Automatic Realization of Light Processing Functions for Programmable Photonics

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Abstract— **We propose an automatic technique to implement light processing on a square-mesh programmable photonic circuit. Our method does not require human design knowledge, and can be applied to realize configurations for different light processing functions (e.g., splitting and filtering) at time scales of minutes.**

I. Introduction

Programmable photonic integrated circuits (PPICs) [1], [2], [3], [4] propose run-time manipulation of the flow of light after a photonic chip is fabricated. Such reconfigurability is achieved by controlling active components (e.g., optical phase shifters [1]) with electrical/thermal signals. Due to their programmability, PPICs are suitable for a wide range of applications such as fast prototyping, optical neural networks, and quantum information processing [1]. A PPIC is made up of a mesh of tunable basic units (TBUs) [2] or analog optical gates [1], often implemented as a 2×2 Mach–Zehnder interferometer (MZI) [1], [2].

In this paper, we focus on a recirculating square-mesh PPIC, for which we propose an automatic technique to implement light processing functions such as splitting and filtering. The key component of our approach is that we use scattering matrix theory to extract the analytical gradient of the mean squared error between the real and target circuit response with respect to the tunable optical phase shifts. Consequently, gradient descent optimization can be carried out to obtain a configuration of phase shifts that implements the desired light processing function. Our simulations demonstrate that our method does not require human design knowledge, and can be applied to realize complex light processing functions in a matter of minutes.

II. Proposed Method and Numerical Examples

Following [1], we consider the TBU in the left of Fig. 1. Assume two time-harmonic optical inputs $\{a_1^{(I)}e^{j\omega t}, a_2^{(I)}e^{j\omega t}\}$ are provided, respectively, at the two left ports $\{A_1, A_2\}$. The output can be calculated based on the transfer matrix $\mathbf{F}$:

$$\begin{bmatrix} b_1^{(O)} \\ b_2^{(O)} \end{bmatrix} = \mathbf{F} \begin{bmatrix} a_1^{(I)} \\ a_2^{(I)} \end{bmatrix} = \underbrace{\alpha \cdot e^{-j\omega \frac{n_{\text{eff}}L}{c}}}_{\text{waveguide}} \underbrace{\frac{\sqrt{2}}{2} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}}_{\text{right DC}} \underbrace{\begin{bmatrix} e^{-j\theta} & 0 \\ 0 & e^{-j\phi} \end{bmatrix}}_{\text{PSs}} \underbrace{\frac{\sqrt{2}}{2} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}}_{\text{left DC}} \begin{bmatrix} a_1^{(I)} \\ a_2^{(I)} \end{bmatrix} \tag{1}$$

where α represents the transmission loss introduced by the waveguides and couplers in one TBU (e.g., $\alpha = 0.99$), n_{eff} is the effective index of the propagating mode, L is the length of the waveguide, and $c = 3 \times 10^8$ m/s is the speed of light. We note that since the TBU is a bi-directional and reciprocal device, we can similarly write another equation: $[a_1^{(O)}, a_2^{(O)}]^T = \mathbf{F}[b_1^{(I)}, b_2^{(I)}]^T$. Using a block-diagonal matrix to write these two equations at the same time, we effectively obtain the scattering matrix relation.

Now we adapt this to a system-level square-mesh PPIC. Specifically, we apply scattering matrix theory to the two propagation directions shown in the bottom row of the right-most figure in Fig. 1, yielding:

$$\begin{bmatrix} a_{2i,j}^{(O)} \\ b_{2i,j}^{(O)} \\ a_{2i-1,j}^{(O)} \\ b_{2i-1,j}^{(O)} \end{bmatrix} = \begin{bmatrix} \mathbf{F} & \mathbf{0} \\ \mathbf{0} & \mathbf{F} \end{bmatrix} \begin{bmatrix} a_{2i-1,j}^{(I)} \\ b_{2i-1,j}^{(I)} \\ a_{2i,j}^{(I)} \\ b_{2i,j}^{(I)} \end{bmatrix} \rightarrow \begin{bmatrix} b_{2i-1,j}^{(I)} \\ b_{2i-1,j}^{(O)} \\ b_{2i,j}^{(I)} \\ b_{2i,j}^{(O)} \end{bmatrix} = \mathbf{V} \begin{bmatrix} a_{2i-1,j}^{(I)} \\ a_{2i-1,j}^{(O)} \\ a_{2i,j}^{(I)} \\ a_{2i,j}^{(O)} \end{bmatrix}, \tag{2}$$

where, to obtain the matrix $\mathbf{V}$, we have rearranged terms by moving those related to 'b' to the left-hand side. We emphasize that the entries in $\mathbf{V}$ are completely determined by $\mathbf{F}$ using basic algorithmic operations like $\{+, -, \times, \div\}$. In Eq. (2), we have applied the scattering matrix theory to a vertical TBU, and we can do the same for a horizontal TBU. After writing the equations for both vertical and horizontal TBUs, we find that they together give the scattering matrix from $\{a_{n,j}^{(I)}, a_{n,j}^{(O)}\}$ to $\{a_{n,j+1}^{(I)}, a_{n,j+1}^{(O)}\}$. If we iteratively perform this process M times, we can obtain the total scattering matrix from $\{a_{n,0}^{(I)}, a_{n,0}^{(O)}\}$ to $\{a_{n,M}^{(I)}, a_{n,M}^{(O)}\}$. Most importantly, all involved operations are differentiable, allowing us to analytically trace the gradient of

