RF and microwave fractional and regular Hilbert transformer based on a Kerr microcomb

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Abstract: We propose and demonstrate a reconfigurable microwave signal processor for fractional and regular Hilbert transform with 17 GHz bandwidth based on an integrated Kerr optical frequency comb source. Transmission responses and temporal characterization are experimentally demonstrated.

1. Introduction

The Hilbert transform is an essential mathematical operation in modern signal processing systems and has wide applications ranging from radar system, single sideband modulators, schemes of sampling band-pass signals, and many other systems [1]. The regular Hilbert transform was generalized to a fractional Hilbert transform in [2], to permit an additional degree of freedom and also to improve the performance of the Hilbert transform.

Generally, a Hilbert transformer can be implemented based on free-space optics [2], which may not be suitable for applications where small size and light weight are required. One of the earliest photonic implementations of a fractional Hilbert transformer phase-shifted Bragg gratings to process arbitrary optical waveforms with bandwidths up to a few hundreds of gigahertz [3]. However, the limitation of using phase-shifted Bragg gratings is that the fractional order is not tunable. In [4], a method by changing the polarization direction of the incident light to the MRR is recently implemented. Such proposed structures could only process the signal in a complex optical field, while an optical fractional-order Hilbert transformer capable of handling the intensity profile of input microwave signals is still unavailable [5]. Frequency combs based on integrated nonlinear micro-resonators – Kerr microcombs – have recently been used for microwave signal processing [6-32].

In this paper, we propose a reconfigurable microwave signal processor for fractional and regular Hilbert transform based on a microcomb. By programming and shaping the power of individual comb lines according to corresponding tap weights, we achieved a reconfigurable Hilbert transformer with phase shifts (φ) of 30°, 60°, 90°. The RF amplitude and phase response of the Hilbert transformer is carried out, and systems demonstrations are performed for Gaussian input pulses, achieving good performance that agrees well with theory.

2. Operation principle and experimental results

Fig. 1. (a) Schematic diagram of the Hilbert transformer based on an integrated 49GHz-spacing micro-comb source. EDFA: erbium-doped fiber amplifier. PC: polarization controller. MRR: micro-ring resonator. WSS: WaveShaper. IM: Intensity modulator. SMF: single mode fiber. OSA: optical spectrum analyzer. PC: computer. BPD: Balanced photodetector. VNA: vector network analyzer. AWG: arbitrary waveform generator. OSC: Oscilloscope. (b) The optical spectrum of the generated soliton crystal combs with 100nm span.

Figure 1(a) shows a schematic diagram of the fractional and regular Hilbert transformer based on an integrated Kerr micro-comb source. It consists of two main blocks: (i) the Kerr comb generation module based on a nonlinear MRR and (ii) a transversal filter module for a reconfigurable fractional Hilbert transformer. The MRR used to generate the Kerr micro-comb was fabricated on a high-index doped silica glass platform using CMOS-compatible fabrication processes [9]. The radius of the MRR was $\sim 592 \mu\text{m}$, corresponding to a free spectral range (FSR) of $\sim 49 \text{ GHz}$. The generated soliton crystal comb, which showed in Fig. 1 (b) was spectrally shaped via two-stage optical shapers (Finisar, WaveShaper 4000S) to enable a broader dynamic range of loss control as well as a higher shaping accuracy. The micro-comb was first pre-shaped to reduce the power difference between the comb lines under 5 dB. Next, the shaped comb lines were fed into an EO intensity modulator (IM) and then through $\sim 2.1\text{-km}$ of standard single mode fibre (SMF) to provide a wavelength dependent delay. The dispersion of the SMF was $17.4 \text{ ps} / (\text{nm} \cdot \text{km})$, corresponding to a time delay T of $\sim 30 \text{ ps}$ between adjacent taps, yielding an FSR_{RF} of about 17 GHz for the Hilbert transformer, 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. Since the Nyquist frequency is 24.5 GHz – in our case, half of the 49 GHz comb spacing, the operational bandwidth of the transversal filter was determined mainly by the FSR_{RF} of 17 GHz .

Fig. 2. (i) Optical spectra of the shaped micro-comb corresponding with different tap weights (ii) Measured frequency responses of the Hilbert transformer with an order of 0.333, 0.667, and 1. Simulated frequency responses are also shown for comparison. (iii) Phase shifts of 30° , 60° and 90° . (iv) Theoretically calculated and the experimentally measured Hilbert transformed pulse.

Figure 2(i) shows the optical spectra which were measured by an optical spectrum analyzer. A good match between the power of the measured comb lines and the calculated ideal taps weights was obtained, indicating that the comb lines were successfully shaped. Fig. 2(ii) and (iii) show the normalized frequency response and phase response of the Hilbert transformer with tunable order of 0.333, 0.667 and 1, corresponding with a phase shift of 30° , 60° and 90° , as can be seen, an excellent fit is achieved between the measured and the simulated results. The output waveform is observed by a high-speed real-time oscilloscope. For comparison, we depict the simulated results, as shown in Fig. 2(iv). As can be seen that the measured curves closely match their theoretical counterparts, achieving good performance that agrees well with theory.

3. Conclusion

We demonstrate a reconfigurable microwave signal processor for fractional and regular Hilbert transform based on a microcomb, operating at a bandwidth of 17 GHz with a phase shift of 30° , 60° , 90° .

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5. References

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