On-chip Rewritable Phase-change Metasurfaces for Programmable Optical Routing

Sanaz Zarei
Department of Electrical Engineering
Sharif University of Technology
Tehran, Iran
szarei@sharif.edu

***Abstract*—Phase-change materials offer a promising solution to implement programmable photonics. In this work, an on-chip programmable optical router based on rewritable phase-change metasurfaces is inverse-designed and Genetic-algorithmically optimized. The presented router can be created by employing the technique of direct laser writing on a Sb_2Se_3 thin film. The rewritable, nonvolatile, and ultra-compact optical router operates at the wavelength of 1.55µm.**

Keywords—programmable optical router, phase-change metasurface, Sb_2Se_3, direct laser writing

I. Introduction

Integration of low-loss Sb_2Se_3 phase change material with a multi-mode interference device has been accomplished in previous works to realize programmable photonics [1-3]. Delany et al. demonstrated a programmable router based on patterns of weakly scattering perturbations induced by switching of the Sb_2Se_3 [1]. The pixel perturbation pattern was optimized using an iterative scheme [1]. How the performance of the presented programmable router is dependent on the Sb_2Se_3 layer thickness is also investigated by the same group in [2]. Wu et al. presented a programmable multifunctional device capable of both wavelength division multiplexing and mode division multiplexing [3]. The device's function is modified by transferring the inverse-designed phase pattern to the Sb_2Se_3 thin film [3]. Direct laser writing technique is employed in all these proposals to create the desired patterns [4]. Compared to programmable mesh structures that require a constant power supply to operate, these multi-mode interference devices are of interest because of their nonvolatile nature and small footprint.

In the presented study, an ultra-compact programmable router is realized based on the concept of wavefront shaping using a system of cascaded on-chip phase-change metasurfaces. The waveguides, router region, and metasurfaces are directly laser-written on a thin Sb_2Se_3 film. A high level of control over the flow of light can be achieved by metasurfaces design and optimization [5]. The metasurfaces are primarily inverse-designed [6-7] and thereafter optimized by a Genetic algorithm [5].

II. Router Design

The programmable router is designed to perform 1×2 beam splitting. The device footprint is 8.2µm×18.5µm, and it is composed of five one-dimensional (1D) metasurfaces (metalines), each of which consists of 20 meta-atoms (please see Fig. 1(a)). The distance between the adjacent metasurfaces, as well as the distance between the last metasurface and the output line (conjunct with two output waveguides), is 3.5µm. The distance between the input line (conjoint with an input waveguide) and the first metasurface is 1µm. The waveguides are 0.8µm wide, and the output waveguides centers are 3.2µm distant.

The Sb_2Se_3 film is 30nm thick and is coated with a 200nm-thick SiO_2 layer. The SiO_2 topcoat is aimed for the protection and oxidation inhibition of Sb_2Se_3. There is a 330nm-thick Si_3N_4 layer beneath the Sb_2Se_3 film, which lays on a standard oxidized substrate. The router region and waveguides are made of crystalline Sb_2Se_3 (cSb_2Se_3), and the metasurfaces are composed of amorphous Sb_2Se_3 (aSb_2Se_3) rods through a cSb_2Se_3 substrate. Like previous studies [1-4], all these components are created by direct laser writing on Sb_2Se_3.

III. Metas-atom Design

The phase-change metasurface is a one-dimensional array of amorphous Sb_2Se_3 (aSb_2Se_3) rods in the crystalline Sb_2Se_3 (cSb_2Se_3) thin substrate with the lattice constant of 400nm. Each meta-atom consists of a single (aSb_2Se_3) rod. By adjusting the dimensions of the (aSb_2Se_3) rod, the

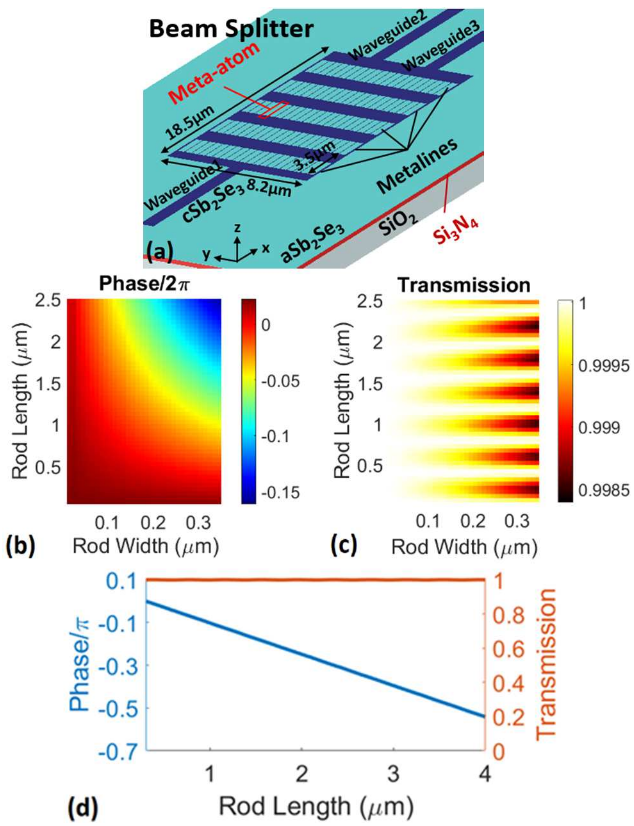

Fig. 1. (a) The schematic of the programmable router implemented in the Sb_2Se_3 thin film using direct laser writing. The electric field transmission phase (b) and amplitude (c) of a meta-atom of the constituent metasurfaces for TE-polarized guided waves versus (aSb_2Se_3) rod's length and width. (c) The transmission amplitude and phase of a meta-atom versus the (aSb_2Se_3) rod's length when the (aSb_2Se_3) rod's width is fixed at 350nm. The diagrams in (b), (c), and (d) are generated using the Lumerical FDTD commercial software package at the wavelength of 1.55µm.

