Reconfigurable fractional microwave signal processor based on a microcomb

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Abstract—We propose and demonstrate reconfigurable fractional microwave signal processing based on an integrated Kerr optical microcomb. We achieve two forms of microwave signal processing functions — a fractional Hilbert transform as well as a fractional differentiator. For the Hilbert transform we demonstrate a phase shift of 45 degrees — half that of a full Hilbert transform, while for the differentiator we achieve square-root differentiation. For both, we achieve high resolution over a broad bandwidth of 17 GHz with a phase deviation of less than 5° within the achieved passband. This performance in both the frequency and time domains demonstrates the versatility and power of micro-combs as a basis for high performance microwave signal processing.

Keywords—Microwave photonics, signal processor, micro-ring resonators.

I. INTRODUCTION

Signal processors, such as Hilbert transformers (HT) and differentiators, are one of the basic and most commonly used components in modern radar and satellite communications systems [1-5]. While all-electronic methods are the traditional approaches used, they are subject to limitations in bandwidth. Photonic techniques are promising solutions for high performance RF filters and signal processors, offering wide bandwidths, high performance and versatility, and strong immunity to electromagnetic interference.

Hilbert transformers and temporal differentiators are both fundamental processing functions that are integral to many RF and microwave systems. They are quadrature filters that feature wideband 90° phase shifts, and are important techniques in the theory and practice of radar mapping, imaging edge detection as well as the realization of advanced modulation formats for digital communications. To further enhance the performance of these advanced signal processing functions, a key approach is to realise fractional orders of these response functions to enable fractional Hilbert transformers, fractional differentiators, and potentially solving differential equations.

Optical fractional-order signal processors have been implemented based on fibre Bragg gratings [6-10], Mach-Zehnder interferometers [11], and ring-resonators [12]. Although these approaches offer many advantages they tend to suffer from limited bandwidth when processing signals.

Another approach is to use individual laser sources to supply the individual tap wavelengths. Better still, approaches that supply all of the tap wavelengths from a single source to generate high quality, and multiple wavelengths offer still further advantages. This can be achieved via mode-locked lasers [23], electro-optical modulation [24], and other approaches, and this provides solutions that have achieved attractive performance.

Optical frequency comb sources based on integrated nonlinear micro-resonators – Kerr microcombs – have recently been used for microwave signal processing [13-22]. They offer distinct advantages such as greatly reduced footprint and complexity and can provide a much higher number of wavelengths, thus offering fundamental advantages for the performance of photonic RF filters [25-32].

Here, we report a reconfigurable fractional microwave signal processor based on integrated microcombs. We report two kinds of signal processing functions, including fractional Hilbert transforms (FHT) and fractional differentiation (FD), achieved by programming and shaping the power of individual comb lines according to the required tap weights. System demonstrations of the FHT and FD are performed, including measurements of the RF amplitude and phase response, as well as the real-time impulse response for Gaussian input pulses.

II. THEORY

The FHT can be defined as the transfer function of a filter as follows:

\[ H_{\varphi}(\omega) = \begin{cases} e^{-j\varphi}, & 0 \leq \omega < \pi \\ e^{j\varphi}, & -\pi \leq \omega < 0 \end{cases} \] (2.1)

where \( \varphi = P \times \pi / 2 \) denotes the phase and \( P \) is the fractional order. As can be seen from (2.1), an FHT is a \( \varphi \) phase shifter and the FHT becomes a classical HT when \( P = 1 \).

The impulse response of a fractional Hilbert transformer is a continuous hyperbolic function

\[ h_p[t] = \begin{cases} \frac{1}{\pi t}, & t \neq 0 \\ \cot(\varphi), & t = 0 \end{cases} \] (2.2)

which is truncated and sampled in time by discrete taps. The null frequency \( f_c \) is determined by the sample spacing \( \Delta t \)

\[ f_c = 1/\Delta t \] (2.3)

In addition, the order of the FHT is continuously tunable by only adjusting the coefficient of the \( 90^\circ \) \( (t=0) \) tap while keeping the coefficients of other taps unchanged. A temporal differentiator has a spectral transfer function that can be expressed as
to the free spectral range of the MRR. The generated Kerr micro-comb served as a multi-wavelength source where the power of each comb line was manipulated by Waveshapers to achieve the designed tap weights.

