A Photonic Integrated Fractional Hilbert Transformer With Continuous Tunability

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Abstract: A continuously tunable fractional Hilbert transformer based on a photonic integrated chip in an InP-InGaAsP material system consisting of semiconductor optical amplifiers and current injection phase modulators is proposed and experimentally demonstrated.

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1. Introduction

The temporal fractional Hilbert transform (FHT) is a fundamental operator for signal processing that can find important applications, such as in communications systems [1] and digital image processing [2]. Compared with the conventional Hilbert transform (HT), the FHT permits an additional degree of freedom [3]. The FHT is usually implemented in the electrical domain using digital electronics, but with limited bandwidth and operating frequency. Due to the advantages of high speed and broad bandwidth offered by optics, the implementation of a microwave FHT using photonic techniques has been widely investigated recently [4-9]. These approaches can be classified into three categories. In the first category, an FHT was achieved based on a phase-shifted fiber Bragg grating (FBG) [4-6]. In [4], Asghari *et al.* proposed a uniform FBG with a single π phase shift in the middle of the grating to perform the HT. To obtain an FHT, Li *et al.* proposed to use the discrete layer peeling (DLP) method by which the FBG was directly designed based on the target response in the frequency domain corresponding to an FHT transmission function with a phase jump less or greater than π [5,6]. The major limitation of the FBG-based FHT is that the fractional order is not tunable. Once the FBG is fabricated, the order of the FHT is fixed. In the second category, an FHT was achieved in a photonic temporal pulse shaping (TPS) system. In [7], an FHT with tunable fractional order based on TPS was proposed and experimentally demonstrated. The fractional order of the proposed FHT was realized by applying a step function to a phase modulator to introduce a phase jump. Although a tunable fractional order was achieved, the system is complicated and costly due to the requirement of a high speed pattern generator to provide a fast step function. In the third category, an FHT was achieved by using a photonic microwave delay-line filter. A continuously tunable FHT can be implemented based on a multitap uniformly spaced or a nonuniformly spaced photonic microwave delay-line filter [8,9]. The multitap uniformly spaced filter should have negative coefficients which was realized based on polarization-modulation and polarization-modulation to intensity-modulation conversion in an optical polarizer [8]. The tunability of the fractional order was achieved by tuning the coefficient of the zero-th tap. Compared with the multitap uniformly spaced filter, a nonuniformly spaced delay-line filter is easier to implement and less costly since the negative coefficients can be equivalently realized through nonuniform sampling [9]. The FHTs in the three categories are implemented using discrete components with large size and poor stability.

In this paper, we propose a chip-scale tunable FHT in an InP-InGaAsP material system with semiconductor optical amplifiers (SOAs) and current injection phase modulators (PMs). The designed photonic integrated FHT employs a ring structure coupled with a bypass waveguide. The tunable coupling between the ring and the waveguide is realized by a multi-mode interference (MMI) Mach-Zehnder interferometer (MZI) coupler. Within the ring, there are two SOAs providing a peak gain of 9.6 dB per SOA to compensate for the MMI splitting loss and the insertion loss as a total of 3.6 dB. In addition, there is a current injection PM in the ring to achieve tunable working wavelength. The use of the device provides, for the first time, an FHT with both tunable fractional order and tunable operation wavelength in a single photonic integrated chip (PIC). The proposed FHT is fabricated and experimentally verified. The operation wavelength is tunable with a working bandwidth of 27.2 GHz, and the fractional order is also continuously tunable with a tunable range from 0 to 1.

2. Principle

The transfer function of an FHT with an order P is given as [2]

$$H_P(\omega) = \begin{cases} e^{-j\varphi}, & \omega \geq 0 \\ e^{j\varphi}, & \omega < 0 \end{cases} \tag{1}$$

