Realization of visible light integrated circuits for all-optical haar transform

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Abstract
Photonic integrated circuits have been designed, simulated, and tested on TriPleX™ platform technology for implementing optical Haar Transform (HT) in the visible spectrum. Optical circuits contain the new building block (BB), designed using the multimode interference (MMI) structure, performing optical HT on a pair of the optical signals. The Outputs of the BB demonstrate the sum and subtraction of the input signals according to the HT operation. 1st-order and 2nd-order optical HT achieved for the green light input signals. Simulation and experimental results have successfully validated the designed photonic circuits’ capability in implementing optical HT.

Keywords Photonic integrated circuits · Optical Haar transform (HT) · Visible spectrum · TriPleX technology · Multimode interference (MMI)

1 Introduction

All-optical circuits have the benefit of prevailing on the constraints originating from Optical-to-Electrical-to-Optical (OEO) steps such as power consumption, computational requirements, and latency, which is essential for real-time communications. Mathematical spatial transformations can be used for optical signal processing and optical data compression by decreasing or removing redundancies or inessential information (Lim 1990; Misiti et al. 1996; Cabeen and Gent 2007; Li et al. 2014). The most common transform for non-stationary signal analysis and image compression is the Discrete Wavelet Transform (DWT) (Misiti et al. 1996). One of the very suitable wavelet transforms for image processing and compression is Haar transform (HT) (Walker 2008), because of its high efficiency and computational speed (Davis et al. 1987). It also can be easily realized by photonic integrated circuits (PIC) or planar lightwave circuits (PLC) (Okamoto 1999).
Different photonic structures, such as asymmetric directional couplers (Mizumoto and Naito 1990; Takagi et al. 1992; Parca et al. 2013; Pinho et al. 2018) and multimode interference (MMI) couplers (Le and Cahill 2008; Cahill and Le 2009; Le 2010; Pinho et al. 2018b, 2019), can be utilized for implementing different orders of optical HT. One of the material platforms that is transparent in the visible spectral range and can be used for fabrication of optical circuits in the visible spectrum is TriPleX™ platform technology (Leinse et al. 2011; 2013; Wörhoff et al. 2015). This technology is quite appropriate for a lot of applications (Muñoz et al. 2017; Micó et al. 2018; Leinse and Geuzebroek 2019; Leinse et al. 2019) that require low propagation losses over a large wavelength range; however, it presents the drawback of being less mature for large-scale production (Leinse et al. 2013; Wörhoff et al. 2015). TriPleX structures are fabricated with CMOS compatible manufacturing equipment, and the main materials used in these structures are based on the chemical end-products of low-pressure chemical vapor deposition (LPCVD) and plasma-enhanced chemical vapor deposition (PECVD) processes that have stable properties and allow for geometrical design (Leinse et al. 2011; Wörhoff et al. 2015). Two key materials in the TriPleX™ platform technology are the silicon nitride (Si$_3$N$_4$) and silicon oxide (SiO$_2$), which are used as the waveguide core and the waveguide cladding, respectively. TriPleX standard waveguides (WG’s) are realized by multilayer-stack of these materials (Leinse et al. 2013). The same manufacturing process can be used for fabricating different waveguide geometries in terms of etching depth, layer thickness and waveguide width. Three standard geometries of TriPleX WG, i.e., box shape, double-stripe, and single-stripe are presented in Fig. 1 (Leinse et al. 2013).

Fig. 1 Three TriPleX™ geometries, i.e., a box shape, b double-stripe, and c single-stripe, based in (Leinse et al. 2013)
In this paper, we present the design, simulation, and experimental test of the photonic integrated circuits based on the TriPleX waveguide technology implementing all-optical HT at the wavelength of 532 nm (green light), to the best of our knowledge, the first in this spectral range. Optical designed circuits have been validated by the simulation and experimental results. Simulations were performed by OptiBPM software employing the 3D beam propagation method (3D-BPM).

