Design of continuously-tunable photonic fractional Hilbert transformer based on a high birefringent planar Bragg grating

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Abstract—**A wideband and continuously tunable integrated fractional order photonic Hilbert transformer is proposed and demonstrated. The device is realized by a simple apodised Bragg grating within a germano-borosilicate high birefringent planar substrate, achieving a 120GHz operating bandwidth and fractional order tuning capability. The order of photonic Hilbert transform can be constantly controlled by changing the polarization state of input light. Schematic design and properties of the device are presented and discussed**

Keywords-component; Integrated Optics; Optical Signal Processing; Microwave Photonics.

I. Introduction

With the unparalleled advantage of large operating bandwidth and fast operating speed, all-optical signal processing technique has attracted increasing interests of related researchers. Among them, photonic Hilbert transformers (HT), including classic HT and fractional-order HT (FrHT) have been widely used in signal processing such as single sideband modulation and image edge filter. The FrHT offers a new degree of freedom, the fractional order, which can be used for a better characterization of a signal under test, or as an additional encoding parameter [1,2]. In the last few years, various FrHT devices, including using fibre Bragg gratings (FBGs) [3], ring resonators [4], phase shift waveguides [5] and photonic crystal nano-cavities [6], have been proposed and demonstrated. Recently, FrHTs with tunable fractional order have also been reported, for example, using a FBG-based interferometric fiber links [11], an InP–InGaAsP integration structure [7] and micro-ring resonators (MRR) [8]. Nevertheless, the FrHTs based on fiber-based system suffers from the limited operation stability. The reported integrated methods [7,8] require fabrication accuracy and constant environmental control, with operating bandwidth less than 50GHz and restricted time-bandwidth product (TBP) [9].

In this work, we proposed and demonstrated an integrated device to realize wideband and tunable FrHTs within the high-birefringent silica-on-silicon substrate. The high birefringence comes from the Germanium and Boron co-dopant in the sample. This monolithically integrated FrHT provides 120GHz operating bandwidth and narrow central notch. As the proposed device benefits from compact dimension, stable operation, large TBP and continuous tunability, it provides great potentials in all-optical processing applications.

II. Principles and Theories

A. Definition

The Fourier transform of conventional HT is given by Eq.(1):

$$H(\omega) = -j\,\mathrm{sgn}(\omega) \tag{1}$$

Where ω is the angular frequency and where sgn(ω) is the sign function (which is +1 for ω>0, 0 for ω=0 and otherwise). When a conventional HT is transformed into a FrHT, the Fourier transform can be given by Eq.(2):

$$\begin{aligned} H_{Fr}(\omega) &= \cos(\varphi) + \sin(\varphi)\,[-j\,\mathrm{sgn}(\omega)] \\ &= \cos(\varphi) + \sin(\varphi)\,H(\omega) \end{aligned} \tag{2}$$

Where $\varphi=\rho*\pi/2$ and ρ is defined as the fractional order. It is obvious in Eq.(2) that the FrHT is a weighted sum of the original signal and the Hilbert transformed signal.

B. Fractional Order Tuning

A highly birefringent planar Bragg grating can be used, to obtain the weighted sum of transformed TM-mode light and non-transformed TE-mode light. The fractional order can be adjusted through the control of the input light, by using a polarization controller and a polarizer. The schematic diagram of the tuning process is shown is Fig.1. The micro-heater for thermal tuning is aimed to compensate the phase difference between TE and TM modes through propagation, similar to the concept of literature [8] where the birefringence of MRR sample is employed.

Supported by the National Natural Science Foundation of China (NSFC 61404056).

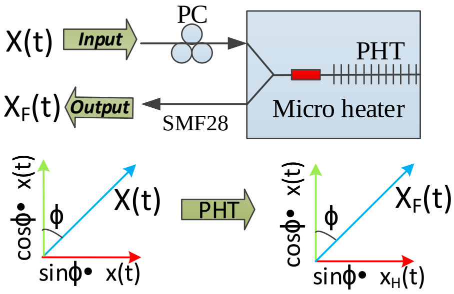

Figure.1 Schematic diagram of the proposed device and fractional order tuning process. PHT: photonic Hilbert transformer; PC: polarization controller.

