Optical Phased Array with Reduced Phase Tuning Resolution

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***Abstract*—This paper studies the minimum thermo-tuning resolution for calibrating and steering the 1-D optical phased array (OPA) through simulation and experiment. Through simulation, we determined the factors, including antenna pitch d, wavelength λ, and calibration procedure, that affect the phase tuning resolution requirement of 1-D OPAs. Simulation results show that the resolution can be reduced to 2 bits without degrading the beam quality. Furthermore, an OPA with 128 antennas is implemented. Experimental results validate that 2 bits resolution is sufficient to calibrate the 1-D OPA with the most power concentrated at the target direction.**

***Keywords*—OPA, Driver, Resolution**

I. Introduction

Optical Phased Arrays (OPAs), illustrated in Fig. 1, consist of antennas, thermo-optic phase shifters (TOPSs), waveguides, and splitters, which draws great attention in recent years for its promising applications in low-cost LiDAR systems. However, the unavoidable fabrication defects and environmental variation make it necessary to calibrate the OPA with complex driving circuits, limiting its wide practical applications. As shown in Table 1, the resolution of these circuits is typically more than 9 bits, which increases circuit complexity and cost.

In this paper, we construct a mathematical model for phase calibration of OPAs. We study the minimum resolution of thermo-optical tuning and investigate the factors that affect the phase tuning resolution, including antenna pitch, number of antennas, wavelength, and calibration procedures. An OPA with 128 antennas and 1.6 μm pitch is implemented. Experiments results match well with our simulation results that 2 bits resolution is sufficient to calibrate the OPA.

TABLE I. STATE-OF-ART OPAs DESIGN

Design	[1] JSSC'19	[2] OE'18	[3] ISSCC'21
Antenna Number	125	512	256
Antenna Pitch	4 μm	1.5 μm	1.4 μm
Resolution	9 bits	16 bits	10 bits
Wavelength	1550 nm		

II. Mathematical Model

Based on the system block diagram in Fig. 1, we structure a mathematic model for the main modules to simulate the phase calibration of OPAs.

A. Model of Random Phase Error

Few works focus on the distribution of phase error of waveguides. We assume the random phase follows Gaussian distribution, which we regard as reasonable and concise. In fact, the distribution has little effect on our simulation. Because during calibration, we allow the algorithms to iterate enough times to achieve optimal solution, eliminating the influence of phase error distribution.

B. Model of TOPSs

The phase model of TOPSs is based on two conditions. One is that extra phase generated by TOPSs is 2π when the TOPS is

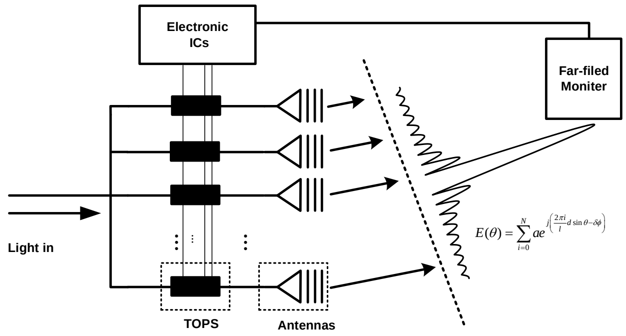

Fig. 1. Basic diagram of 1-D OPAs.

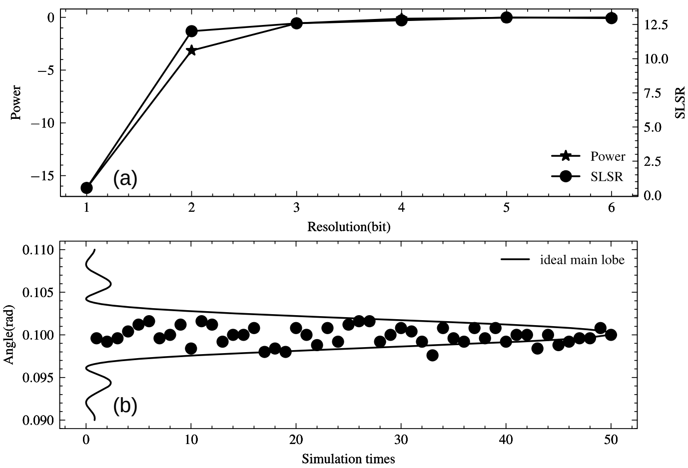

Fig. 2. Simulation results of minimum resolution: a) Ideal resolution required b) Angle error when the resolution is 2 bits.

