# Independent dual beams generated by array element division in integrated optical phased arrays

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Received Month X, XXXX; accepted Month X, XXXX; posted online Month X, XXXX

Optical phased arrays (OPAs) have broad application prospects due to their advanced capability in beamforming and steering. In this work, we achieve independent dual beams in the far field by dividing the array elements of the OPA, with the maximum scanning range reaches 100°. Based on the working principle of OPA, theoretical considerations of such a multi-beam generation are presented. A phase data allocation approach for OPAs in presence of fabrication-induced random phase variation is developed. Simulations of large ensembles of OPAs with various levels of random residual phase errors have been conducted to help analyze the results. This approach can help OPAs to realize multi-beams for light detection and ranging (LiDAR).

**Keywords**: Optical phased arrays; Beamforming; Phase error calibration; Array elements division DOI: 10.3788/COLXXXXXXXXXXXX.

## 1. Introduction

LiDAR is in high demand and rapid development owing to the burgeoning autonomous driving technology. Optical phased arrays (OPAs) [1] have great potential in the field of LiDAR [2], due to the lack of mechanical components and the ability to achieve precise and fast beam scanning. Recently, benefiting from the advancement of photonic integrated circuit (PIC) technology [3], integrated OPAs have been devised and reported. Such devices can realize a wide scanning range with no aliasing beam [4,5], high resolution[6,7], compact size [8], and low power consumption [9], which are highly desirable features in LiDAR applications [10]. Furthermore, optical phased arrays also show promising applications in optical wireless communications (OWC) and sensing.

However, most integrated OPAs typically use a single beam for detection and ranging [11], which does not fully utilize the OPA's flexible beam control ability. In principle, an OPA can independently control multiple beams [12], which helps to reduce the scanning range required for a single beam and improve the frame rate [13,14], simultaneously track multiple objects, or communicate with multiple users in OWC. Some efforts have been made in the special design of system hardware, such as cascading multiple OPAs [15] or introducing Butler matrix into the OPA system [5], to achieve multi-beam scanning. In addition, specially designed gratings [13] and polarization multiplexing [16,17] can also help to realize multi-beam forming in OPAs. Usually, multibeam generation tends to be more complicated/difficult [18]. It is not easy to make directions of multiple beams independent from each other in experiment, and the relative difference of beam angles (or their sine values) are often fixed, which does not offer the flexibility needed for handling multiple objects moving independently in advanced application scenarios.

In this work, we demonstrate independent control of dual-beam by dividing the OPA into non-uniform sub-arrays of elements. This paper is organized as follows. In the second section, theoretical considerations of this multi-beam generation approach will be presented based on the working principle of OPA. Then, in the third section, we present the simulation of optical multiple beamforming and the schematic of a uniform division of array elements for generating dual independent beams. In the fourth section, experimental work of dual-beam generation will be reported with uniform or non-uniform division. In the fifth section, we discuss the effect of residual phase distribution errors on beamforming through simulation.

## 2. Principle of optical multiple beamforming

For an OPA with *N*uniformly distributed emitters, the electric field distribution E of its far-field satisfies

$$E(\theta) = \sum_{m=1}^{N} a_m \exp[j(mkd\sin\theta + \varphi_m)], \qquad (2)$$

where  $\theta$  is the angle between the observation direction and the axis normal of the OPA.  $a_m$  is the radiation amplitude of the *m*-th element. k is the wave vector number of input light and d represents the distance between the adjacent element.  $\varphi_m$  is an additional phase shift added on the *m*-th element, which can be modified by the phase shifter embedded in the OPA. To achieve a single beam pointing at an angle of  $\theta$  in the far field, it is necessary to linearly modify the phase of each emitter, and the phase spacing between adjacent elements is  $-kdsin\theta$ . To ensure a wide field of view (FOV) and point to multiple targets, the OPA ideally requires that the field generated by each element in the array is completely

controllable in phase [19]. Ideally, the pitch of the emitters should be half-wavelength [1] to avoid generating grating lobes. Grating lobes are secondary beams generated by an OPA with large emitter pitches. They are steered together with the primary beam, and hence are not independent beams. For independent multibeam generation, an OPA with half-wavelength emitter pitch would be preferred: otherwise, mixing the dependent and independent multi-beam would cause complication in many scenarios.