III. SIMULATION AND DISCUSSION

Using the above-mentioned principle and the grating coupling mode equations, the Matlab software is employed to simulate the frequency responses of both TM-mode and TE-mode and the output of the FrHT in time domain. Based on our previous work [10], a silica-on-silicon wafer with a photosensitive germano-borosilicate planar core layer achieves a significant difference of 5×10^{-4} between the effective refractive indices of the TM-mode and the TE-mode, under phase matching condition for 1550nm wavelength, thus leading to a displacement of ~0.5nm between two grating central wavelengths.

Considering the parameters of the high birefringent waveguide, the Hilbert transform grating is set to 23mm long, operating bandwidth Δf=250GHz, refractive index modulation depth Δn_{max}=0.0006, the TE mode effective index n_{eff}=1.4478 in simulation. The spectrum responses of TE and TM modes are shown by the blue solid curve and the yellow spotted curve in Fig.2. The overlapping area boxed out by blue dashed line in Fig.2 is the working area where the sum of weighted original and transformed signal can be realized, i.e. realizing tunable FrHT.

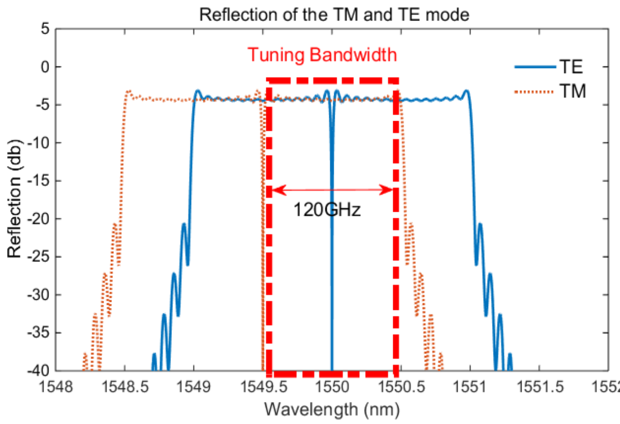

Figure.2 The spectrum response of both TM and TE modes (the yellow spotted curve and the blue solid curve) and the spectrum of the input pulse (the blue dashed curve)

Situations with different input light polarization states are simulated by the Matlab. The frequency responses including amplitude and normalized optical phase for proposed planar grating based FrHT (with the fractional order ρ of 0.5 and 0.8 for instance) are shown in Fig.3.

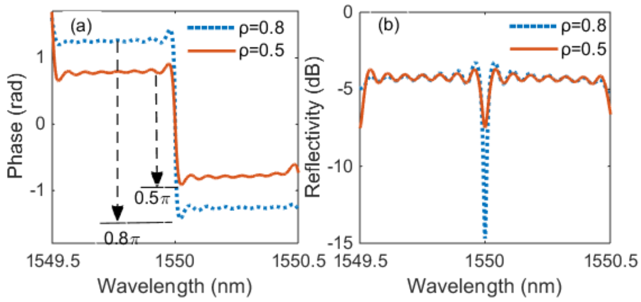

Figure.3 Simulated frequency response for the proposed device. (a) Phase response with fractional order ρ=0.8 and 0.5; (b) Amplitude response with ρ=0.8 and 0.5.

To further analyse the time-domain characteristics of the proposed tunable device, a Gaussian pulse with full-width-half-maximum (FWHM) of 20ps (equivalent to ~50GHz) is used as a input optical signal waveform. The simulated impulse response in time domain is shown in Fig.4 below. From Fig.4, it is obvious that the simulated results are well matched with the ideal FrHT.