driven by the maximum voltage, the other is that driving voltage and the extra phase has a quadratic relationship [4]. That is to say, when the resolution of driving circuit is 2 bits, corresponding phase TOPSs can generate is $\frac{0*2\pi}{9}$, $\frac{1*2\pi}{9}$, $\frac{4*2\pi}{9}$, $\frac{9*2\pi}{9}$.

C. Model of Far-Field Distribution

As well known, each antenna emits radiation of $E = ae^{\frac{2\pi}{\lambda}dsin\theta-\delta\phi}$, where a is the amplitude that does not influence the phase variation, d is the grating pitch, λ is the wavelength, θ is the target angle, and $\delta\phi$ is the initial phase error. After they coherent at far-field, the radiation is given by (1).

$$E(\theta)=\sum_{i=0}^{N} ae^{j\left(\frac{2\pi i}{\lambda}d\sin\theta-\delta\phi\right)} \quad (1)$$

D. Evaluation of Beam Quality

Side lobe suppression ratio (SLSR) is introduced to evaluate the beam quality. And it is defined as the ratio of the main lobe intensity to the utmost side lobe intensity.

III. Simulation Results

Antenna pitch d, antenna number N, and wavelength λ are the three main design parameters of OPAs. Through simulation, we find calibration algorithms also affect the results. So we investigate the influence of these factors on thermo-tuning resolution in detail. Considering that the wavelength is typically 1550 nm and that it has the same position with antenna pitch in (1), we study the influence of the ratio of antenna pitch to wavelength instead of each of them.

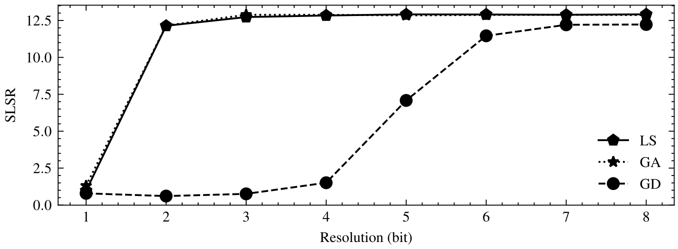

Fig. 3. Influence of different algorithms on resolution.

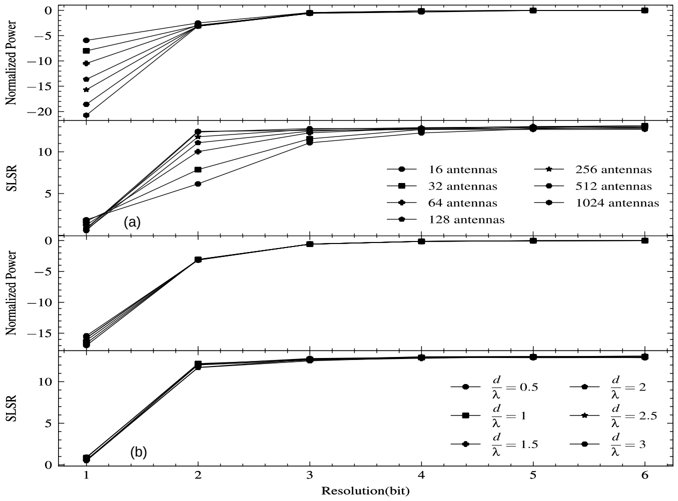

Fig. 4. Influence of antenna number N and wavelength λ on resolution.

