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Energy-efficient Silicon Optical Phased Array with Ultra-sparse Nonuniform Spacing

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Abstract *We experimentally demonstrate an ultra-sparse 120-channel silicon optical phased array with a large aperture size of 6 mm × 5 mm. A 162° field of view was achieved with a total power consumption of 0.47 W and thermo-optic power efficiency of 3.1 mW/π . ©2022 The Author(s)*

Introduction

Optical phased array (OPA), as a novel solid-state beam steering method, is becoming a promising alternative to mechanical beam steering modules for light detection and ranging (LiDAR) systems[1]–[4]. Also, integrated OPAs feature low size, weight, power, and cost (SWaP-C) and hold a high potential for mass production[5]–[10].

To achieve a large beam steering range and a small beam divergence simultaneously for long-distance detection, a large emitting aperture containing lots of phase shifters is needed. Various phase tuning techniques have already been demonstrated on silicon platforms for the OPAs , such as thermo-optic effect[9],[11],[12], electro-optic effect[10],[13], and MEMS[14]. Among them, benefit from its superiority in simple structure and easy fabrication process, thermo-optic phase shifter has been widely used for OPAs. However, a typical thermo-optic silicon phase shifter consumes tens of milliwatts per π phase shift[15]. Hutchison *et al.* demonstrated an 128-channel OPA using conventional thermo-optic phase shifters with a total power consumption of 10 W[16]. Although the power consumption can be reduced with certain sacrifices[17]–[20], it is still challenging to balance the trade-off among power consumption, insertion loss, modulation bandwidth, and footprint.

The total power consumption is proportional to the scale of OPAs. For the half-wavelength-pitch uniform OPAs which achieve a 180° FoV[11], a large emitting aperture size (corresponding to small beam divergence in the far-field) requires thousands of channels, which will largely increase the power consumption. On the other hand, the nonuniform OPA schemes can realize the same performance of FoV and aperture size with less number of channels[13],[16]. Therefore, the total power consumption can be smaller than that of uiform OPAs with a same emitting aperture.

Here we first show a thermo-optic round-spiral phase shifter that reduces the power consumption to 3.1 mW/π while maintaining a good balance on other performances such as insertion loss (0.6 dB), modulation speed (34 kHz), and footprint (42 µm × 42 µm) simultaneously. Then we applied the packed phase shifters into an ultra-sparse nonuniform 120-channel OPA with a large aperture size of 6 mm × 5 mm (50 µm averange pitch). Finally, a record-large FoV of 162° in the phase-tuning direction is observed, with a total power consumption of 0.47 mW.

Energy-efficient optical Phase shifter

Figure 1(a) shows the schematic of the round-spiral optical phase shifter. The 1.2-mm length

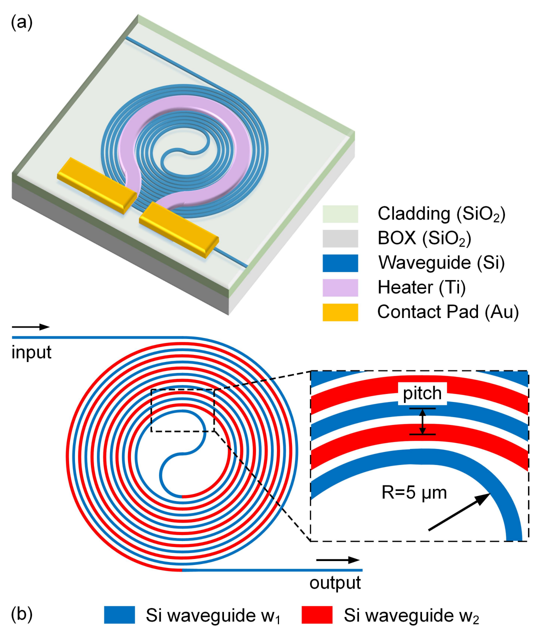

Fig. 1: (a) Schematic of the round-spiral phase shifter. (b) Top-view of the round-spiral phase shifter, The inset indicates that the minimum radius is 5 µm.