TABLE I. THE UTILIZED HYPER-PARAMETERS IN THE GENETIC ALGORITHM OPTIMIZATIONS.

Split Ratio	Population Size	Selection Rate	Mutation Rate	Cross-over Rate	Reinitialization Rate [5]	Number of Generations in an Optimization [5]	Total Number of Generations	Initial Perturbation Range [5]
50-50	30	20%	20%	40%	20%	20	180	$\{\Delta RL \in [-400nm, 400nm]\}$
100-0	30	20%	20%	40%	20%	20	240	$\{\Delta RL \in [-400nm, 400nm]\}$

transmission amplitude and phase of a meta-atom for TE-polarized guided wave can be acquired. Figures 1(b) and 1(c) depict the transmission phase and amplitude of a meta-atom, respectively, versus the (aSb_2Se_3) rod length and width. If the rod width is fixed to 350nm and the rod length is swept between 300nm and 4µm, the transmission phase changes more than $\pi/2$, with the transmission amplitude very close to 1 (Fig. 1(d)). The simulation results of Fig. 1 are calculated using the Lumerical FDTD commercial software package at the wavelength of 1.55µm, setting the fundamental TE mode for excitation and the x-axis for the injection axis.

IV. RESULTS

The 1×2 programmable router is designed for two target split ratios of 50-50 and 100-0 while keeping the total device transmission as near as possible to 0dB. The system of cascaded metasurfaces is primarily designed using the inverse design method presented in [6-7]. Thereafter, the designed metasystems are further optimized using a Genetic algorithm [5], the hyper-parameters of which are summarized in Table I. In the Genetic algorithm optimizations, the 2.5D variational FDTD solver of the Lumerical Mode Solution is exploited for structural modeling. The variable parameters in the design and optimization are (aSb_2Se_3) rod lengths (RL), which are restricted to be in the range of $300nm \le RL \le 3.4\mu m$. There are 50 variable parameters for the router with the 50-50 split ratio (due to the equivalence of the outputs and the resulting symmetry with respect to y=0) and 100 variable parameters for the router with the 100-0 split ratio that need to be adjusted. Figure 2 illustrates the finally optimized devices and the x-y view of the electric field distribution at the midplane of the Sb_2Se_3 film through these devices. For the router of figures 2(a) and 2(c), the transmission of output waveguides, normalized to a reference straight waveguide, is -4.2dB at the wavelength of 1.55µm, while for the router of figures 2(b) and 2(d), the normalized transmissions of output waveguides are -0.44dB (bottom) and -16.5dB (top).

The cascaded on-chip phase-change metasurfaces provide an alternative means for on-chip wavefront shaping and programmable optical flow control to the ones presented in [1-3]. Compared to the multimode interference devices integrated with Sb_2Se_3 in [1-3], the presented router has a smaller footprint. The presented scheme for realizing programmable photonics takes advantage of the ultralow-loss Sb_2Se_3, ultra-compact footprint, and nonvolatility, which is beneficial compared to programmable mesh structures. Interferometer meshes that are based on thermo-optic effect or electro-optic effect, although underpin many new technologies for fully programmable optical circuits, suffer from large programming energy, large footprint, and volatile nature. Furthermore, the function of the proposed device can be easily changed by erasing and rewriting.

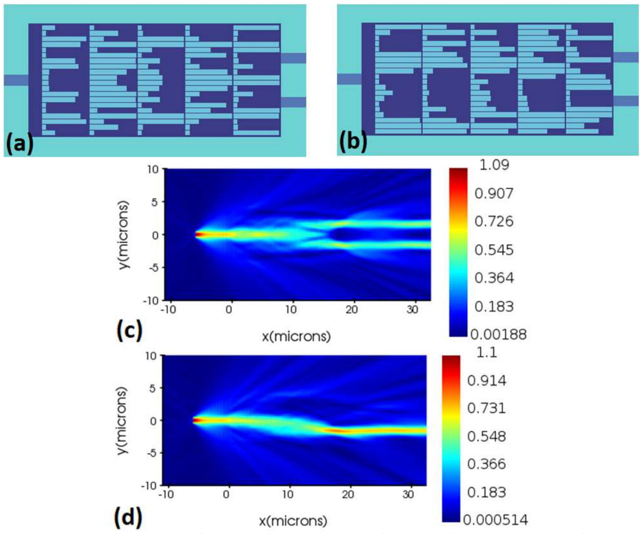

Fig. 2. 2D schematic of the optimized optical router for the target split ratio of 50-50 (a) and 100-0 (b). The x-y view of the electric field distribution at the midplane of the Sb_2Se_3 film through the router designed for 50-50 (c) and 100-0 (d) split ratios.

V. CONCLUSIONS

In summary, an ultra-compact scheme for programmable optical routing with a footprint of 8.2µm×18.5µm is presented. The proposed scheme can be realized by direct laser writing on a Sb_2Se_3 phase-change film. Therefore, it is non-volatile and rewritable, with easy correction of the writing errors by locally erasing and restoring. Inverse design combined with a Genetic algorithm optimization is utilized for the design of a 1×2 beam splitter with different split ratios. This scheme can be used in a variety of applications, such as optical routing, analog computing, and artificial intelligence.

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