A. *The Minimum Resolution*

With the mathematical model, an OPA ($N = 1024, d = 1.6\ \mu m, \lambda = 1550\ nm$) is calibrated and steered to 0.1 rad with different resolution to figure the minimum resolution that manages the phase tuning of OPAs. The simulation results depicted in Fig. 2(a) is the relationship between resolution with main lobe power and resolution with SLSR. Fig. 2(b) shows the target of the main lobe of each simulation when the resolution is 2 bits and the main lobe is steered to 0.1 rad. The results imply that when the resolution is 2 bits the beam quality and main lobe position are decent.

B. *Influence of Different Algorithms on Resolution*

Genetic Algorithm (GA), Local Search-based Algorithm (LS) [1], and Gradient Descent Algorithm (GD) [2] are the of widely adopted optimal algorithms. Fig. 3 shows the relation between the beam quality and resolution with different algorithms, suggesting that GA and LS perform well in low-resolution circumstances, whereas GD requires a higher resolution.

C. *Influence of Antenna Number N and Ratio of Pitch to Wavelength $\frac{d}{\lambda}$ on Resolution*

As depicted by Fig. 4(a), the number of antennas has little impact on the phase tuning resolution required. For most applications whose antenna number is greater than 128, 2 bits resolution may be enough. Fig. 4(b) shows the ratio of pitch d to wavelength λ has almost no influence on the resolution required for most lines in the graph coincide.

IV. Experiment Results

Based on the simulation results, an OPA with 128 antennas ($d = 1.6\ \mu m, \lambda = 1550\ nm$) is implemented. Fig. 5 shows the

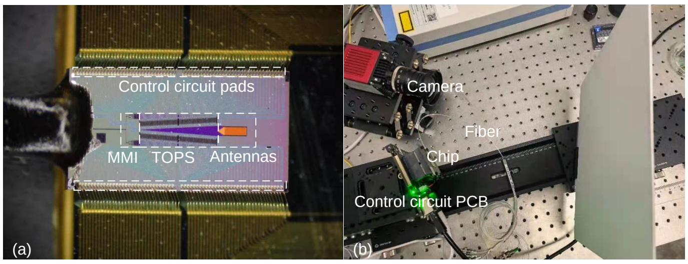

Fig. 5. Micrograph of the OPA chip and experiment platform setup.

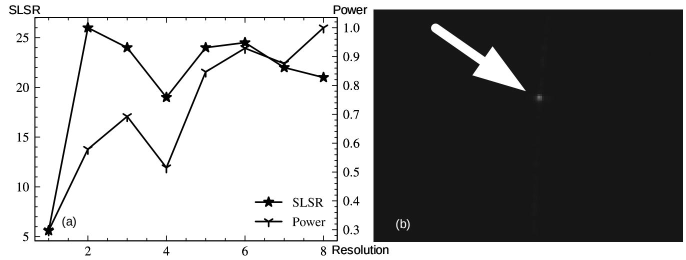

Fig. 6. Experiment results a) Beam quality with different resolutions b) Far-Filed beam when the resolution is 2 bits.

micrograph of the OPA chip and experiment platform. Fig. 6(a) depicts the relationship between resolution with SLSR and resolution with normalized power with the genetic algorithm, consistent with the simulation results. A slight drop of beam quality when the resolution is 4 bits is caused by the local optimal solution of GA. The SLSR in the experiments is much higher than the ideal value for the limiting experiment platform, as Fig. 5(b) shows, cannot collect the side lobe completely. Fig. 6(b) is the far-filed beam, calibrated with 2 bits resolution, demonstrates the efficiency of ultra-low resolution.

V. Conclusion

In this study, we determine the factors that influence the thermo-tuning resolution requirement of 1-D OPAs. The antenna pitch d, wavelength λ, and antenna number N have just a minor impact, while the calibration procedures have a significant impact on the minimum resolution. Furthermore, we also figure out the minimum phase tuning resolution required for calibrating and controlling 1-D OPAs. Experimental results agree well with our simulation results that 2 bits resolution is sufficient to tune OPAs with specified algorithms. We are optimistic that this finding will reduce the complexity and cost to drive OPAs, promoting the co-design of optical devices and control circuits of OPAs and encouraging the widespread use of OPAs.

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