In order to achieve multiple beams, the entire array elements can be divided into several sub-arrays, each of which can be regarded as an independently controlled sub-OPA. By applying phase distributions with varying degrees of linear variation to different parts, thereby achieving multi-beam scanning. To illustrate the principle, here we consider the case of dual beams generated by the OPA with uniform radiation element for simplification. In such situation, the far-field intensity can be calculated as

$$I(\theta) = \left[\frac{\sin(N_1u_1/2)}{\sin(u_1/2)}\right]^2 + \left[\frac{\sin(N_2u_2/2)}{\sin(u_2/2)}\right]^2 + 2\frac{\sin(N_1u_1/2)}{\sin(u_1/2)}\frac{\sin(N_2u_2/2)}{\sin(u_2/2)}$$
(3)  
  $\times \cos\left[\varphi_1 - \varphi_2 + (N_1 - 1)\frac{u_1}{2} - (N_2 - 1)\frac{u_2}{2} - N_1u\right],$   
 $u = kd\sin\theta, \quad u_1 = u + \Delta\varphi_1, \quad u_2 = u + \Delta\varphi_2.$ 

where  $N_1$  and  $N_2$  are the numbers of emitters in the two subarrays, respectively. Besides,  $\varphi_1$  or  $\varphi_2$  is the phase of starting element of each sub-array and  $\Delta \varphi_1$  or  $\Delta \varphi_2$  is the phase step between adjacent elements in each sub-array. It is easy to verify that the third term in  $I(\theta)$  comes from the interaction between two beams. Besides, the specific intensity at  $\theta_1$  can be further simplified to Eq. (3), if it satisfies  $\theta_1 = -\sin^{-1}(\Delta \varphi_1/kd)$ , which also means  $u_1 = 0$ .

$$I(\theta_{1}) = \underbrace{N_{1}^{2}}_{I_{1}} + \underbrace{[1 - \cos(N_{2}u_{2})]/[1 - \cos(u_{2})]}_{I_{2}} + \underbrace{2N_{1}\frac{\sin(N_{2}u_{2}/2)}{\sin(u_{2}/2)}\cos\left[\varphi_{1} - \varphi_{2} - (N_{2} - 1)\frac{u_{2}}{2} - N_{1}u\right]}_{I_{1}v^{2}}.$$
(4)

Here,  $I_1$  and  $I_2$  represent the direct contributions of the two subarrays to the intensity at angle  $\theta_1$ , while  $I_{1\&2}$  stems from the interference between the two parts as mentioned before. Due to the symmetry, the equation for the beam intensity at the other angle  $\theta_2$  (equals to  $-\sin^{-1}(\Delta \varphi_2/kd)$ ) is formally similar to Eq. (3). Obviously, the contribution of  $I_1$  is the most significant at angle  $\theta_1$ when  $N_1$  is large, and the direct contribution  $I_2$  from the intensity of beam 2 is small at angle  $\theta_1$ . The effect of term  $I_{1\&2}$  tends to be small because  $I_{1\&2}/I_1 \sim 1/N_1$ . Additionally, it is easy to verify that when the phase distribution returns to the situation corresponding to a single beam, I will evolve into  $(N_1 + N_2)^2$ , which is consistent with the theory of single beam formation [20].

