Programmable Phase-change Metasurface for Multimode Photonic Convolutional Neural Network

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Abstract — We demonstrate a programmable TE₀-to-TE₁ mode converter utilizing phase change material Ge₂Sb₂Te₅ based phase gradient metasurface integrated on a waveguide. This compact mode converter features high energy efficiency, high precision and broadband performance and is very promising toward a large-scale photonic processor for neural networks.

Keywords—phase-change material, metasurface, optical neural network

I. Introduction

Phase change materials (PCMs) are a very promising type of candidate materials to realize reconfigurable photonic devices as they afford drastic, non-volatile changes in the optical properties such as refractive index and extinction coefficient [1-3]. Meanwhile, integrated phase gradient metasurface structures can be used to control guided waves at subwavelength intervals, showing the advantages such as small footprints and large operation bandwidth [4]. By designing and fabricating the typical PCM material GST into the phase gradient metasurface and utilize the drastic change of GST’s refractive index during phase transition, we demonstrate a phase-change metasurface TE₀-to-TE₁ mode converter (PMMC).

II. Device structure

As illustrated in Figure 1a, a metasurface with a phase gradient \( \frac{d\Phi}{dx} \) formed on top of an optical waveguide enables efficient coupling between different waveguide modes [4]. Once the generalized phase-matching condition, \( k_0 (n_{TE0} - n_{TE1}) = N \cdot \frac{d\Phi}{dx} \), is satisfied, the fundamental TE₀ mode can be converted into TE₁ mode efficiently, where the \( k_0 = 2\pi/\lambda_0 \) is the free-space wavevector, \( n_{TE0} \) and \( n_{TE1} \) are the effective mode index of TE₀ and TE₁ mode, respectively. \( N \) is the number of the interactions between the guided modes and the phase gradient.

Figure 1 (a) Unidirectional phase gradient \( \frac{d\Phi}{dx} \) on top of waveguide converts TE₀ mode into TE₁ mode. (b) SEM image of the whole device. (c) SEM image of the TE₀/TE₁ directional coupler used for output mode component detection. (d) SEM image of the GST phase gradient metasurface before Al₂O₃ encapsulation. (e) Phase of scattered light from a single GST antenna located on a Si₃N₄ waveguide as a function of the antenna length. Shaded area presents the lengths used in phase gradient metasurface. Inset shows the cross-sectional schematic of the antenna structure.
The phase of GST can be precisely controlled all-optically and thus introduced additional turnability into the phase gradient metasurface. Figure 2a shows the controllable output mode purity when a guided TE₀ mode passes through the metasurface. Mode purity for TE₀ (TE₁) mode is defined by \( \beta = P_{TE0} (P_{TE1}) / (P_{TE0} + P_{TE1}) \), where \( P_{TE0} \) and \( P_{TE1} \) are the transmitted power carried by TE₀ mode and TE₁ mode, respectively. When switching the GST from aGST to cGST phase, the PMMC efficiently converts TE₀ mode to TE₁ mode, changing the mode purity from \( \beta_{TE0} > 80\% \) to \( \beta_{TE1} > 85\% \) over a broad bandwidth, showing an excellent agreement with the numerical simulation results. We also measure their power and calculate the difference to determine the mode contrast \( \Gamma = \beta_{TE0} - \beta_{TE1} \), which is used as a programming parameter. Fig. 2b demonstrates the multi-level programmability of the PMMC, in which \( \Gamma \) is sequentially set to 64 distinguishable levels between -73\% to +67\% at 1555 nm.

As shown in Fig. 2c, we design a prototype optical CNN using a small network of PMMCs to implement patch-kernel matrix multiplication to compute convolution. An input image of dimensions \( n \times n \) is convolved with a kernel of dimensions \( k \times k \) to compute an activation map of dimension \( (n-k+1) \times (n-k+1) \). When operating the OCNN, we group the input image into \( (n-k+1)^2 \) patches (the shaded area) with the same dimensions as the convolution kernel, \( k^2 \). Each patch corresponds to the receptive field of an element in the activation map accordingly. The patch matrices of the input image are optically fed into the photonic kernel sequentially while the kernel elements, that is, the PMMCs, are programmed to fixed values. At each timeframe of the computation, the corresponding patch matrix is reshaped into a single column of data with the length \( k^2 \). The data is input into the optical system in \( k^2 \) channels as sequences of incoherent optical pulses, whose power amplitude is controlled by a variable optical attenuator (VOA) to encode the value of each pixel value \( X_i \) in the image. The corresponding element \( W_{ij} \) of the kernel matrix is programmed as the mode contrast \( \Gamma \) of each PMMC. The resulting transmitted power of TE₀ and TE₁ modes are then summed incoherently using two photodetectors. Their difference is calculated electronically and used in post-processing steps. As a result, the output will correspond to a time series of patch-kernel MVM with the amplitude encoding the values of the computation results, which is the activation map of convolution.

Figure 2 (a) The mode purity is controlled by the mode converter to >80\% for both modes. (b) The programmable mode converter controls the mode contrast \( \Gamma \) at 64 distinct levels, corresponding 6-bit programming resolution. Upper inset: zoomed-in view of the contrast levels. Lower inset: histograms of 20 programming operations to set the contrast two adjacent levels (30 and 31). (c) Schematic of optical convolution for image processing. An array of \( k^2 \) PMMC is programmed to store the kernel matrix.

IV. Conclusion

We have demonstrated a programmable waveguide mode converter using GST based phase gradient metasurface. The output mode purity can be controlled by all-optically setting the phase of GST. This compact mode converter shows high efficiency with a broadband performance, hence is potentially suitable for mode- and polarization-division multiplexing which promise to increase the capacity of future optical communication channels. Besides, we built a photonic kernel based on an array of such devices and implemented an optical convolutional neural network.

V. REFERENCES

[1] Rios.C, et al. “Integrated all-photonics non-volatile multi-level memory.” Nat. Photonics 2015, 9 (11), 725-732.
[2] Cheng, Z, et al. “On-chip photonic synapse.” Sci Adv 2017, 3 (9), e1700160.
[3] Feldmann, J, et al. “Calculating with light using a chip-scale all-optical abacus.” Nat. Commun. 2017, 8 (1), 1256
[4] Li, Zhaoyi, et al. "Controlling propagation and coupling of waveguide modes using phase-gradient metasurfaces." Nat. Nanotech. 2017, 12(7)