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 microring 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):

\[ H(\omega) = -\text{sgn}(\omega) \]

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

\[ H_{Fr}(\omega) = \cos(\varphi) + \sin(\varphi) \left[ -\text{sgn}(\omega) \right] \]

\[ = \cos(\varphi) + \sin(\varphi) H(\omega) \]

Where \( \varphi = \rho \times \pi / 2 \) and \( \rho \) 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).
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 $5 \times 10^{-4}$ 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 $\Delta f=250$GHz, refractive index modulation depth $\Delta n_{\text{max}}=0.0006$, the TE mode effective index $n_{\text{eff}}=1.4478$ 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.

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 an 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.

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.
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.

References