2 Design

The Continuous Wavelet Transform (CWT) for a continuous signal $f(t)$ is given as (Ning et al. 2014):

$$CWT_f(\tau, a) = \frac{1}{\sqrt{a}} \int f(t) h^*(t - \tau/a) dt$$

where $h((t - \tau)/a)$ is the mother wavelet shifted and scaled by variables $\tau$ and $a$, respectively. To discretize the wavelet transform in binary, shift and scale variables are defined as $a = 2^j, j \in \mathbb{Z}$ and $\tau = ka, k \in \mathbb{Z}$ and the mother wavelet is given by (Misiti et al. 1996):

$$h_{j,k} = 2^{-j} h(2^j t - k)$$

Substituting (2) into (1) yields DWT for a discrete-time signal $f(n)$ as (Misiti et al. 1996):

$$DWT_f(j, k) = \sum_{n \in \mathbb{Z}} f(n) h_{j,k}(n)$$

HT, like other wavelet transforms, decomposes a discrete-time signal into two sub-signals of equal length: a running average or trend, and a running difference or fluctuation (Walker 2008). For a discrete signal $f$ with the length of $N$, the first running average $a^1$ and the first running difference $d^1$ are given as (Walker 2008):

$$a^1 = (a_1, a_2, \ldots, a_{N/2})$$

$$d^1 = (d_1, d_2, \ldots, d_{N/2})$$

$$a_m = \frac{f_{2m-1} + f_{2m}}{\sqrt{2}} \text{ for } m = 1, 2, 3, \ldots, N/2$$

$$d_m = \frac{f_{2m-1} - f_{2m}}{\sqrt{2}} \text{ for } m = 1, 2, 3, \ldots, N/2$$

The first order of HT is the mapping $H^1$ defined by (Walker 2008):

$$f^H \mapsto F = (a^1, d^1)$$

The HT mapping matrix has a general form of $H^k_{2k \times 2k}$, where $k$ is the order of HT. Transfer matrix of the 2-point 1st-order HT is expressed as (Gonzalez and Woods 2002):
Multiplying the above matrix by two values of a discrete signal gives sum and subtraction signals. In Fig. 2, an optical scheme is illustrated, which has a transfer matrix same as (9). This scheme consists of a 2×2 restricted interference multimode (RI-MMI) coupler (Soldano and Pennings 1995; Berry, Burke 1995; Latunde-Dada and Payne 2008; Leick et al. 2001) with the length of \( L_{\pi}/2 \) along with two \( \pi/2 \) phase shifters placed at its upper arms and can be used to implement 2-point 1st-order optical HT (Le 2010). \( L_{\pi} \), the beat length of two modes in the coupler with the lowest orders, is obtained by (Soldano and Pennings 1995):

\[
L_{\pi} = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_r W_e^2}{3\lambda_0}
\]  

(10)

\[W_{ev} \approx W_e = W_M + \delta W\]

(11)

\[
\delta W = \left( \frac{\lambda_0}{\pi} \right) \left( \frac{n_c}{n_r} \right)^{2\sigma} (n_r^2 - n_c^2)^{-1/2}
\]

(12)

where \( \beta_0 \) and \( \beta_1 \) are the propagation constants of two modes with the lowest orders, \( n_r \) and \( n_c \) are the waveguide core and cladding effective refractive index, \( W_{ev} \) is the coupler effective width considering the lateral penetration for each mode, \( W_e \) is the effective width for the fundamental mode, \( W_M \) is the coupler physical width, \( \lambda_0 \) is the free-space wavelength, and \( \sigma \) equals 0 and 1 for TE and TM mode, respectively.

The mentioned scheme was utilized for the design and realization of a 2-point HT building block (BB) at the wavelength of 532 nm (green light), the basic element in the following designed optical circuits. Our proposed design is based on the single stripe TriPleX (TriPleX_SS) waveguide platform from LioniX company (Wöhrhoff et al. 2015), which is well-matched with the photonic circuits design in the visible spectral range. The design of the photonic circuits is based on the TM mode.