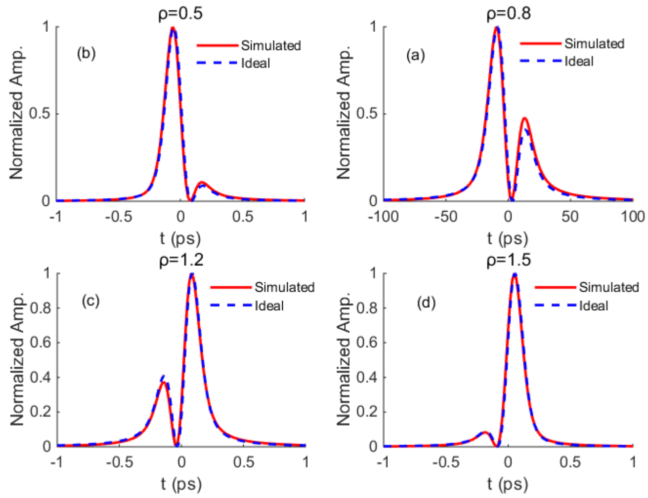

Figure.4 Simulation results (red solid curve) of the output pulse for the proposed tunable FrHT with different ρ. (a) ρ=0.5; (b) ρ=0.8; (c) ρ=1.2; (a) ρ=1.5. Ideal FrHTs with corresponding orders are also plotted (blue dashed curve).

Considering the dispersion effect caused by the refractive indices difference of TE and TM, the outcome of the device would lead to phase mismatch between the two modes， similar to the (polarization mode dispersion) PMD influence. Hence, a tunable micro-heater was introduced in the waveguide to compensate PMD as shown in Fig.1.

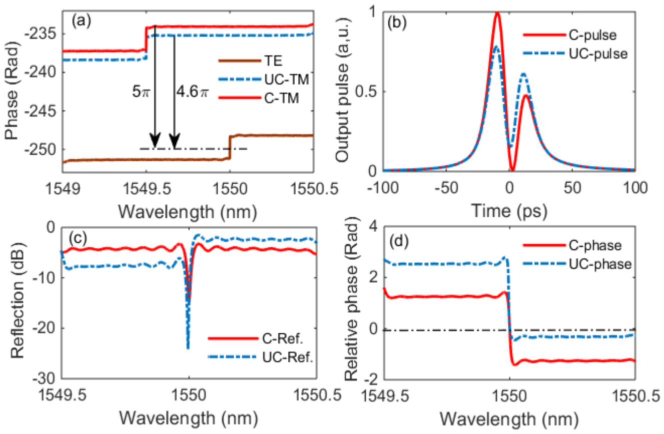

Figure.5 (a) Schematic graph of the phase compensation; (b) Outputs pulse of the compensated (C) and uncompensated (UC) FrHTs with 0.8 fractional order; (c) Reflection spectrum of the C and UC devices; (d) Phase response of the C and UC devices, where C-results and UC-results are plotted in red curves and dashed blue curves respectively.

In the design of the device, a micro heater is used for PMD compensation as to change the length of path length to adjust the phase difference between the TM and TE modes. As shown in Fig.5(a), the original phase difference is about 4.6 π (which is mismatched), while the compensated phase difference is exactly 5π (matched). Fig.5(b) shows the output pulse for the compensated 0.8-order-FrHT (red curve), which is well matched with ideal FrHT, as the same as in Fig.4. In comparison, the mismatched output (blue dashed curve) is distorted. In addition, Fig.5(c) and (d) show the amplitude and phase response of the proposed FrHT respectively. It is obvious that the frequency response after compensation is well matched with ideal FrHT.

This proposed planar waveguide based tunable FrHT presents favorable frequency and time-domain responses for a ultra-fast Gaussian pulse with 20ps FWHM duration, well matched with corresponding ideal FrHTs. As shown in Fig.(2) the proposed FrHT could have around 120GHz maximum bandwidth and around 2.5GHz (~0.02nm) central notch bandwidth, i.e. TBP of 40, a substantial operating range. Compared to the previous work [7-9], planar Bragg grating in this work shows improved temperature insensitivity and has a larger working bandwidth of around 120GHz. Furthermore, unlike the photonic differentiation, this FrHT device could be utilized for the instant and distinctive edge detection of the ultrafast optical signal.

IV. Conclusion

In conclusion, we have theoretically demonstrated the 120GHz-bandwidth continuously-tunable integrated FrHT using a high birefringent planar Bragg grating. The polarization state of the input light could be adjusted, giving the weighted sum of transformed TM-mode light and non-transformed TE-mode light. With advantages of simple layout, stable operation as well as large bandwidth, the proposed FrHT device could have great potential in future all-optical signal processing applications.

Acknowledgment

The authors thank the theoretical discussion and lab assistance of Prof. Y. Yu from Wuhan National Laboratory of Optoelectronics, Huazhong University of Science and Technology, China.

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