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High bandwidth, versatile and highly reconfigurable, RF and microwave photonic Hilbert transformers using Kerr micro-combs

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ABSTRACT

We experimentally demonstrate bandwidth-tunable RF photonic Hilbert transformer based on an integrated Kerr micro-comb source. The micro-comb is generated by an integrated micro-ring resonator with a free spectral range of 48.9 GHz, yielding 75 micro-comb lines in the telecom C-band. By programming and shaping the generated comb lines according to calculated tap weights, we demonstrate high-speed Hilbert transform functions with tunable bandwidths ranging from 1.2 GHz to 15.3 GHz, switchable center frequencies from baseband to 9.5 GHz, and arbitrary fractional orders. The experimental results show good agreement with theory and confirm the effectiveness of our approach.

Keywords: Kerr frequency comb, Hilbert transform, integrated optics, all-optical signal processing.

INTRODUCTION

The Hilbert transform is a fundamental signal processing function with wide range of applications in radar systems, signal sideband modulators, measurement systems, signal sampling, and many others [1-8]. Fractional Hilbert transforms provide an additional degree of freedom in terms of a variable phase shift, which can meet the special requirements of unilateral communication [2] and confidentiality of hardware keys [3]. In practical applications such as multiplexing and demultiplexing signals, analyzing individual sub-channel spectral components, etc., Hilbert transformers are typically realized as a truncated or windowed version of the ideal Hilbert transform impulse response [5-7]. Therefore, Hilbert transformers covering a wide range of different band pass regions are highly desirable.

Compared to electrical Hilbert transformers that suffer from intrinsic bandwidth bottlenecks, photonic integrated devices have shown advantages in high-speed signal processing. RF photonic Hilbert transformers have been proposed based on fiber Bragg gratings [9-15], micro-ring / micro-disk resonators [16, 17], and integrated reconfigurable microwave processors [18]. However, most of these schemes focus on generating the Hilbert transform of the complex optical fields rather than the actual RF signal. In order to realize highly reconfigurable RF photonic Hilbert transformers, transversal schemes with a high reconfigurability have been investigated [19, 20]. However, the use of multiple discrete laser sources presents limitations in the overall system footprint, processing performance, and the potential for full monolithic integration.

Recently, micro-combs that offer a large number of coherent wavelengths from one compact device have attracted significant interest as a fundamentally powerful tool for microwave processing [8, 21-40]. They have been used for various advanced signal processing [8, 41-64] and neural networks [65-67]. In Ref. [1], we reported a fractional Hilbert transformer with a RF bandwidth ranging from 5 to 9 octaves depending on the fractional order. It was based on a soliton crystal micro-comb with FSR = 48.9 GHz, and 17 taps were selected from the 75 wavelengths generated in the C band as discrete taps.

In this paper, we further demonstrate a photonic Hilbert transformer with variable bandwidth and RF center frequency [1]. It is based on a transversal filter system with a soliton crystal Kerr micro-comb source. In the experimental demonstration, we used 40 comb lines in the C-band [1]. By programming and shaping the comb lines according to calculated tap weights,

the center frequency of Hilbert transform was tuned from baseband to 9.5 GHz, and the bandwidth of RF amplitude and phase responses was tuned from 1.2 to 15.3 GHz, confirming the high reconfigurability of our system. The experimental results show good agreement with the theory, confirming the feasibility of our approach towards the realization of high-speed reconfigurable Hilbert transformers with reduced footprint, lower complexity, and potentially reduced cost.

OPERATION PRINCIPLE

The figure.1 shows is a schematic diagram of a Hilbert transformer based on a micro-comb. The micro-comb is produced on a high-Q MRR by pumping. The CW laser is used and the EDFA is used to amplify the MRR whose polarization state is aligned with the TE mode. When the pump wavelength is manually swept across one of the resonances of the MRR and the pump power is large enough to generate sufficient parameter gain, the optical parameter oscillation will occur, and finally a Kerr frequency comb with a spacing equal to the MRR free spectral range will be generated.