Figure 3 shows the layout of the designed 2-point HT BB which performs 1st-order optical HT on a pair of the optical inputs. As mentioned before, the BB has two main parts: phase shifters and a 2×2 RI-MMI coupler. For realizing the \( \pi/2 \) phase shifters, delay lines phase shifters have been considered (Lorenzo et al. 2000). As shown in Fig. 3, in the designed delay lines phase shifters, \( W_t \) is the width of the wider side of the taper section, \( L_t \) is the taper length and \( L_s \) is the length of the straight section which their values for obtaining a \( \pi/2 \) phase shift,
calculated using the equations in (Lorenzo et al. 2000), are 2.6 μm, 15 and 16 μm, respectively. \( W_{WG} \) is the width of the single mode TriPleX_SS waveguide which equals to 1.6 μm at the wavelength of 532 nm. The first step in designing the 2×2 RI-MMI is to determine the width of the coupler \( W_M \). The distance between upper and lower arms of the MMI section must be 1/3 of the MMI width (Soldano and Pennings 1995); therefore, the width should be determined in such a way that the coupling effect between access waveguides is negligible. Taking into account this fact, we have chosen the width of 18 μm for the MMI section. Using relations (10)-(12), the length of the MMI is calculated as \( L_{M}=L_f/2=828 \) μm. By utilizing the equations reported in (Lorenzo et al. 2000), \( W_T \) and \( L_T \), width and length of the tapers placed in the input and output of MMI section, were obtained as 3.2 and 50 μm, respectively, in a way that higher order modes were not excited in the tapers and they remained single mode. Some parameters of TriPleX_SS waveguide are commercially confidential and can’t be presented here.

The input signals to the upper and lower arms are divided into two signals at the output arms with approximately identical amplitudes. On the other hand, the output signals at the upper arm have almost the same phase, but the output signals at the lower arm have a phase difference of around π. Therefore, at the upper output arm we have the sum, and at the lower output arm we have the subtraction of the input signals, and this is equivalent to the HT operation of the input signals. The BB parameters are listed in Table 1.

The photonic circuit shown in Fig. 4 is an 8-point optical HT circuit, consisting of six HT BBs, that accomplishes 2nd-order optical HT on a linear array of eight optical inputs. This circuit comprises of two sections: (i) in the first section, there are four BBs, each one performs 1st-order HT on a pair of optical inputs. The whole section performs 1st-order HT on the eight inputs and produces four sum signals and four subtraction signals, sum signals enter the second section and subtraction signals are directed to the circuit output; (ii) in the second section, two BBs are carrying out the 2nd-order optical HT on four sum signals coming from the first section. There are two sum signals and two subtraction signals at the output of this section; Therefore, the designed circuit totally generates two sum signals and six subtraction signals.  

**Fig. 3** The layout of the designed optical HT BB
3 Results and Discussion

The designed photonic circuits were fabricated through a LioniX multi-wafer project (MPW) manufacturing process based on the visible single-stripe TriPleX™ technology, and tested/characterized in our laboratory facilities. The 1 × 2 and 1 × 8 splitters were realized at the input of the designed circuits to guarantee the input signals are the same (in amplitude and phase).

A test setup was built up using the available equipment in the laboratory for testing and characterizing the fabricated circuits. A block diagram and a generic overview of the setup are shown in Figs. 5 and 6, respectively. Setup is included the main equipment such
as green light laser source, positioners, v-groove, objective lenses, beam profiler, microscope and single-mode fiber (SMF) pigtails. In the setup, the laser source, the first objective lens and the free space to fiber adapter have been placed on the positioners located at the proper distances from each other to couple the light from free space to the SMF pigtail. The v-groove has been placed on the first positioner and the SMF pigtail connected to the laser source, has been fixed on the v-groove. The fabricated chip including the designed photonic circuits has been fixed on the second positioner and the second objective lens has been located on the third positioner situated at the proper point between the chip output edge and the beam profiler. The first step of the characterization is the coupling of light into the chip circuits. A straight waveguide has been designed in the chip directed from the input to the output which its main purpose is to facilitate the light coupling into the circuits.