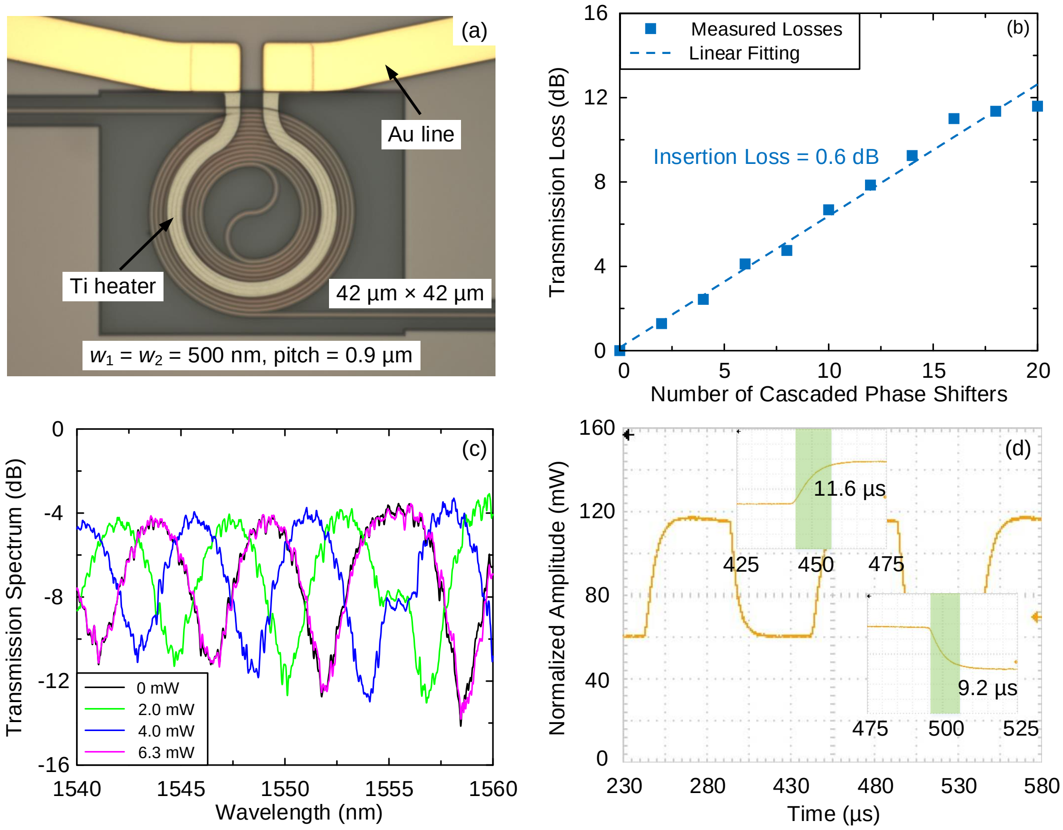

Fig. 2: (a) Microscope image of the proposed round-spiral phase shifter. Experimental result of (b) insertion loss, (c) power consumption per π, and (d) modulation speed.

phase shifter consists of two spiral waveguides and an S-bend connector. The spiral waveguides have two widths of w_1 and w_2, as shown in Fig. 1(b). The insertion loss consists of waveguide loss mainly due to the material loss and sidewall scattering, bend loss due to the sharp bend waveguide, and coupling loss due to the dense distribution. We balance the trade-off and optimize the relevant parameters to minimize the insertion loss. Finally, the radius of the S-bend connector, the pitch between two spiral waveguides, and the waveguide widths are carefully optimized as 5 µm, 0.9 µm, and $w_1 = w_2 = 500$ nm, respectively. The phase shifters are fabricated on a silicon-on-insulator (SOI) chip using a standard silicon photonic fabrication process. Figure 2(a) shows the microscope image. The passive waveguide pattern is defined after the E-beam lithography (EBL) and the deep reactive ion etching (DRIE) process. Then a 1-µm SiO_2 layer is deposited on the chip for protection. After that, an 80-nm-thick Ti layer is deposited, acting as the heater. The 2.5-µm width of the heater is significantly narrower than the total spiral-waveguide width (11.3 µm measured in Fig. 2(a)), therefore the residual heat spreading around can be maximally absorbed by the dense silicon waveguide, and thus the energy efficiency would be improved[18],[21].

The straight waveguide, which is fabricated on the same chip with phase shifters, whose loss is measured to be 2.7 dB/cm using the cut-back method. Then we utilize the same method to measure and calculate the insertion loss of the optical phased array 0.6 dB, as shown in Fig. 2(b). We also designed a Mach-Zehnder interferometer (MZI) to measure the power efficiency of the phase shifters. Figure 2(c) indicates a power consumption of 3.1 mW/π. Finally, we modulate the heater with a 5 kHz square-wave pulse train to measure the modulation bandwidth. The rising time and falling time are 11.6 µs and 9.2 µs, respectively, indicating a modulation speed of 34 kHz, calculated by the cut-off frequency for resistor-capacitor (RC) circuits[22].

Ultra-sparse nonuniform optical phased array

To simultaneously achieve large FoV and large aperture size, we utilize the Genetic algorithm to optimize the nonuniform 120 pitches in the range from 40 µm to 60 µm. Figure 3(a) illustrates the schematic of the proposed nonuniform OPA. The light is designed equally distributed to 120 channels by the cascaded couplers. Then

