Silicon photonic optical phased array with integrated phase monitors

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SUMMARY The optical phased array (OPA) is an emerging non-mechanical device that enables high-speed beam steering by emitting precisely phase-controlled lightwaves from numerous optical antennas. In practice, however, it is challenging to drive all phase shifters on an OPA in a deterministic manner due to the inevitable fabrication-induced phase errors and crosstalk between the phase shifters. In this work, we fabricate a 16-element silicon photonic non-redundant OPA chip with integrated phase monitors and experimentally demonstrate accurate monitoring of the relative phases of light from each optical antenna. Under the beam steering condition, the optical phase retrieved from the on-chip phase monitors varies linearly with the steering angle, as theoretically expected.

key words: Silicon photonics, Optical phased arrays, Optical phase monitoring

1. Introduction

The optical phased array (OPA) [1–3] is a solid-state beam steering device, which is expected in versatile applications, including light detection and ranging [4–7], computational imaging [8–16], photonic switching [17–19], free-space optical communication [5, 6], and image projection [20–23]. Compared to conventional mechanical beam-steering devices, OPAs can be more compact, high-speed, and reliable owing to their non-mechanical operation principle. Large-scale OPAs have been demonstrated on various integration platforms, including silicon [5, 6, 24–26], indium phosphide [27, 28], and silicon nitride [29]. Moreover, by employing electro-optic phase shifters, ultrahigh-speed beam steering can be realized [20, 27, 30, 31].

The output beam of an OPA is steered to the desired direction by emitting precisely phase-controlled lightwaves from N optical antennas. In practice, however, it is difficult to control the phase of light at each waveguide in a deterministic manner due to several reasons. For example, inevitable fluctuation of the effective refractive index is present as a result of small fabrication errors. In addition, nonzero crosstalk between adjacent phase shifters may also be a problem, especially when thermo-optic (TO) phase shifters are used [32–34]. Therefore, real-time monitoring and calibration of the optical phase errors are mandatory.

One method of phase calibration is to observe the far-field pattern (FFP) using an external camera and to iteratively adjust the voltages applied to all phase shifters so that the desired beam pattern is obtained [25, 26, 35]. While this is the simplest method commonly employed in laboratories, the use of a bulky and costly camera may not be acceptable in practical systems. In addition, as N increases, it becomes more and more challenging and time-consuming to optimize the driving conditions of N phase shifters using only the intensity information of FFP, which is influenced by the complex optical fields emitted from all N antennas. While camera-free OPA systems with on-chip FFP monitors have been demonstrated [36–38], the complexity of retrieving the phase information from FFP remains to be an issue.

Another method is to directly detect the phase difference of light propagating through adjacent waveguides by employing on-chip interferometers and power monitors [39]. Since the optical phases at all N waveguides can be retrieved sequentially, phase errors can be calibrated without an iterative optimization process. Moreover, this scheme is fully compatible with aperiodic OPAs, where the optical antennas are located with non-uniform spacings to enhance the number of resolvable points beyond N [22, 23, 40, 41]. As an extreme case of interest, a non-redundant OPA (NROPA) that employs the concept of a non-redundant array (NRA) [42–47] offers the highest spatial resolution, which scales at N² [41]. By integrating on-chip phase monitors to an NROPA, therefore, N² resolvable points can be obtained with only N power monitors. While there are a few reports on OPAs with integrated phase monitors [28, 39], implementation of on-chip phase monitors to an NROPA has not been demonstrated.

In our recent work [48], we developed a silicon photonic NROPA chip that consists of 16 phase shifters (N = 16) and germanium-based photodiodes (PDs) to demonstrate on-chip optical phase monitoring functionality. In this article, we provide detailed descriptions of the fabricated device as well as its operation principle. We then present comprehensive experimental results, including the phase monitoring properties measured for all 16 antennas. Finally, we clarify the origin of the discrepancy from the theory by comparing the results with rigorous numerical analysis.