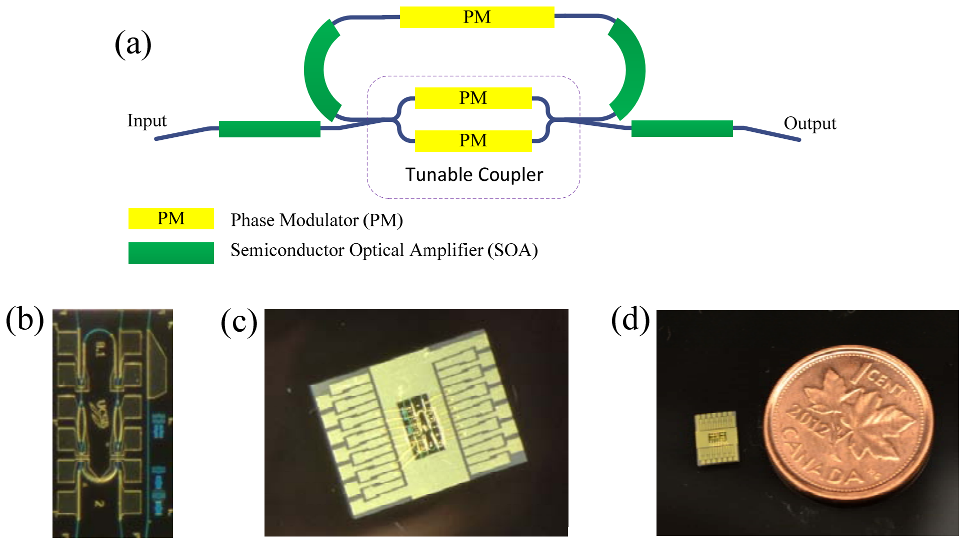

Fig. 1. (a) The schematic of the proposed on-chip FHT. (b) The fabricated on-chip FHT prototype (c) with wire bonding to a carrier and (d) its comparison to a Canadian penny

where $\varphi = P\pi/2$ and P is the fractional order. The FHT becomes a conventional HT when $P = 1$. For $P = 0$, we have $H_0(\omega) = 1$, which means that the signal at the output of the transformer is identical to the input signal. For $0 < P < 1$, the output is a weighted sum of the original signal and its conventional HT.

The FHT with tunable fractional order and central wavelength can be implemented based on a configuration shown in Fig. 1(a), which has a ring structure incorporating two active SOAs and a current injection PM. The frequency response of the ring in Fig. 1(a) can be considered as a periodical narrow-notch filter with its phase response determined by the coupling coefficient between the ring and the waveguide and its free spectral range (FSR) determined by the length of the ring. By locating the central frequency of the input signal at one of these notch filters, an FHT signal can be operated with its fractional order determined by the phase response of the notch filter. In our design, to achieve an FHT with a tunable fractional order and a tunable operating wavelength, the phase response of the notch filter is achieved by a tunable coupler between the ring and the waveguide, which is realized by the MMI MZI coupler in the configuration. By changing the injection current to the PMs in the tunable coupler, the coupling coefficient can be continuously tuned from 0% to 100%, which allows a continuously tunable fractional order from 0 to 1. In order to change the operating wavelength, the notch location of the FSR can be tuned by changing the injection current into the PM in the ring. In this way, an FHT with continuously tunable fractional order and operating wavelength can be achieved. To compensate for the propagation loss and the MMI splitting loss, there are two active SOAs in the ring, and two additional active SOAs at both input and output waveguides are designed to compensate for the fiber coupling losses.

3. Experiment

A prototype of the proposed FHT is fabricated in an InP-InGaAsP material system, as shown in Fig. 1(b), which is wire-bonded to a carrier for experimental demonstration as shown in Fig. 1(c). The chip size is 1 mm by 2 mm, and the comparison of its size with a Canadian penny is shown in Fig. 1(d). In the prototype, the length of the deeply etched waveguide ring is 3 mm. Two 400-µm SOAs with a confinement tuning layer offset quantum well (CTL-OQW) structure are fabricated in the ring to provide a peak gain of 9.6 dB per SOA. With 3 mm of ring length and 1.7 dBcm^{-1} of passive waveguide loss, the total waveguide propagation loss is 1.6 dB. For a ring with 10% cross coupling and 0.5 dB MMI insertion loss, the couplers add about 2 dB of loss for a total round-trip loss of 3.6 dB, which is compensated for by the two 9.6 dB max gain SOAs. Two additional active SOAs are incorporated in both input and output waveguides to compensate for the fiber coupling losses. In addition, the waveguides are angled at 7° to minimize the reflections. Phase modulation in the ring and the tunable MMI MZI coupler is accomplished in forward bias via current injection and free carrier absorption through the carrier plasma effect. The PMs in the chip are fabricated with a standard length of 300 µm.