III. EXPERIMENTAL RESULTS OF FHT

The integrated MRRs were fabricated on a high-index doped silica glass (n = 1.7 at 1550 nm) platform using CMOS-compatible fabrication processes. The radii of the MRRs were both designed to be ~592 μm, corresponding to FSRs of ~0.4 nm (~49 GHz), which enabled a large number of comb wavelengths up to 80 in the C band and over 160 in the C+L band.

To generate Kerr micro-combs, the pump power was set at ~30.5 dBm and the wavelength swept from blue to red. When the detuning between the pump wavelength and the MRR’s cold resonance became small enough, such that the intracavity power reached a threshold value, modulation instability driven oscillation was initiated. As the detuning was changed further, distinctive ‘fingerprint’ optical spectra of soliton crystals were observed (Fig. 2) that are indicative of soliton crystals [19,29,30]. The comb was then spectrally shaped by two stages of Waveshapers (Finisar, 4000S) in order to enable a larger dynamic range of loss control and higher shaping accuracy than a single stage.

The micro-comb was first pre-shaped to reduce the power difference between the comb lines to under 5 dB. Next, the shaped comb lines were fed into an EO intensity modulator (IM) and then through a 2.1-km of standard single mode fibre (SMF) to provide a wavelength dependent delay. The dispersion of the SMF was 17.4 ps / (nm · km), corresponding to a time delay T of ~30 ps between adjacent taps, yielding an FSR_{RF} of ~17 GHz for the fractional signal processor. The shaped comb lines were then amplified and accurately shaped by a Waveshaper according to the designed tap weights. For the second Waveshaper, a feedback control path was adopted to increase the accuracy of the comb shaping, where the power in the comb lines from one of the port of waveshaper were detected by an optical spectrum analyzer and then compared with the ideal tap weights in order to generate error signals for calibration. Finally, the weighted positive and negative taps with the ideal tap weights in two stages of Waveshapers (Finisar, 4000S) in order to enable a larger dynamic range of loss control and higher shaping accuracy than a single stage.
The system RF frequency response was then characterized by using a vector network analyzer (VNA, Agilent MS4644B) to measure the system RF amplitude and phase frequency response. In Fig. 3 (a), we measured the RF amplitude and phase frequency response of the fractional Hilbert transform filters with a 45 degree phase shift for 5, 9, 13 and 17 taps, respectively. Fig. 3 (b) shows the theoretical results which all exhibit the expected behaviour. The theoretical normalized bandwidth / FSRRF as a function of the tap number is shown in Fig. 3 (c). With a 17 tap filter, the FHT with a 45 degree phase shift exhibited a 3 dB bandwidth from 0.034 GHz to 16.45 GHz, corresponding to more than 8 octaves. Also, as can be seen, the theoretical BW increases with tap number, yielding a significant improvement in frequency selectivity.

The input Gaussian pulses were generated from an arbitrary waveform generator (AWG, KEYSIGHT M9505A), shown in Figs. 4 and 5. As can be seen, the full-width at half-maximum is 50 ps with a bandwidth of 5 GHz. A good match between the power of the measured comb lines (red and blue solid lines) and the calculated ideal tap weights (red and blue dots) was obtained, indicating that the comb lines were successfully shaped.

The normalized frequency response and phase response of the FD with phase shift of 45 degree, corresponding to a tunable order of 0.5 is shown in Fig. 5. We also performed systems demonstrations of real-time square root differentiation for the Gaussian input pulses. The measured output waveform agrees well with theory, further confirming the feasibility of our approach.

IV. Conclusions

We demonstrate a reconfigurable microcomb-based fractional signal processor. The Kerr optical comb is produced via a CMOS-compatible nonlinear MRR, which greatly increases the processing bandwidth. By programming and shaping the individual comb lines’ power according to the calculated taps weights, we successfully demonstrate a fractional Hilbert transformer and differentiator with an order of 0.5. The RF amplitude and phase response of the fractional signal processor are characterized, and system demonstrations of the real-time fractional signal processor are performed for Gaussian input pulses. The experimental results agree well with theory, verifying a promising new way to implement microwave photonic fractional signal processors featuring compact device footprint, high processing bandwidths and reconfigurability, for future ultra-high-speed microwave and computing and information processing systems.

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