The spectral transfer function of a general fractional Hilbert transformer is given by [1, 8]:

$$H_P(\omega) = \begin{cases} e^{-j\varphi}, & \text{if } 0 \leq \omega < \pi \\ e^{j\varphi}, & \text{if } -\pi \leq \omega < 0 \end{cases} \quad (1)$$

where $j = \sqrt{-1}$, $\varphi = P \times \pi / 2$ denotes the phase shift, P is the fractional order (when P = 1, it becomes a standard Hilbert transformer). The corresponding impulse response is given by a continuous hyperbolic function:

$$h_P(t) = \begin{cases} \frac{1}{\pi t}, & t \neq 0 \\ \cot(\varphi), & t = 0 \end{cases} \quad (2)$$

This hyperbolic function is truncated and sampled in time with discrete taps for digital implementation. The null frequency is given by:

$$f_c = 1/\Delta t \quad (3)$$

where Δt denotes the sample spacing. The coefficient of the tap at $t = 0$ can be adjusted to achieve a tunable fractional order [1]. The normalized power of each comb line is:

$$P_n = \frac{1}{\pi|n-\frac{N}{2}+0.5|} \quad (4)$$

where N is the number of comb lines, or taps, and $n = 0, 1, 2, \dots, N-1$ is the comb index.

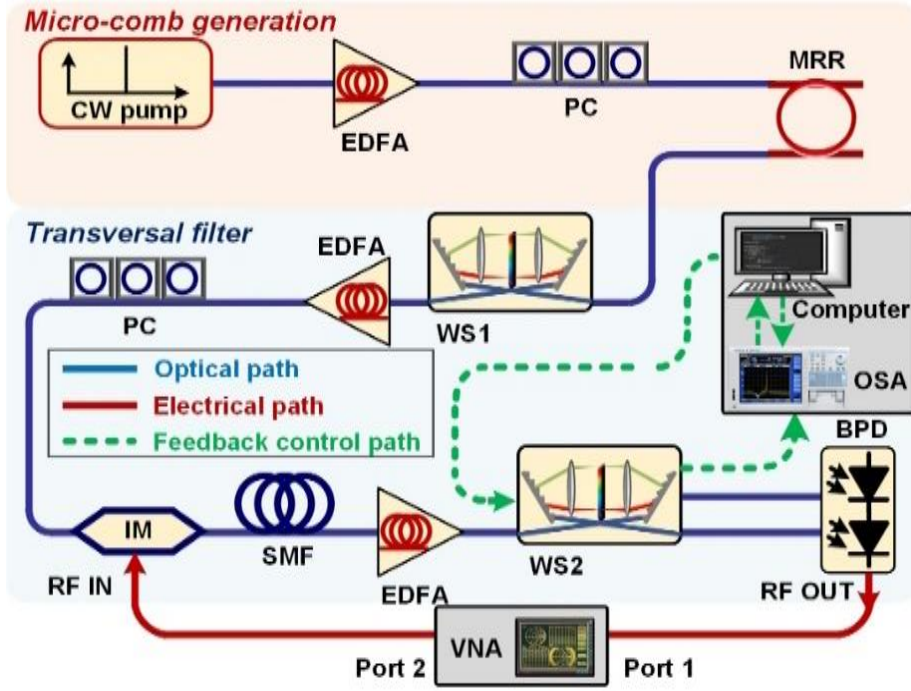


Fig. 1. Schematic diagram of fractional Hilbert transformer based on an integrated Kerr micro-comb source. EDFA: erbium-doped fiber amplifier. PC: polarization controller. MRR: micro-ring resonator. WS: WaveShaper. IM: Intensity modulator. SMF: single mode fiber. OSA: optical spectrum analyzer. BPD: Balanced photodetector. VNA: vector network analyzer.

In order to scale the bandwidth of the standard and fractional Hilbert transformers, we design the spectral transfer function of the Hilbert transformer through the Remez algorithm [69], and change the operating bandwidth by multiplying the corresponding impulse response with the cosine function. Therefore, the resulting discrete impulse response becomes:

$$h_{TBWHT}(n) = P_n \cdot \cos(2\pi n \cdot f_{BW}) \quad (5)$$

where f_{BW} is the scalable bandwidth. To further switch the centre frequency of the Hilbert transformer, the tap coefficients were multiplied by a sine function to shift the RF transmission spectrum. The corresponding discrete impulse response is given by

$$h_{TCFHT}(n) = P_n \cdot \sin(2\pi n \cdot f_{BW}) \quad (6)$$

we use the transverse method to realize the Hilbert transformer with RF center frequency and variable bandwidth. The transfer function [1, 8, 9, 70-78] can be described as:

$$F(\omega) = \sum_{n=0}^{M-1} h(n) e^{-j\omega n T} \quad (7)$$

where M is the number of taps, ω is the RF angular frequency, T is the time delay between adjacent taps, and $h(n)$ is the tap coefficient of the n th tap.