### 3. Simulation and analysis

To analyze the characteristics of dual-beam generation, we have simulated the far-field intensity distribution of a 32-element optical phased array. Representative single-beam pointing at several angles are shown in Fig. 1(a). Note that here we have assumed an OPA with half-wavelength emitter pitch to avoid the generation of grating lobes (dependent beams). Full consideration of the beam intensity also needs to consider the influence of the envelope,  $I_r(\theta) = F(\theta) \cdot I(\theta)$ , where  $I_r(\theta)$  denotes the real intensity and  $F(\theta)$  represents the envelope function. The  $F(\theta)$  in Fig.1 (a) is simulated from a waveguide with size of 450 nm × 220 nm through the 3D-FDTD simulation software. The envelope effect originates from the angular dependence of waveguide radiation intensity [4]. To illustrate the dual beam generation, we first consider to two single beams at -10° and 30° in Fig. 1(b). When we divide the OPA into two halves, one half uses the phase setting for the beam pointing at -10° and the other uses the phase setting for the beam pointing at 30°. As such, dual-beam pointing at -10° and 30° is obtained as shown in Fig. 1(c). Similarly, dual-beam pointing at -20° are illustrated in Fig. 1(e) based on phase settings of the two single beams shown in Fig. 1(d). The OPA division scheme is illustrated in Fig. 1(f).



Fig.1. The simulation of far-field beamforming. (a) Far-field patterns of beams pointing at different angles (each beam intensity is represented by a unique color), whose peak intensity follows an envelope function. (b) Two single beams point at  $-10^{\circ}$  (red) or  $30^{\circ}$  (green), respectively; and (c) the dual-beam points at both angles (blue). (d) Two single beams point at  $-20^{\circ}$  (red) or  $20^{\circ}$  (green), respectively; and (e) the dual-beam points at both angles (blue). (f) Schematic diagram of a uniform dividing scheme for generating independent dual beams.

#### 4. Experimentation

#### 4.1 Experimental setup

A schematic for the silicon-based integrated OPA chip used here is shown in Fig. 2(a), which consists of a single input grating coupler, power splitting components, phase shifters, and an output emitters array. Power splitting is based on the cascaded  $1 \times 2$ multimode interference couplers (MMIs) and splits the input light evenly into 32 channels. Then the light is sent to phase shifters, thus controlling the phase of each channel. Phase shifters are wire-bonded to a printed circuit board (PCB) to establish the electrical connection as shown in Fig. 2(b). The measured resistance of each shifter is about 540  $\Omega$  and the power needed for thermo-optically generating a  $\pi$  phase shift  $P_{\pi}$  is about 18.5 mW. Meanwhile, a trench is added between the adjacent phase shifters to reduce thermal crosstalk. The structure is designed with a 220 nm silicon-on-insulator (SOI) wafer, a 2 µm thick buried oxygen layer. Here, the OPA adopts waveguide-based broadband end-fire emitters and waveguide superlattice (SC5b type, consisting of waveguides with widths of 480 nm, 420 nm, 360 nm, 450 nm and 390 nm, and uniform height of 220nm) with a spacing of 0.8 µm is periodically arranged on the end face of the chip to suppress the crosstalk [4,21]. Therefore, the aperture linearity of emitter array is about 25 µm. It is worth noting that this method is actually applicable to OPA devices utilizing grating emission [22–24]. The emitter radiation efficiency is estimated about 80%. As shown in Ref. [4], the change of envelope for different waveguide widths in the waveguide superlattice is small and can be neglected. The experimental system setup is shown in Fig. 2(c). The emitted laser of 1550 nm is coupled into the grating coupler through a polarization-maintaining fiber. Finally, the far-field intensity distribution of OPA is measured by a photodetector that scans the far-filed angles through mechanical rotation.



Fig.2. (a) Schematic of the OPA structure. (GC, grating coupler; MMIs, multi-mode interference couplers; PS, phase shifter; WEA, waveguide emitter array). Not drawn to exact scale and to exact number of elements. (b) An optical microscope image of the OPA chip after wire-bonding, and wires are protected by black resin. (c) Schematic of the experimental setup used to characterize the OPA. (TL, tunable laser; FPC, fiber polarization controller; SMF, single-mode fiber; DUT, device under test; PD, photodetector; MVS, multi-channel voltage source, PC, personal computer).

