Enhanced Suppression of Grating Lobes for Optical Phased Arrays via a Random-Phase Metasurface

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Optical phased arrays (OPAs) are promising beam-steering devices for a variety of applications, including light detection and ranging, free-space optical communication, optical imaging, and biomedical sensing. Current OPAs suffer from a limited field of view due to grating lobes. In addition, the OPA technology faces challenges such as complex design of antenna arrays and the need for high-precision and widely tunable integrated lasers. In this study, we demonstrate through simulations that the use of a passive random-phase metasurface can suppress grating lobes, even when the OPA pitch exceeds several times the half wavelength. Using our theoretical and numerical investigations we explore the relationship between sidelobe suppression ratio (SLSR) and the number of OPA channels. Additionally, our simulations show that two-dimensional (2D) beam steering can be achieved with a one-dimensional (1D) OPA combined with a random-phase metasurface, without the need for lenses or wavelength tuning. Finally, we analyze the effects of the parameters of a random-phase metasurface on the SLSR. Our method provides a practical, low-cost, flexible, and mass-producible solution for advanced LiDAR systems.

Introduction

Optical phased arrays (OPAs) are a very interesting photonic solution due to their ability to steer light beams at high speed without mechanical movement[1]. However, OPAs face a significant challenge: grating lobes arise when the spacing between antenna elements exceeds half a wavelength. These grating lobes limit the field of view (FoV) and degrade the overall performance [2]. For two-dimensional (2D) OPAs, efforts to address this issue have involved the use of compact gratings [3] or non-uniform OPA configurations [4]. Despite these attempts, the FoV remains restricted to $24^\circ \times 16^\circ$[4], and routing challenges persist. In contrast, for one-dimensional (1D) OPAs, beam steering along a single axis is typically achieved through non-uniform 1D configurations [5] or specialized waveguide array [6]. Non-uniform 1D OPAs require sophisticated optimization algorithms to suppress sidelobes [7] and maintaining a high suppression of sidelobe level across a wide FoV remains challenging. Specialized waveguide arrays, such as superlattice waveguide arrays [6], suffer from suppression lengths of a few hundred micrometers, limiting the resolution. A common solution to steering the beam in the orthogonal dimension to a 1D OPA is the use of wavelength sweeping [1]. However these methods only provide a limited steering range ($\leq 30^\circ$), with limited state-of-art wavelength tuning range of laser. Furthermore, developing high-speed, high-precision, wide-range tunable integrated laser remains particularly challenging.

Using metasurfaces to extend FoV of integrated OPA systems is a novel approach introduced in recent years [8]. Despite this progress, most existing methods utilize metasurfaces as either lenses or routers, which still achieve limited FoV extension. Random phase metasurfaces have also been applied in wavefront shaping, replacing conventional disordered media to enhance focusing resolution on various applications [9]. Additionally, random phase metasurfaces have been used to extend the FoV of liquid crystal spatial light modulators (LC-SLMs) with a pixel size of approximately 15 μm, enabling large-angle beam steering [10]. However, LC-SLMs are not ideal for beam steering due to their low modulation speed, typically below 1 kHz. Moreover, unlike integrated OPA systems, LC-SLMs generally feature a high fill factor, meaning grating lobes are not the primary factor restricting their FoV.

In this study, we demonstrate that a random phase metasurfaces can be employed to suppress the grating lobes in OPA systems by breaking the phase correlations. Firstly, a theoretical model is used to investigate the relationship between the sidelobe level and the number of channels, revealing the scalability of this approach. Furthermore, we demonstrate the numerical simulation results to verify the theoretical prediction. Moreover, the random-phase metasurface can also mask the position information, achieving 2D beam steering using a 1D OPA system. Finally, we analyze the effect of the parameters of the metasurface on the performance.

Principle

Fig. 1(a) illustrates the schematic of our proposed OPA system, which consists of a N-channel OPA paired with a random phase metasurface, whose phase pattern is generated randomly. Without the metasurface, enhancing the main lobe also strengthens the grating lobes due to their strong phase correlation. By introducing the random-phase metasurface, this correlation is disrupted, hence when we refocus the light in the desired direction via phase tunning, the grating lobes are suppressed.

