Micro-machining for TE/TM mode phase matching in high-birefringence planar waveguide and implementation in continuously-tunable Fractional Hilbert transform

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Abstract: A continuously-tunable fractional Hilbert transformer based on a high-birefringence planar silica waveguide is demonstrated. The fractional transform order is precisely controlled, with TE/TM phase-matching via a precision dicing technique.
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1. Introduction

The fractional-order Hilbert transform (FrHT) has been explored in signal processing, with a new degree of freedom, the fractional order, which can be further implemented for secure communication systems [1, 2]. Various photonic FrHT devices utilizing fiber Bragg gratings (FBGs) [3], ring resonators [4], phase shift waveguides [5] and silicon nano-cavities [6], have been proposed and demonstrated. Recently, tunable FrHTs have also been reported, for example, using FBG-based interferometric fiber links [7], InP-InGaAsP integration structures [8] and micro-ring resonators (MRRs) [9]. Nevertheless, FrHTs based on the fiber-based system [7] suffers from complexity and limited stability. The reported integrated methods [8,9] require fabrication accuracy and constant environmental control, with limited operating bandwidth less than 50GHz and restricted time-bandwidth product (TBP).

This paper presents ultra-precious micro-machining for TE/TM mode phase matching in high-birefringence planar silica-on-silicon waveguides, to realize an integrated continuously-tunable fractional Hilbert transform device. Compared with other existing methods, our integrated FrHT has unique advantages of compact dimensions, stable operation, large TBP and continuous tuning capacity [10]. As the high-birefringence generates polarization mode dispersion [11], the essential phase matching between TE mode and TM mode by the length of the optical waveguide is investigated. In this work, the micromachining dicing technique [12] is used to change optical path by dicing a micron thin layer from the waveguide input facet and achieving favorable phase matching experimentally.

2. Principle and theory

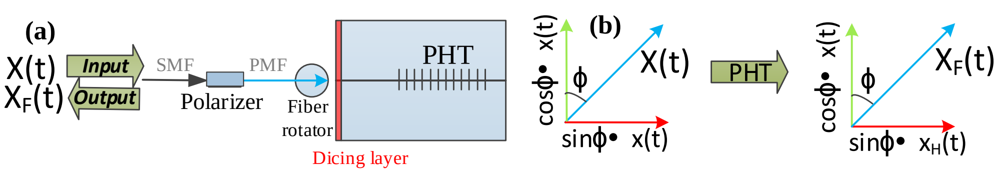

Fig.1 Schematic diagram of the proposed device (a) and fractional order tuning concept (b).

The transfer function of the FrHT in frequency domain is given by [2, 7]

$$H_{Fr}(\omega) = cos(\varphi) + sin(\varphi)\,[-jsgn(\omega)] = cos(\varphi) + sin(\varphi)\,H(\omega) \qquad (1)$$

with $\varphi=\rho*\pi/2$ and where ρ is defined as the fractional order. It is obvious from Eq. 1 that the FrHT is a weighted sum of the original signal and the Hilbert transformed signal. The proposed FrHT device is schematically shown in Fig.1 (a) and the tuning process is conceptually presented in Fig.1 (b). In this work, a highly birefringent planar Bragg grating is realized to obtain the weighted sum of transformed TM-mode light and non-transformed TE-mode light. The fractional order is adjusted through the polarization control of the input light using the fiber rotator. In Fig.1(a), the machining zone, shown by the red area, is adjusted to tune the TE/TM polarization mode dispersion.

2. Simulation and discussion

Based on the device principle and the grating coupled mode equations, Matlab software is employed to simulate the frequency response of both TM-mode and TE-mode. Based on previous work [11], a silica-on-silicon wafer with a photosensitive germano-borosilicate planar waveguide was fabricated with significant birefringence, 5×10^{-4}, between TM-mode and TE-modes. Bragg gratings fabricated for operation at a wavelength of ~1550 nm leads to a displacement of ~0.5 nm between the two central wavelengths.

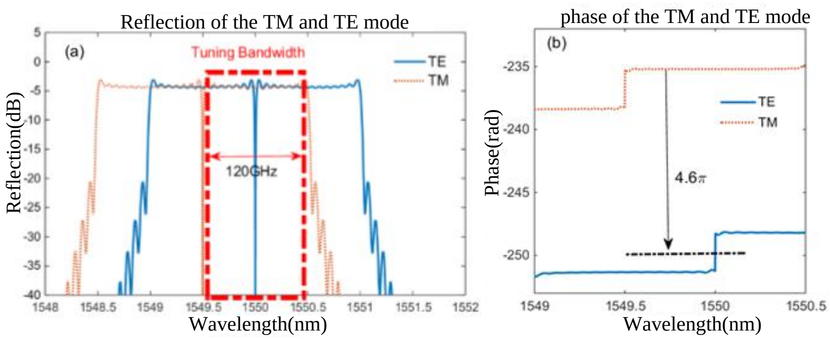

Fig.2 (a) Reflectivity of TE mode (blue solid) and TM mode (red dotted); (b) phase response of TM (blue solid) and TE mode (red dotted).