Ideally, the phase difference between adjacent elements of OPA are usually a constant according to theory. Due to the fabrication variation, random phase errors are present in all channels of an optical phased array. This requires the compensation of such phase errors (via phase calibration) and makes the phase allocation in beam generation a non-trivial process, which can be even more complicated for the multi-beam generation case. Simultaneous phase calibration for multiple beams from multiple sub-arrays is difficult. Here we develop a phase data allocation method using phase data based on multiple steps of phase calibration. The phase data allocation method can be explained with the help of Fig. 1(f). Two single beams are generated first for the entire OPA to build up the phase data of each beam (which has the phase errors compensated), which can be obtained with the help of, for example, an iterative phase calibration method such as particle swarm optimization (PSO) [4]. Then the uniform or symmetrical division scheme is used to assign half of the phase data of the previous two single beams to the two sub-arrays, resulting in the two independent beams simultaneously.

# 4.2 Experimental results of independent dual-beam generation

Based on the forementioned uniform dividing scheme, we have implemented the dual-beam that can be independently controlled using an OPA chip, as can be seen in Fig. 3(a)-(g). Here the cases of two beams on different sides and on the same side of 0° are presented, with the maximum scanning range reaches 100 ° (from -50 ° to 50 °). The required phase data are collected and organized from single beams, which is obtained from PSO optimization. The comparison of peak intensity between the two beams is consistent with theory, that is, if the beam position is closer to 0°, its value will be higher. And the interference will exist, no matter where the beams are located, as shown in Eq. (2). It also can be seen that some beams partially deform, which should be attributed to the residual phase errors and is discussed in Sec. 5.



Fig.3. Experimental far-field patterns of dual beams through uniform division. The dual-beam points at same side: (a)  $-40^{\circ}$  &  $-10^{\circ}$ , (b)  $10^{\circ}$  &  $30^{\circ}$  and (c)  $-40^{\circ}$  &  $-20^{\circ}$  simultaneously; at different sides: (d)  $-10^{\circ}$  &  $20^{\circ}$ , (e)  $-20^{\circ}$  &  $30^{\circ}$ , (f)  $-30^{\circ}$  &  $-30^{\circ}$  and (g)  $-50^{\circ}$  &  $-50^{\circ}$ . Beam patterns are normalized to their peak intensity.

In order to reduce the possible difference in peak light intensity due to the envelope effect when multiple beams are generated, a non-uniform division scheme can be introduced. Specifically, in the case of dual beams, the peak intensity  $[I(\theta_1) \text{ and } I(\theta_2)]$  at two pointing angles  $\theta_1$  and  $\theta_2$  will roughly follow the relationship as I  $(\theta_1)/I(\theta_2) = N_1^2 \cos^2 \theta_1 / N_2^2 \cos^2 \theta_2$ . Here,  $N_1$  and  $N_2$  represent the number of elements in each submatrix and we have  $N_1 + N_2 = N$ , where N is the total element number. Therefore, as a preliminary validation of this concept, the peak intensity of different beams can be adjusted to a close level, by assigning appropriate numbers of emitter elements to each beam. For example, if we want to use the forementioned 32-channel OPA to achieve dual beams pointing at -30° and 10° simultaneously, with almost equal intensity, then the corresponding number of array elements should be around 17 and 15. Generally, as the total element number N of an OPA increases, the result of intensity balance should be better, as it can achieve more precise adjustment. Furthermore, this scheme can also be applied to achieve other beam intensity ratios between the two beams.

To validate this scheme, we conducted simulations and experiments, and the results are shown in Fig. 4(a)-(d). The Fig. 4(a) and (c) belong to uniform division, while the Fig. 4(b) and (d) are the corresponding ones with non-uniform division. Through the non-uniform division scheme, the intensity of the two beams becomes more balanced and all measured multi-beam far-field patterns are in reasonably good agreement with the simulation results in terms of beam divergence. Specifically, the difference between two beam's intensities in Fig. 4(c) are reduced from about 0.5 to almost very small in Fig. 4(d), thus verifying the feasibility

of the scheme. Furthermore, the ratio between the peak intensities of the two beams can be flexibly set, as shown in Fig. 4(e)-(g). In such cases, the  $-50^{\circ}$  beam has a relative intensity of 1.0, while the relatively intensity of the other beam is 1.0, 0.5, and 0.3, respectively. Furthermore, it is worth noting that this scheme is suitable for the multi-beam generation instead of just two (of course, to generate more beams usually prefers an OPA with more elements, which is usually true for most multi-beam generation approaches).