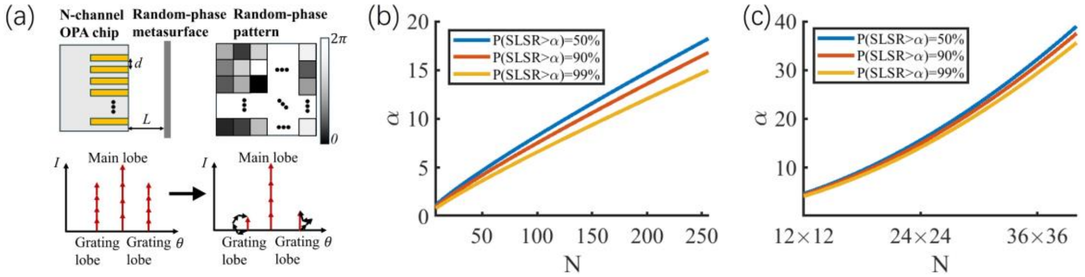

Fig 1: The principle and theoretical curves (a) Schematic of the proposed method. (b) 1D OPA for a 1D beam steering with a 5 μm pitch, FoV = 160°. (c) 2D calculation for a 2D OPA with a 20 μm pitch, and $\mathrm{FoV}_x = \mathrm{FoV}_y$ =160°. The 2D OPA is arranged in $\sqrt{N} \times \sqrt{N}$.

Because the grating lobes are eliminated and only side lobes exist in this method, to quantify the suppression, the sidelobe suppression ratio (SLSR) defined as $\mathrm{SLSR} = I_{\mathrm{mainlobe}}/max\{I_{\mathrm{sidelobe}}\}$ is introduced. Firstly, the scalability of this method is analyzed via a function of the SLSR dependent on number of channels, N. We emphasize that with this method, we cannot guarantee that every metasurface will achieve the target SLSR. However, we can calculate the probability of achieving a certain SLSR and, consequently, determine the pass rate of qualified metasurfaces. The probability originates from the randomly generated phase pattern in the design. However, it can also account for random errors introduced during fabrication and random variations in the alignment of the metasurface with the OPA during calibration. A high probability result would highlight the method's high tolerance and robustness.

When focusing on a specific direction (i.e., a point in the far-field pattern), we optimize the phase of each channel such that all optical fields are in phase at the main pointing direction. While for other directions, considering N independent field patterns, the intensity distribution at each point of the superimposed field follows an exponential distribution which is derived under the assumption of a single polarization. This assumption aligns with the single-mode waveguide design in most OPA chips. Using the distribution, we can calculate the probability:

$$P_0(\mathrm{SLSR} > \alpha) = \left(1 - e^{\frac{N}{\alpha}}\right)^{N_\varphi}, \tag{1}$$

where N_φ is the number of independent angles in the far-field pattern, determined by the FoV and the aperture D. We can estimate N_φ as $\mathrm{FoV}/(\lambda/2D)$ for 1D beam steering and $(\mathrm{FoV}_x \cdot \mathrm{FoV}_y)/(\lambda/2D_x \cdot \lambda/2D_y)$ for 2D beam steering, where λ is the wavelength. To determine the probability of scanning across the entire FoV, we assume that each focused far-field pattern is independent, and the probability for the entire FoV can be derived as

$$P(\mathrm{SLSR} > \alpha) = [P_0(\mathrm{SLSR} > \alpha)]^{N_\varphi}. \tag{2}$$

Using a 1D OPA for 1D scanning, Fig. 1(b) shows the relationship between the probability of the SLSR exceeding a certain value, α, and the number of channels, N. We can see from Eq. (1), when N is sufficiently large, the term N/α in the exponent of e, predominantly determines the probability, even when N_φ is not small. We can also see the curve in Fig. 1(b) becomes nearly linear as N increases. For 2D OPA, a large pitch is needed for the gratings to achieve enough efficiency and routing[3]. Fig. 1(c) shows using 2D OPA with a 20um pitch, we can still scan over $160° \times 160°$. Fig. 1(b) and (c) demonstrate that a large enough channel count, a high SLSR can be achieved across the entire FoV, even when the pitch is several times the wavelength and the FoV is large.

