effectiveness of our approach. In particular, our scheme provides a new way to implement microwave photonic intensity differentiators with high processing bandwidth and re-configurability, thus holding great promise for future ultra-high-speed computing and information processing.

Declarations

Competing interests:

The authors declare no competing interests.

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Table 1

TABLE I. Tap coefficients for first-order, second-order, and third-order differentiation

Order of differentiation	Number of taps	Tap coefficients
First-order	8	[-0.0226, 0.0523, -0.1152, 1, -1, 0.1152, -0.052, 0.0226]
Second-order	6	[0.0241, -0.1107, 0.0881, 0.0881, -0.1107, 0.0241]
Third-order	6	[0.0450, -0.4076, 1, -1, 0.4076, -0.0450]

Figures

Fig. 1. Simulated RF amplitude and phase responses of the (a) first-, (b) second-, and (c) third-order temporal differentiators. (d) RMSEs between calculated and ideal RF amplitude responses of the first-, second-, and third-order intensity differentiators as a function of the number of taps.

Figure 1

Simulated RF amplitude and phase responses of the (a) first-, (b) second-, and (c) third-order temporal differentiators. (d) RMSEs between calculated and ideal RF amplitude responses of the first-, second-, and third-order intensity differentiators as a function of the number of taps.

Fig. 2. Schematic illustration of the reconfigurable microwave photonic intensity differentiator. TLS: Tunable laser source. EDFA: erbium-doped fibre amplifier. PC: polarization controller. BPF: optical bandpass filter. TCS: temperature controller stage. MZM: Mach-Zehnder modulator. SMF: single mode fibre. OC: optical coupler. PD: photodetector. OSA: optical spectrum analyzer. VNA: vector network analyzer. AWG: arbitrary waveform generator.

Figure 2

Schematic illustration of the reconfigurable microwave photonic intensity differentiator. TLS: Tunable laser source. EDFA: erbium-doped fibre amplifier. PC: polarization controller. BPF: optical bandpass filter. TCS: temperature controller stage. MZM: Mach-Zehnder modulator. SMF: single mode fibre. OC: optical coupler. PD: photodetector. OSA: optical spectrum analyzer. VNA: vector network analyzer. AWG: arbitrary waveform generator.

Fig. 3. (a) Hydex MRR. (b) SEM image of the cross-section of the Hydex MRR before depositing the SiO₂ upper cladding.

Figure 3

(a) Hydex MRR. (b) SEM image of the cross-section of the Hydex MRR before depositing the SiO₂ upper cladding.

Fig. 4. (a) Optical spectrum of the generated Kerr comb in a 300-nm wavelength range. Inset shows a zoom-in spectrum with a span of ~ 32 nm. (b)–(d) Measured optical spectra (red solid) of the shaped optical combs and ideal tap weights (green crossing) for the first-, second-r, and third-order intensity differentiators.

Figure 4

(a) Optical spectrum of the generated Kerr comb in a 300-nm wavelength range. Inset shows a zoom-in spectrum with a span of ~ 32 nm. (b)–(d) Measured optical spectra (red solid) of the shaped optical combs and ideal tap weights (green crossing) for the first-, second-r, and third-order intensity differentiators.

Fig. 5. Measured and simulated RF amplitude and phase responses of (a-i)–(a-ii) the first-order, (b-i)–(b-ii) second-order, and (c-i)–(c-ii) third-order intensity differentiators.

Figure 5

Measured and simulated RF amplitude and phase responses of (a-i)–(a-ii) the first-order, (b-i)–(b-ii) second-order, and (c-i)–(c-ii) third-order intensity differentiators.

Fig. 6. (a) Measured temporal waveforms of a Gaussian input pulse. Theoretical (red dashed) and experimental (blue solid) responses of the (b) first-, (b) second-, and (c) third-order differentiators.

Figure 6

(a) Measured temporal waveforms of a Gaussian input pulse. Theoretical (red dashed) and experimental (blue solid) responses of the (b) first-, (b) second-, and (c) third-order differentiators.