Fig.4. Simulated and experimental intensity distributions of the dual-beam pointing at (a)  $\cdot 30^{\circ} \& 10^{\circ}$  through uniform division, (b)  $\cdot 30^{\circ} \& 10^{\circ}$  through non-uniform division, (c)  $\cdot 50^{\circ} \& \cdot 10^{\circ}$  through uniform division and (d)  $\cdot 50^{\circ} \& \cdot 10^{\circ}$  through non-uniform division scheme. Experimental intensity distributions of the dual-beam pointing at  $\cdot 50^{\circ} \& 50^{\circ}$  through non-uniform division scheme and the intensity ratio of the two beams are (e) 1.0, (f) 0.5, and (g) 0.3. All beam patterns are normalized to their peak intensity.

# 5. Discussion

According to the theory of wave optics, when the emission angles of two beams are relatively close, the influence of this interference term may cause severe beam deformation. By changing the overall phase of these beams, destructive interference can be formed here, thereby reducing beam degradation. Through this method, we obtain a dual-beam pointing at -3 ° and 2 ° simultaneously, as shown in Fig. 5 (a) & (b). Besides, we can even apply different phase modulations to different light beams to label them.

It is worth noting that there is a small discrepancy between the experimental and simulation results, which we think is due to the residual phase errors. Due to manufacturing errors, there may be accumulated random phase errors in waveguide [25,26]. For example, before calibration, the average phase error in this OPA to generate 0 ° beam is about  $0.8\pi$ , and the standard deviation is about  $0.6\pi$  (roughly inferred by the needed phase shift of each channel). Although most part of the phase errors have been compensated during the phase calibration process in the phase data allocation, small residual phase errors could remain. The use of larger or more advanced optimization processes should further reduce residual errors, but complete elimination should still be difficult. Here we introduce residual phase errors of different amplitudes  $\Delta \phi$  into the standard phase distribution and calculate the cosine similarity  $\rho$  between the newly generated far-field and the ideal one [27], which can be calculated as  $\int I_1(\theta) I_2(\theta) d\theta / ($  $\sqrt{\int I_1^2(\theta) d\theta} \sqrt{\int I_2^2(\theta) d\theta}$ , where  $I_1(\theta)$  and  $I_2(\theta)$  are the angular intensity distributions with and without residual phase errors, respectively. A similarity value deviating more from unity indicates a larger difference between two beams, which also means a larger residual phase error. We have simulated the angular intensity distributions of a large ensemble of samples of OPAs with random residual phase errors. Figure 5 (c)-(e) shows the average similarity between the actual and ideal distribution of a single/dual beam under the influence of various levels of phase errors. From this, we can see that compared to dual beams, single beams have stronger robustness, which can maintain a similarity of approximately 0.9 under maximum phase error, but only about 0.8 remains for the dual-beam. Moreover, as the beam pointing angle increases, the sensitivity to phase error also increases.



Fig. 5. (a) Experimental far-field pattern of a dual beam pointing at -3 ° & 2 ° through uniform division. (b) The corresponding infrared image of (a) when camera is facing the chip. Simulated average similarity between the far-field with and without residual phase error, for the case of (c) single beams, (d) symmetric dual beams, and (e) asymmetric dual beams. The phase error added to the ideal value randomly varies within the range of  $[-\Delta\phi,\Delta\phi]$ , and the maximum phase error  $\Delta\phi$  is represented as the horizontal axis. (Uni, uniform division; Non, non-uniform division).