Simulations and Analysis

The numerical simulations are made using MATLAB. In all simulations presented in this article, a pitch of 5μm and an initial beam size of 1.2μm are used to demonstrate even when the pitch is several times the half wavelength and element factor is narrow, a wide beam steering can still be achieved. Fig. 2(a) shows a scanning result by a 128-channel 1D OPA, which scans from -80° to 80°. The phase pattern is selected by "rand()" function instead of dedicated design. Then, by generating different random-phase patterns of the metasurface 1000 times, we collect a frequency distribution for calculating the probability of achieving the SLSR or other relevant parameters. Fig. 2(b) presents the comparison between numerical simulation and theoretical modeling using 1D OPA and focusing on 0°, particularly highlighting the nearly linear trends which is predicted by the theory.

It has been proved that this method not only breaks the correlation along the axis parallel to the OPA array but also disrupts the correlation along the vertical axis, similar with scattering media [11][12], which suggests its ability to form a non-strip pattern in the far-field and achieve 2D beam steering. The simulation result of 2D beam steering achieved using a 1D 64-channel OPA is shown in Fig. 2(c).

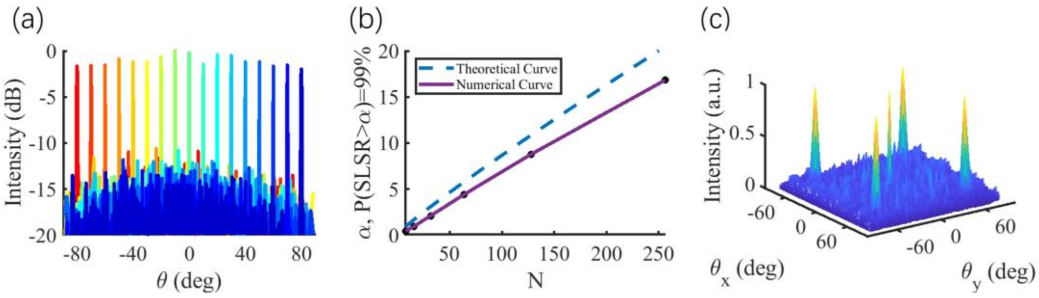

Fig 2: Numerical simulation results. (a) A beam steering result. The normalized intensity is in dB scale, and different colors correspond to different focus angles. (b) Theoretical and numerical curves. (c) Five steering points, located at (-60°, -60°), (-60°, 60°), (0°, 0°), (60°, -60°), and (60°, 60°), are achieved

The same 1D 64-channel OPA is used to illustrates several key requirements for the metasurface. Fig. 3(a) demonstrates that the SLSR decreases significantly when the phase range falls below 1.75π. Additionally, as shown in Fig. 3(b), the SLSR becomes considerably lower when the pixel size exceeds 1μm, particularly when focusing over 30°, indicating that a sufficiently small pixel size is essential to achieve scanning over a large FoV.

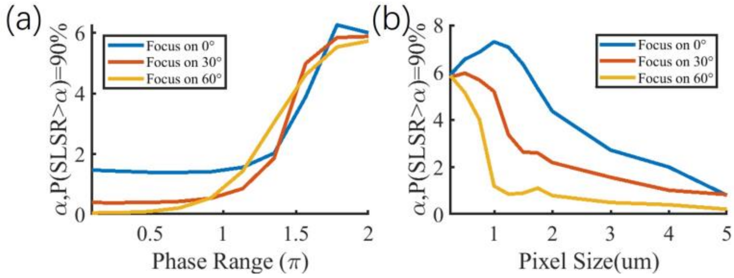

Fig. 3. Effects of metasurface parameters. (a) The effect of the random phase range . (b) The effect of the pixel size.

Conclusions

We propose a method via random-phase metasurface to suppress grating-lobe in OPA systems. We found that the SLSR is almost linearly dependent on the number of channels. Moreover, using this method, a 1D OPA can achieve 2D beam steering. Finally, we analyze the influence of various metasurface parameters and found out that sub-wavelength pixel size and random phase range close to 2π are required for wide beam steering. Our method provides a practical, low-cost, flexible, and mass-producible solution for advanced LiDAR systems.

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