the PPIC response with respect to any tunable phase shifts. This makes gradient descent optimization possible for realizing complex light processing functions. Due to page limits, here we demonstrate using the proposed method to realize splitting and filtering on a 5×5 square-mesh PPIC in Fig. 2. An interval of length two (e.g., $[-1, 1]$) on the normalized frequency axis is equivalent to a real frequency range of $c/(2n_{\text{eff}}L) \approx 3 \times 10^8$ m/s $/ (2 \times 2.35 \times 250$ µm$) \approx 255$ GHz in our case.
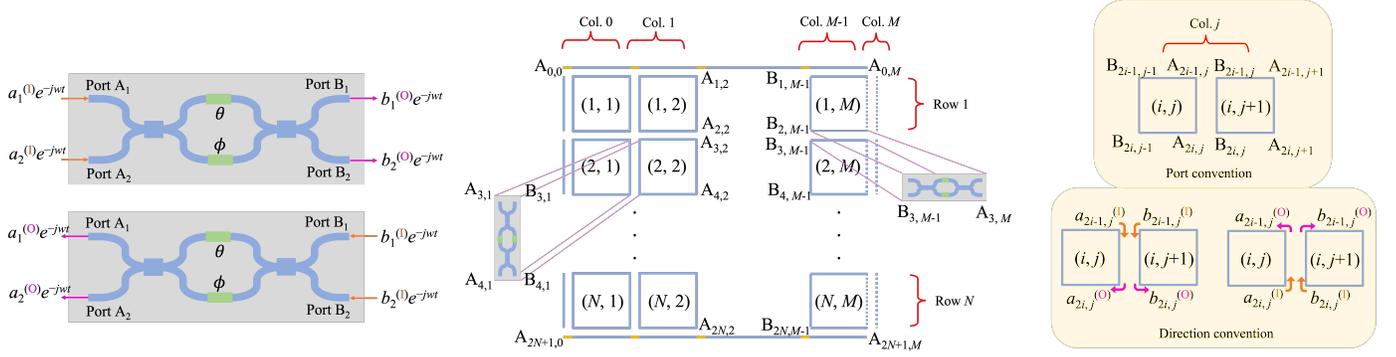

Fig. 1. **Left**: Schematic of a tunable basic unit (TBU), made up of two 50%:50% directional couplers (DCs) on the left and right, and two phase shifters (PSs) parameterized by $\{\theta, \phi\}$ in the middle. The phase shifts $\{\theta, \phi\}$ could be adjusted freely in $[0, 2\pi)$. **Middle**: Schematic of a $N \times M$ square PPIC. For derivation simplicity, we ignore the TBUs at the right-most column marked by dashed lines and assume the orange lines are ideal. **Right**: Naming conventions for port and direction. Capitalized 'A' and 'B' should be regarded as port names, and small 'a' and 'b' are the complex magnitudes ahead of $e^{-j\omega t}$.
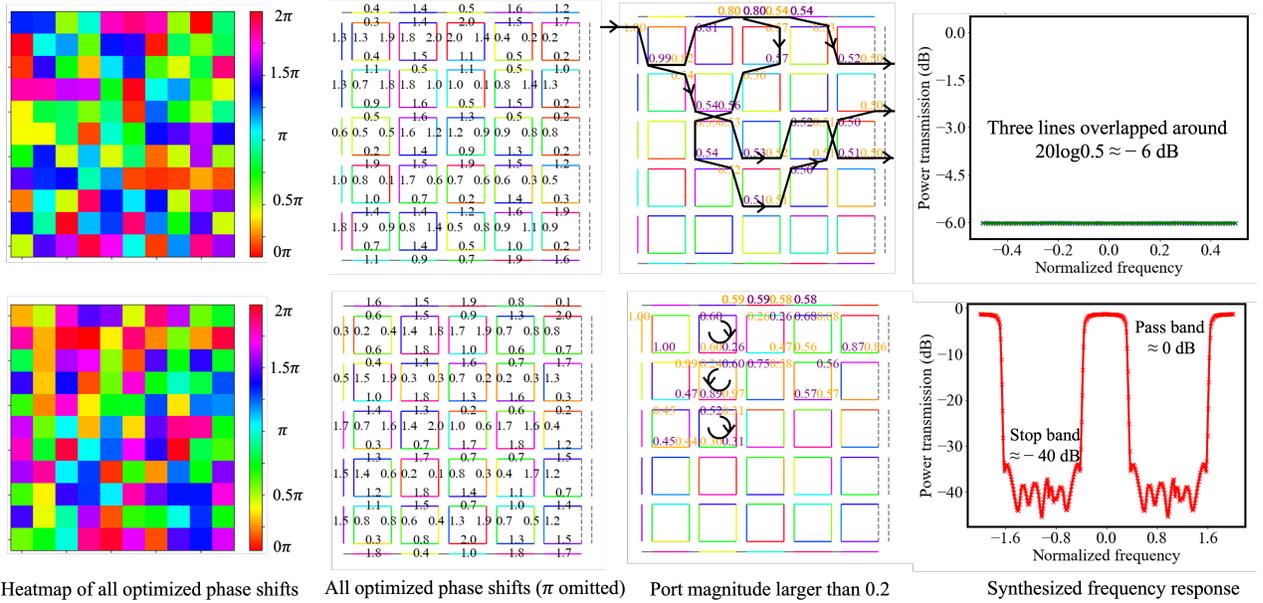

Fig. 2. **Top**: Splitting one input to three outputs; synthesis time: 1.2 (mins). **Bottom**: An optical band pass filter; synthesis time: 23.5 (mins).

III. CONCLUSION

We propose an automatic technique to realize complex light processing functions on a square-mesh recirculating PPIC. This technique does not rely on human design knowledge, and can be applied to find phase shift configurations for desired light processing functions within minutes. While demonstrated here for a square-mesh PPIC, our computation and optimization approach is extendable to a variety of PPIC structures and fabrics.

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