Fig.2 shows the simulated results of the amplitude and phase response of the proposed FrHT. The red dotted curve and solid blue curve in Fig.2 (a) represent the response of TM and TE modes. There is around 0.5 nm shift of central wavelength at 1550 nm and thus the operating bandwidth is about 130 GHz, as shown by the red dashed box in Fig.2 (a). In addition, the phase difference between the TM and TE modes is calculated as 4.6π in Fig.2 (b). This phase difference caused by the birefringence needs to be adjusted to an integer multiple of 2π, which requires the phase compensation along the optical path, where the micromachining technique is employed in the experiment.

3. Phase matching and spectral response

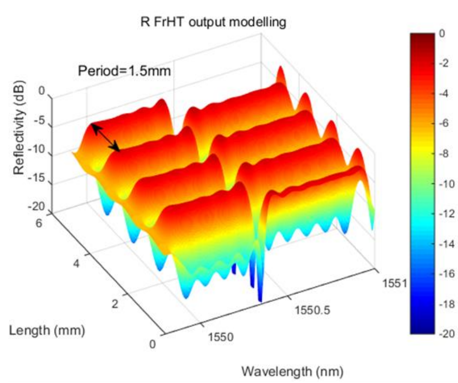

Fig.3 The 3D plot of reflectivity as a function of waveguide length and wavelength.

The phase difference between TE and TM modes is proportional to the optical path when propagating through the waveguide, thus the optical path can be directly changed by dicing a thin layer from the chip facet (red layer region in Fig.1(a)). Precise control through dicing of the waveguide can be used to then compensate the phase difference to integral times of 2π to guarantee the phase condition for FrHT. The calculated relationship between the length of the waveguide and the phase difference between TM and TE modes is given by,

$$\Delta\phi = (k_{TE} - k_{TM})L = \frac{2\pi(n_{eff.TE} - n_{eff.TM})L}{\lambda} = \frac{2\pi\Delta n_{eff}L}{\lambda}. \quad (3)$$

For a 15 mm FrHT waveguide with 30° launching angle (0.67-order FrHT), the simulated 3D result of the reflectivity as a function of waveguide length and wavelength is shown in Fig.3., and it can be seen that there is 1.5 mm period for length change. When the propagating waveguide region in front of the grating region in the chip is diced off, a periodical change in the reflection spectrum could be observed.

Ultra precision dicing techniques for silica photonic device fabrication have been developed [11]. The waveguide with ultra-smooth micron scale features is realized and could be straightforwardly employed for the phase-matching required in this work. In the experiment, the chip facet was precisely diced off with 100 µm increments and the reflective spectrum of the FrHT waveguides was measured. The spectral amplitude change is plotted with phase-mismatch (-0.5π, 0.5π) and phase-match (0π) conditions, and the amplitude results of 0.5-order (45°) and 0.67-order (30°) FrHT for the waveguide with a 15 mm grating are shown in Fig.4. The experimental results show similar shapes and change trends compared with the simulations. To be noted is that the measured amplitude responses are not as flat as the simulated results and contain unwanted extra sidelobes, this is believed to originate from a nonlinear photorefractive response during the grating fabrication. Improved device responses will be presented in the future work.

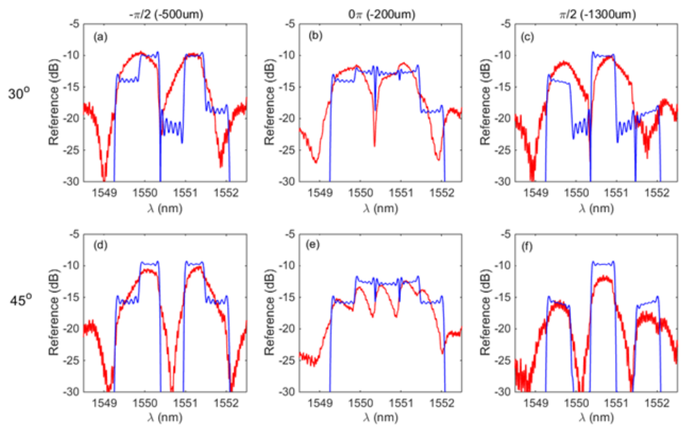

Fig.4 The comparison of the simulated and experimental broadband reflective spectrum of 15 mm FrHT waveguide with 30° and 45° polarization state in the dicing process.

4. Conclusion

The proof-of-principle demonstration of an integrated fractional Hilbert transformer based on a high-birefringent silica-on-silicon substrate has been presented. The TE/TM phase matching condition is discussed and successfully realized by precision dicing of the waveguide. The device reflective amplitude response is experimentally presented.

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