EXPERIMENTAL RESULTS

The MRR used here is manufactured on the platform based on Hydex glass [30, 33, 34, 38, 39] using CMOS manufacturing process. First, use PECVD to deposit Hydex film ($n \sim 1.7$ at 1550 nm), and then pattern by deep ultraviolet (UV) and reactive ion etching [79] to obtain waveguides with very low surface roughness. Finally, the upper cladding layer composed of silicon dioxide ($n \sim 1.44$ at 1550 nm) is deposited. The main advantage of our platform is that it has ultra-low linear loss ($\sim 0.06 \text{ dB} \cdot \text{cm}^{-1}$) and moderately high optical nonlinear parameters ($\sim 233 \text{ W}^{-1} \cdot \text{km}^{-1}$). Because the platform has ultra-low loss, our MRR has a Q factor of up to about 1.5 million. The radius of the MRR is $\sim 592 \mu\text{m}$, which corresponds to an optical FSR of 0.393 nm or 48.9 GHz. Such a small FSR greatly increases the number of wavelengths available on the C-band, up to 75 wavelengths, which is more than twice that of our previous results [58].

In order to generate the micro-comb, the CW pump power is amplified to $\sim 30.5 \text{ dBm}$. When the detuning between the pump wavelength and the cold resonance of the MRR becomes small enough so that the cavity power reaches the threshold, modulation instability will occur (MI) driven oscillation [23]. Then the main comb is generated, the spacing of which is determined by the MI gain peak value. As the detuning changes, it forms a spectrum similar to that reported by the spectral interference between the solitons that are closely packed in the cavity, that is, the soliton crystal [27-29]. This crystal is mainly used as the basis of radio frequency oscillators with low phase noise [80].

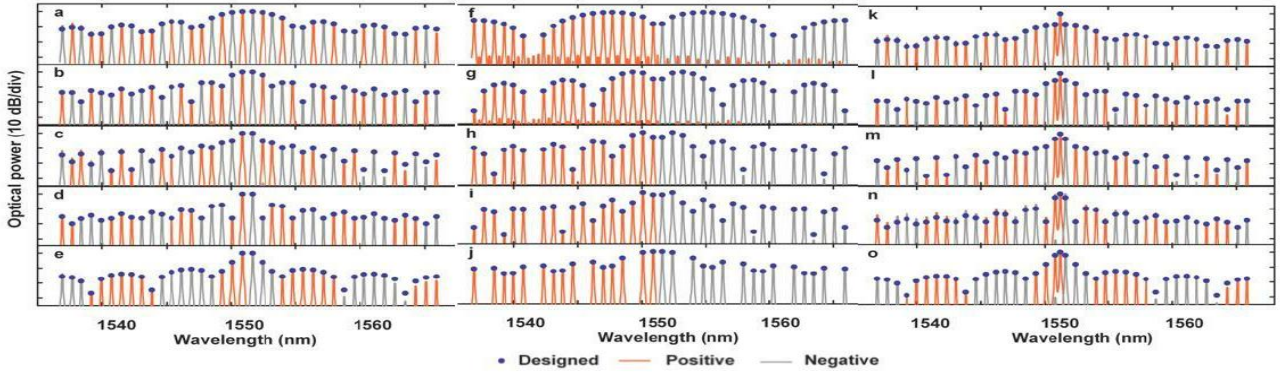


Fig. 2. Designed and measured optical spectra for (a)~(e) Tunable bandpass Hilbert transformer with 90-degree phase shift. (f)~(j) Tunable lowpass Hilbert transformer with 90-degree phase shift. (k)~(o) Tunable bandpass fractional Hilbert transformer with 45-degree phase shift.