Given that the thickness of the TriPleX waveguides is about several tens of nanometers, light coupling from a single-mode optical fiber, placed on the v-groove, into the input waveguide of a circuit was the most difficult part of the test, hardly done by fine-tuning the first and second positioners. Some methods can be realized to improve the light coupling issue, e.g., using of spot size converter (Roeloffzen et al. 2018), micro-lens structures (Scarcella et al. 2017; Marchetti et al. 2019), and single-mode large

Fig. 6 Implemented setup for test and characterization of the fabricated photonic circuits
cross-section waveguides (Zhang et al. 2006). The green light was coupled from the free space laser source to the SMF pigtail by the exact alignment of the laser source, objective lens, and free space to fiber adapter. Newport and BeamOnU3 beam profilers along with the objectives 10x were used to capture output beam profiles of the chip circuits.

Simulation and experimental results for the designed 2-point BB with identical input signals are illustrated in Fig. 7. Simulation results attain an output power of $\sim -0.6$ dBm and $\sim -38.9$ dBm in the upper and lower arms, respectively, and a structure insertion loss (IL) of $\sim 0.6$ dB. Coupling ratios (CR) of 100:0 and 88:12 (Pinho et al. 2019) are achieved from the simulation and experiment, respectively. These results indicate that the designed BB has an acceptable performance in realizing 1st-order optical HT on two optical signals, thus sum and subtraction signals are obtained in the output arms.

Figure 8 shows the simulation and experimental results for the designed 8-point optical HT circuit with the eight identical optical inputs (same amplitude and phase). Simulation results indicate a structure IL of $\sim 1.2$ dB a CR of $\sim 0:0:50:0:0:50:0:0$. Simulated power in the output ports is presented in Table 2. An experimental CR of $\sim 2:3:40:5:4:42:3:1$ is attained for the 8-point circuit. It can be apparently seen from the results that sum operation is obtained in outputs 3 and 6 and subtraction operation is achieved in outputs 1, 2, 4, 5, 7, and 8. As anticipated by the simulations, the experimental power observed in the subtraction outputs is much lower than that in the sum outputs, showing the 2nd-order HT

Fig. 7  a Amplitude of the propagating optical field and b output power beam profiles of the 2-point optical BB
Realization of visible light integrated circuits for all-optical... operation has been appropriately carried out by the designed photonic circuit. The simulation and experimental results for CR of the 2-point BB and the 8-point HT circuit show a discrepancy of 12% and 10%, respectively, due to fabrication error.

**Fig. 8** a Amplitude of the propagating optical field and b output power beam profiles of the 8-point HT circuit

**Table 2** Simulated power in the outputs of the 8-point HT circuit

| Output Arms | Power (dBm) |
|-------------|-------------|
| 1           | − 45        |
| 2           | − 44.1      |
| 3           | − 4.2       |
| 4           | − 45        |
| 5           | − 45        |
| 6           | − 4.2       |
| 7           | − 44.2      |
| 8           | − 44.9      |
4 Conclusions

Photonic integrated circuits were designed based on the TriPleX™ waveguide technology for realizing optical HT in the visible spectral range. An optical building block was designed and implemented using a RI-MMI coupler performing optical HT on a pair of optical signals. Designed optical circuits for the implementation of the 1st-order and the 2nd-order optical HT were fabricated and tested. Experimental results have successfully validated the realization of the optical HT by the designed photonic circuits as anticipated by the simulations.

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Availability of data and material The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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