Two ideal far-field distributions and their variation range under the influence of specific phase error, are shown in Fig. 6 (a)-(b). Obviously, there is a larger uncertain range of beam variation in the case of dual-beam generation even though its maximum phase error is smaller, which corroborates the previous conclusion that a single beam is more robust. This may be because in the dual-beam situation, the number of elements involved in generating one beam is reduced by nearly half compared to a single beam, and such situation will become more obvious, when generating more beams. Two samples of simulated dual-beams with phase errors are shown in Fig. 6 (c), which illustrates the possibilities of how the beams may be affected. By comparing the similarity, we can roughly estimate the standard deviation of the residual error in far-field of Fig. 3 (f) is about  $0.14\pi$ . Furthermore, we have simulated the performance of OPAs with different number of elements N, for the case of single or dual-beam generation under random phase variation. The average similarity of the beam is plotted against N for various levels of maximum phase errors in Fig. 6 (d)&(e). The results shows that the stability of their generation is closely related to the number of OPA channels. For a given degree of phase error, the far-field distribution will gradually approach the ideal value as the number of elements increases. Such a trend is consistent with the single beam generation case [2]. With more elements embedded, the independent multi-beamforming will be more robust against phase error, and widened beam will be compressed. Meanwhile, the improved full field scanning speed and multi-target tracking ability are preserved. Therefore, the element division method can greatly increase the applicability range of an OPA, which can switch back to single beam operation mode with high resolution whenever needed, and it also have scalability. Besides, this method also has good scalability and is suitable for OPA with various number of elements.



Fig. 6. The variation range of OPAs' far-field distribution with phase error and the corresponding ideal far-field distribution, for the case of (a) single beam pointing at 0° and (b) dual-beam pointing at  $-30^{\circ}$  and  $30^{\circ}$ . (c) Far-field samples with phase error influence (maximum phase error  $0.15\pi$ ) is shown in the case of dual-beam which pointing at  $-30^{\circ}$  and  $30^{\circ}$ . The legends show the maximum range of phase error variation, and the intensity value is normalized to the peak value of the ideal beam. The stability of the far field distribution of OPA under residual phase error with different total numbers of elements N, for the case of (d) single beam pointing at  $0^{\circ}$ . (e) dual-beam pointing at  $-30^{\circ}$  and  $30^{\circ}$ .

Here, we compared several conceptual works on generating multiple beams based on OPA, which are shown in Table 1. The method proposed in this article does not rely on special chip designs and therefore can be used more widely and readily. Moreover, independent beam control allows for handling multiple objects moving independently. Moreover, the dependency between the beams is very low, allowing for flexible modulation. Besides, compared to integration of multiple individual OPAs (assuming the multiple OPAs has the numbers elements summed up equal to the number of elements in this approach), this approach provides the flexibility of adjusting the number of elements in each subarray.

Table 1. Comparison of Several Multi-beam Schemes			
Ref.	Method	Special Chip	Beam
		Design	Dependence
[5]	Butler Matrix	Yes	Yes
[13]	Special Grating	Yes	Yes
[15]	Multiple OPAs	Yes	No
Our work	Subarray Division	No	No

# 6. Conclusion

We have generated dual beams that can be independently controlled with the OPA system and the maximum scanning range reaches 100°. Phase data for the dual-beam generation can be built up from the single-beam generations through multiple steps of phase calibration. The difference in light intensity between the two beams caused by the envelope effects can be compensated by introducing a non-uniform division scheme. Through the same approach, the flexible adjustment of the intensity ratio between the two beams has also been achieved. In addition, we also investigate the impact of phase error during the beam generation process. Simulations of large ensembles of OPAs with various level of random residual phase errors have been conducted to help understand the results. Under the same level of residual phase error control, increasing the number of elements should effectively improve the quality of beam generation, although in this work the available number of elements are limited due to fabrication/testing costs. Such a multi-beam approach is also applicable to OPA using grating emission, not limited to waveguide end-fire emission as shown in this article. It also should be noted that the method proposed here is not limited to the generation of dual beams, but it is generally applicable in multi-beam scenarios. This work may pave the way for handling multiple independently moving objects in solid-state LiDAR systems and optical wireless communications.

## Funding

This work is supported in part by the National Natural Science Foundation of China (No. 62175103 and 62165015) and in part by the National Key Research and Development Program of China (2017YFA0303700).

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