The soliton crystal is first flattened by a spectrum shaper (wavelength shaper 4000s), and then modulated with an RF input signal to broadcast the RF waveform to all wavelength channels at the same time, generating 75 replicas, but we only use 38 or 39 of them as taps. The 98 GHz interval ($2 \times 48.9 \text{ GHz}$), through 3.84 kilometers of standard single-film fiber (SMF), provides a progressive time delay between wavelengths. The fibre was approximately twice as long as that used in [58] in order to yield comparable RF bandwidths. The dispersion of the SMF was $\sim 17.4 \text{ ps/nm/km}$, corresponding to a time delay $\Delta t = 26.25 \text{ ps}$ between adjacent wavelengths. Next, the second WaveShaper accurately shaped the comb power according to the designed tap coefficients, with the shaped comb spectrum shown in Fig. 2, for the integral order (90 degree phaseshift) tunable bandpass (a)~(e), integral order (90 degree phaseshift) tunable lowpass (f)~(j), and tunable fractional order (45 degree phaseshift) bandpass filter (k)~(o). Note that all devices used a $\sim 100 \text{ GHz}$ tap spacing (or more precisely $48.9 \times 2 = 97.8 \text{ GHz}$), yielding 39 tap lines across the C-band. Note the fractional order device used an extra single tap line at the centre wavelength, yielding 40 wavelengths overall, with the centre 3 wavelengths then being spaced at 48.9 GHz. The result was that the Nyquist zone for the fractional device was 24.5 GHz rather than 48.9 GHz for the integral order devices. For standard Hilbert transformer, this extra specific tap coefficient is not needed and so in principle the full 48.9 GHz comb (75 lines over the C-band) could have been used although these results are not shown here.

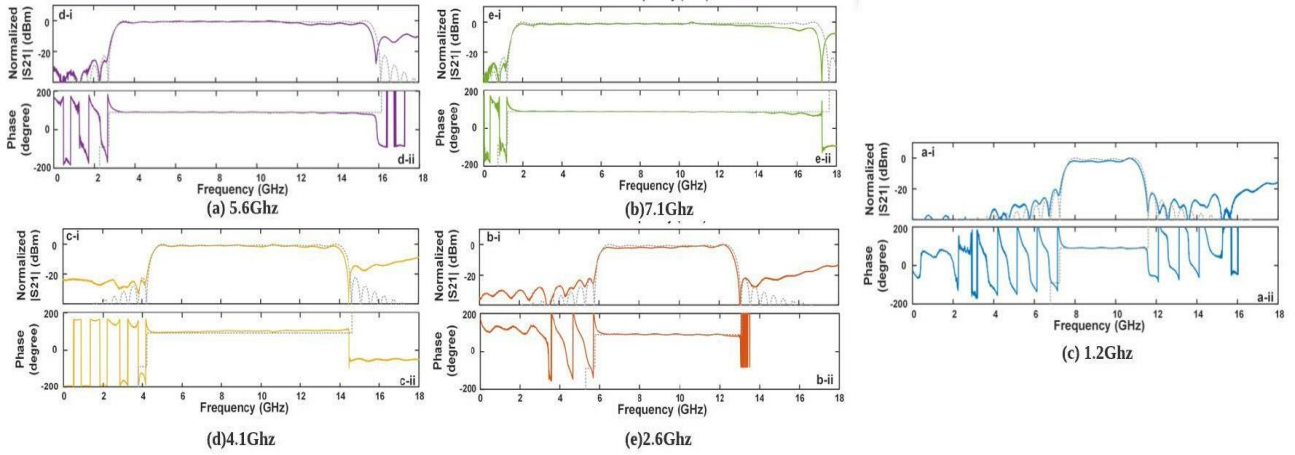


Fig. 3. Simulated (dashed curves) and experimental (solid curves) results of tunable lowpass Hilbert transformer with 90-degree phase shift.(a. purple 5.6 GHz ,b. green 7.1GHz, c. blue 1.2GHz, d. yellow 4.1GHz and e. red 2.6GHz)

The wavelength channels for both positive (solid red line) and negative (solid grey line) taps were separately measured by an optical spectrum analyser (OSA), achieving good performance that agreed well with the theory (blue dot). Finally, the weighted and delayed replicas were combined and converted back into the RF domain via a balanced photodetector (Finisar BPDV2150R).

The system RF frequency response was characterized with a calibrated vector network analyser (VNA, Agilent MS4644B) to measure the RF transmission and phase response. Fig. 3 (a-e) presents the simulated (dashed curves) and measured (solid curves) RF frequency response for both the magnitude and phase of the standard Hilbert transformer, yielding variable bandwidths ranging from 3.4 to 15.3 GHz. The centre frequency of the Hilbert transformer was set into half of the FSR_{RF} , which was $19/2 = 9.5$ GHz in our case.