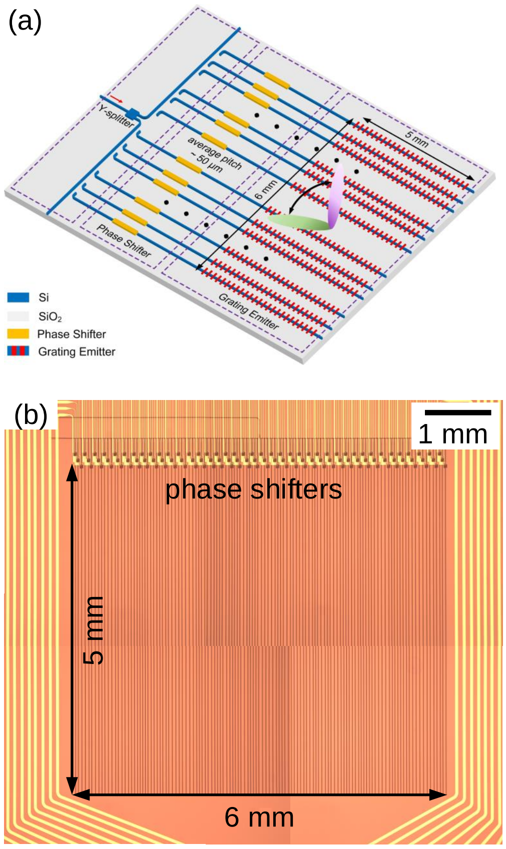

Fig. 3: (a) Schematic of ultra-sparse nonuniform OPA. (b) Microscope image of fabricated OPA with an aperture size of 6 mm $\times$ 5 mm.

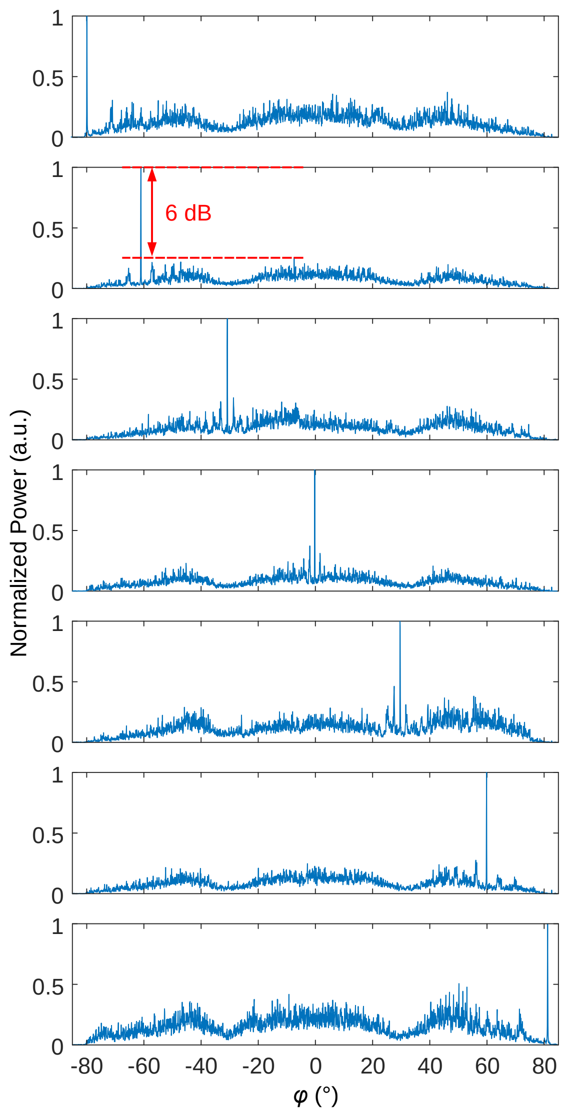

Fig. 4: The beam is steered from -80° to 82° , achieving a FoV of 162° in the φ direction.

the lights are independently modulated by the energy-efficient optical phase shifters mentioned above. And finally, the light is emitted by the shallow-etched grating emitter. The microscope image of the OPA is shown in Fig. 3(b). The aperture size is as large as 6 mm $\times$ 5 mm, indicating an average pitch of 50 μm in the φ direction.

We calibrate and converge the far-field beam to the specific angles by the gradient descent algorithm. Figure 4 shows the beam is steered from -80° to 82° in the φ direction, achieving a record largest 162° FoV in the φ direction. The largest SLSR is calculated as 6 dB. The beamwidth in the φ direction is measured to be 0.13°, which is limited by the measurement setup. The theoretically calculated beamwidth is 0.014°. Finally, we measure and calculate the total power consumption of the OPA in the working state. When the beam is steered to the maximum angle, i.e., 82°, the power consumption on each channel is measured, and the total power consumption is summed to be 0.47 W.

Conclusions

We have proposed and demonstrated a well-designed optical round-spiral phase shifter with a low thermo-optic power consumption of 3.1 mW/π. The phase shifter also maintains a good balance on other performances such as insertion loss (0.6 dB), modulation speed (34 kHz), and footprint (42 μm $\times$ 42 μm) simultaneously. Based on this, we experimentally demonstrated an an ultra-sparse nonuniform 120-channel OPA with an extremely large aperture size of 6 mm $\times$ 5 mm (50 μm averange pitch). A record FoV of 162° in the φ direction is realized with a maximum total power consumption of 0.47 W.

Acknowledgments

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