An experiment to validate the FHT is implemented. The FSR of the on-chip FHT is measured to be 27.2 GHz by an optical vector analyzer (OVA, Luna) as shown in Fig. 2(a). By changing the injection current to the PM in the ring, the notch location of the FSR is tuned and the FSR is slightly changed; the phase response corresponding to the

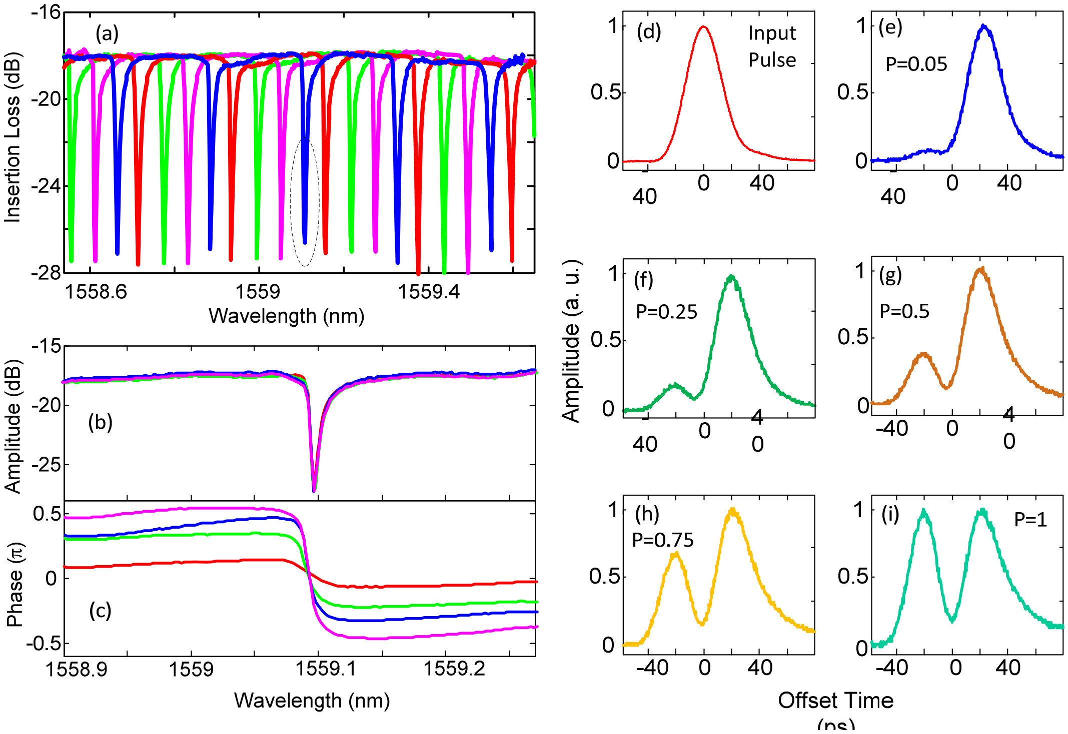

Fig. 2. (a) The spectral response of the proposed on-chip FHT at different injection current of the PM in the ring. (b) The spectral and phase responses of a selected notch at different coupling coefficient. (d) Input signal. FHT signal with a fractional order of 0.05 (e), 0.25 (f), 0.5 (g), 0.75 (h), and 1 (i).

fractional order of the FHT can also be tuned by changing the coupling coefficient, as shown in Fig. 2(b), which is achieved by changing the injection current to the PMs in the tunable MMI MZI coupler. To validate the operation of the FHT, a spectrally tailored Gaussian pulse train as shown in Fig. 2(d) generated by a mode-locked laser (MLL) source (IMRA Femtolite 780) with its central frequency at 1559.1 nm and a bandwidth of 0.2 nm is coupled into the FHT chip. By changing the coupling coefficient through controlling the injection current to the PMs in the tunable coupler, the input signal is fractionally Hilbert transformed with a tunable fractional order from 0.05 to 1, as shown in Fig. 2(e) (f) (g) (h) (i). The fractional order of the proposed FHT can be continuously tunable from 0 to 1.

4. Conclusion

We have proposed and experimentally demonstrated, for the first time to our knowledge, a photonic integrated FHT that provides both continuously tunable fractional order and tunable operation wavelength on a single chip. An FHT with a tuanble fractional order from 0 to 1and a tunable operation wavelength of 27.2 GHz was demonstrated.

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