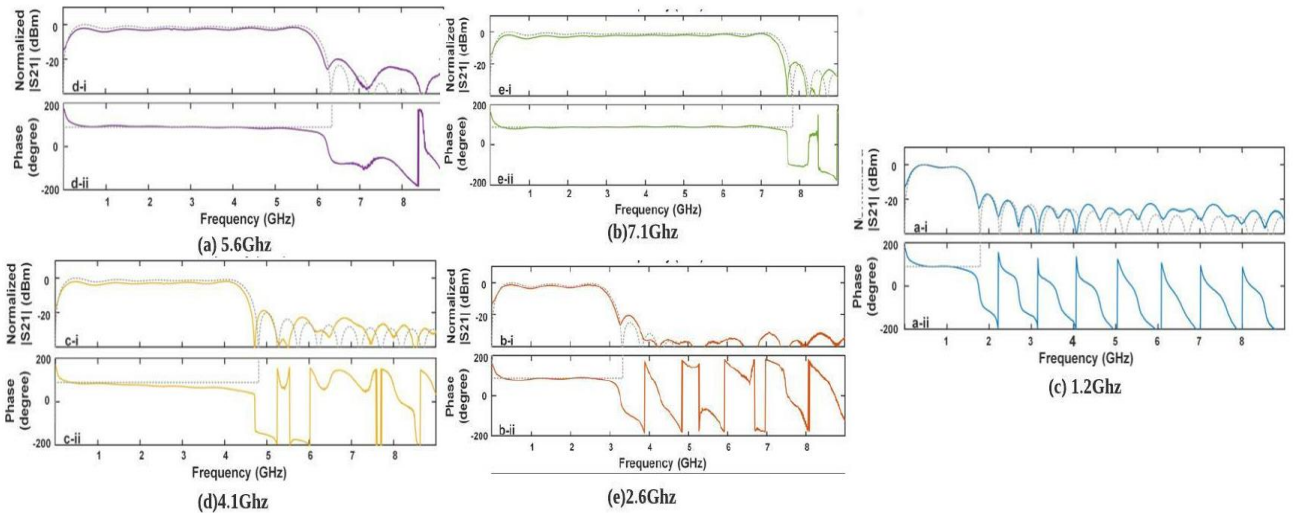


Fig. 4. Simulated (dashed curves) and experimental (solid curves) results of tunable bandpass Hilbert transformer with 90-degree phase shift. (a: purple, 5.6 GHz. b: green, 7.1 GHz. c: blue, 1.2 GHz. d: yellow, 4.1 GHz. e: red, 2.6 GHz.)

Figure.4 shows the measured results for the RF amplitude and phase response of the lowpass Hilbert transformer, showing tunable bandwidths ranging from 1.2 to 7.1 GHz that match closely with the simulated results. We also performed a demonstration of a fractional Hilbert transformer with switchable RF bandwidths ranging from 3.5 to 15.2 GHz. The

simulated and measured RF amplitude and phase responses are shown in Fig. 6. We achieved a fractional order of 0.5, which corresponds to a 45-degree phase shift, using up to 39 wavelengths or taps. The increased number of taps used here compared with our previous work (39 here versus 17 taps in [58]) only resulted in an increase in overall bandwidth of about 0.6 GHz, although the performance in octaves was improved a bit more than this (5 octaves for 17 taps versus 6.3 octaves achieved here, as shown in Table I). These results have significant implications for the broader field of microwave photonics [81-127] including the wider use of micro-comb sources, [128-241] even potentially for applications in the mid-IR [242-248] since this approach has a wide range of microwave and RF applications and functions.

Table 1. Calculated performance of the standard Hilbert transformer

	4 taps	16 taps	38 taps	80 taps
Lower cutoff frequency (GHz)	16.3	17.9	18.2	18.4
Upper cutoff frequency (GHz)	2.2	0.5	0.2	0.1
3-dB bandwidth (GHz)	14.1	17.4	18	18.2
Octaves	2.9	5	6.3	7.4

CONCLUSION

We demonstrate a photonic Hilbert transformer with variable bandwidth and RF center frequency. Up to 39 wavelengths or taps are used, enabling tunable bandwidths from 1.2 to 15.3 GHz and switchable center frequencies from baseband to 9.5 GHz. Dynamic adjustment of bandwidth and center frequency is achieved by changing the tap weights. This micro-comb-based approach provides a solid foundation for the realization of fully integrated photonic signal processors in future ultra-high-speed RF systems.

Competing interests: The authors declare no competing interests.

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