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The photocurrent signal $i_n$ obtained from the $n$-th PD ($n = 1, 2, ..., N - 1$), which monitors the interference of the lightwaves from the $n$-th and $(n + 1)$-th waveguides, can be written as

$$i_n = \frac{\eta}{4} \left[ |E_n|^2 + |E_{n+1}|^2 + 2 |E_n| |E_{n+1}| \cos (\Delta \phi_{n,n+1}) \right],$$  \hspace{1cm} (1)$$

where $\eta$ is a coefficient describing the responsivity of the PD, $E_n$ is the complex amplitude of the light from the $n$-th waveguide, $\Delta \phi_{n,n+1} \equiv \phi_n - \phi_{n+1}$, and $\phi_n$ is the optical phase of light from the $n$-th waveguide. For the sake of convenience, Eq. (1) can be written in a simplified form as

$$i_n \equiv \alpha_n \cos (\Delta \phi_{n,n+1}) + \beta_n,$$  \hspace{1cm} (2)$$

where $\alpha_n$ and $\beta_n$ are real-valued constants. Although $|E_n|$ in Eq. (1) should ideally be equal for all $n$, any variation among $N$ waveguides due to the inevitable non-uniformity at the $1 \times N$ splitter, the grating couplers, and the MMI couplers would result in different values of $\alpha_n$ and $\beta_n$ depending on $n$. Note that both $\alpha_n$ and $\beta_n$ can be derived from a priori loss measurement and the input optical power, which is monitored by the $N$-th PD. As a result, the phase difference $\Delta \phi_{n,n+1}$ in Eq. (2) can be extracted from the measured $i_n$ and its small-signal response by applying a small dithering to each phase shifter as shown in Fig. 2.

We should note that in reality, there is a non-negligible optical path length from the grating couplers to the optical phase monitoring circuit, leading to the accumulation of optical phase error. Therefore, the relative optical phase at the input of the optical phase monitoring circuit is not necessarily equal to that at the output of the grating couplers. Taking these accumulated optical phase errors $\Psi_n$ into account, the actual optical phase emitted from the $n$-th grating coupler can be written as $\Phi_n \equiv \phi_n - \Psi_n$. For convenience, we define $\Delta \Phi_{n,n+1}$ as $\Delta \Phi_{n,n+1} \equiv \Phi_n - \Phi_{n+1}$ to represent the actual optical phase difference of lightwaves emitted from adjacent...
Accordingly, the measured phase difference $\Delta \theta$ and $n$ is the distance between optimizing the phase shifters to focus the beam at $\theta_i$ derived from a single calibration step by recording $\Delta \Psi$. Note that $\Delta \Psi$ can be derived from a single calibration step by recording $i_n$ after optimizing the phase shifters to focus the beam at $\theta = 0$.

### 3. Device Fabrication and Experimental Setup

In order to demonstrate the feasibility of on-chip phase monitoring, we fabricated a silicon photonic OPA chip with 16 phase shifters ($N = 16$) and on-chip phase monitors using a 200 nm silicon-on-insulator (SOI) multi-project wafer foundry service. The SOI wafer consisted of a 220-nm-thick silicon layer and a 2 µm buried oxide layer. Figure 3 shows the micrograph of the device.

We employed a 400-nm-wide strip silicon waveguide to ensure single-mode operation and designed each component to operate at the fundamental transverse electric (TE) mode. To equally distribute the input light to 16 waveguides, 4 stages of $1 \times 2$ MMI couplers were cascaded. The $1 \times 2$ MMI couplers were designed to have 5-µm width and 21.6-µm length, with 10-µm-long tapers at the input and output ports. At each waveguide, a 220-µm-long TiN TO phase shifter was attached to control the optical phase. The resistance of the TO phase shifter was approximately 1.2 kΩ, which could induce $2\pi$ phase shift at approximately 20 mW driving power.

After the phase shifter section, approximately 60% of the light was emitted to free space using 750-µm-long waveguide-based grating antennas with a grating pitch of 720 nm and a duty cycle of 50%, which were realized by shallow etching (~10 nm) of the silicon waveguide core. They were located sparsely at the positions defined by a Golomb ruler [41, 43] with a unit spacing of 2 µm. The remaining portion of light was split by $1 \times 2$ MMI couplers, mixed with the light from adjacent waveguides by $2 \times 1$ MMI couplers, and detected by 100-µm-long germanium PDs. The waveguides were carefully designed so that the geometrical lengths from the input port to the grating couplers as well as those from the grating couplers to the phase monitor sections were identical for all waveguides. We should note, however, that due to the inevitable deviation of the effective refractive index of the silicon waveguides, non-negligible optical phase errors accumulate, which had to be calibrated using the phase monitors.

Figure 4 shows the experimental setup. All phase shifters and PDs were wire-bonded to a printed circuit board, via which they were connected to a driver and a detector circuit. We used a driver circuit with 10-bit digital-to-analog converters to drive all the 16 phase shifters independently. A reverse bias of 0.1 V was applied to all PDs. The dark current was approximately 30 nA. In contrast, average photocurrent was in the order of few µA when the input optical
power to the chip was set to 5 dBm. The effect of dark current was, therefore, negligible in our experiments. The photocurrent from each PD was amplified and detected by an analog-to-digital converter. We retrieved the relative optical phase from the detected photocurrent signals of on-chip monitors (red triangles) as a function of sin θ for the five beam steering angles θ shown in Fig. 6. The theoretical values of ΔΦ₀,₀+₁ calculated by Eq. (3) are plotted by the black dotted lines for comparison. The experimentally retrieved ΔΨ₀,₀+₁ is indicated in each figure, which is almost random due to the stochastic nature of the accumulated optical phase errors. We also indicate the root mean square error Ξ₀,₀+₁ for each monitoring port, which is defined as

\[ Ξ₀,₀+₁ = \sqrt{\frac{1}{5} \sum_{\sin \theta} (ΔΦ₀,₀+₁ - ΔΦ₀,₀+₁;\text{theory})^2} \]

where ΔΦ₀,₀+₁ denotes the experimentally retrieved relative optical phase and ΔΦ₀,₀+₁;theory denotes the theoretical relative optical phase. In most cases, we can confirm that the retrieved ΔΦ₀,₀+₁ is proportional to sin θ and d₀,₀+₁ in agreement with the theory. In particular, Ξ₀,₀+₁ is as small as 0.21 rad for ΔΦ₀,₁₀, which is the best port combination due to the excellent overlap of light at the far-field plane. In contrast, in some ports, there are relatively large discrepancies between the experiment and theory. This can be attributed to the poor overlap of light from adjacent waveguides at the far field plane, as we discuss in the next section. From these results, the feasibility of tracking the optical phase at each waveguide in OPA by on-chip monitors is demonstrated.

5. Discussion

While the validity of on-chip phase monitors is verified experimentally to some extent in the previous section, relatively large errors are confirmed in some ports as shown in Fig. 7. We attribute these errors to the undesired fluctuation in the...
emission angle along the \( \psi \) direction due to the fabrication errors at the grating couplers. The imperfect focusing in \( \psi \) direction would then result in imperfect interference along \( \theta \) direction as observed in Fig. 6. To investigate this assumption, we numerically calculate how the FFP changes when the emission angle \( \psi \) from 16 grating couplers has a standard deviation of \( S(\psi) \).

Figure 8 shows the numerically simulated FFP of a
16-channel 1D NROPA based on the Golomb ruler when \( S(\psi)/\Delta\psi \) increases from 0 [Fig. 8(a)] to 3 [Fig. 8(e)], where \( \Delta\psi \) is the full-width-at-half-maximum (FWHM) of the FFP from each grating coupler. Here, we assume that \( \Phi_1 = \Phi_2 = \cdots = \Phi_{16} \) so that a single beam should ideally be formed at \( \theta = 0 \). When \( S(\psi)/\Delta\psi \) is large, however, we can see that FFPs from 16 antennas distributed along \( \psi \) do not interfere perfectly. Consequently, the residual noisy components emerge in Fig. 8 even when Eq. (4) is satisfied. In particular, Fig. 8(d) and Fig. 8(e) well resemble the experimentally obtained features in Fig. 6, where multiple stripes of interference fringes with various spatial frequencies are generated. This implies that some pairs of adjacent antennas have poor contribution to the focused beam at FFP, which causes weaker correlation to the actual steering angle \( \theta \) as observed in Fig. 7.

As a unique property of NROPA, interference of light from every pair of waveguides generates different spatial frequency components in the FFP [16, 41]. Therefore, poor overlap between the beams from different grating couplers directly corresponds to the loss of a specific spatial frequency component, which would disturb the beam quality. We should note that an error in the emission angle of a grating coupler generally originates from the deviation in the effective refractive index of the silicon waveguide. This issue can be solved by making the waveguide wider at the grating section so that the effective index is less sensitive to the fabrication errors [49–51]. Once the emission angle errors are suppressed, the NROPA configuration would offer a substantial advantage over other OPA configurations, since the high spatial resolution can be obtained with a minimal number of optical antennas and on-chip phase monitors.

6. Conclusion

We have fabricated a silicon photonic NROPA chip with on-chip phase monitors and experimentally demonstrated its capability to track the optical phase of light emitted from each antenna. The retrieved optical phases from the photocurrent signals were compared with the measured FFP of the OPA to show reasonable agreement. The residual discrepancy was attributed to the non-uniform emission angles of grating couplers, which can be improved in the future design. This work shows the feasibility and effectiveness of the integrated phase monitors for measuring and controlling the output wavefront from an OPA without external bulky systems. The demonstrated scheme would especially be attractive for an NROPA since a minimal number of phase monitors are needed to achieve the required spatial resolution.

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References

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