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Design of an Aperiodic Optical Phased Array Based on the Multi-Strategy Enhanced Particle Swarm Optimization Algorithm

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Abstract: We have proposed a multi-strategy enhanced particle swarm optimization (PSO) algorithm to optimize the antenna spacing distribution of an optical phased array (OPA). The global search capability is improved by incorporating circle chaotic mapping initialization and an updated strategy based on adaptive inertia weights and dynamic learning factors. We used the peak side-lobe level (PSLL) at different steering angles as the fitness function, which effectively suppresses the rapid degradation of PSLL during scanning. Based on this approach, 32- and 64-channel aperiodic OPAs were designed with a scanning range of $\pm 60^\circ$, with improvements of the PSLL of 1.94 and 2.05 dB at 60° , respectively. In addition, the analytical and numerical simulation results are in good agreement. We also analyzed the influence of spacing deviations on PSLL and found that the obtained OPAs exhibit sufficient robustness.

Keywords: optical phased array; peak side-lobe level; enhanced particle swarm optimization algorithm; antenna spacing distribution optimization



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1. Introduction

Solid-state light detection and ranging (LiDAR) is a laser radar solution that does not require mechanical beam steering systems. Among various approaches, optical phased arrays (OPAs) are considered a promising solid-state laser scanning method due to their high precision, fast response, and strong reliability [1]. With the continuous advancement of semiconductor integration processes, waveguide-integrated OPAs have gained significant attention for their advantages of miniaturization and low cost [2,3].

Achieving a large field of view and low side-lobe level in OPAs has always been challenging. Due to fabrication limitations and waveguide coupling effects, achieving antenna spacing below half a wavelength in the OPA emission region is difficult. This results in grating lobes with high intensity in the far field, which not only disperse radiation power at target steering angles but also severely limit the OPA's scanning range. Aperiodic antenna arrays provide another solution to avoid grating lobes [4–9]. Search algorithms such as the genetic algorithm (GA) [8,10–12] and particle swarm optimization (PSO) [4,13–17] have been used to design aperiodic antenna arrays. Additionally, most studies use the peak side-lobe level (PSLL) at the steering angle of 0° as the fitness function, leading to a rapid increase in side-lobe level and background noise during scanning. In [18], an aperiodic OPA was reported, with a PSLL of 20.05 dB at 0° , rapidly decreasing to 15.41 dB at 60° . In [19], the PSLL of the aperiodic OPA decreases from 8.9 dB to 2 dB over a 150° scanning

range. It is evident that suppressing the PSLL degradation during large-angle scanning is essential.

In this work, we have proposed a multi-strategy enhanced particle swarm optimization algorithm by introducing a circle chaotic mapping initialization strategy and an update strategy based on adaptive inertia weights and dynamic learning factors to improve the algorithm's global search capability. We used the enhanced PSO algorithm and the PSLL at different steering angles as the fitness function to search for the optimal antenna spacing distributions of aperiodic OPAs with 32 and 64 channels. Numerical simulations show that the results are in good agreement with the analytical simulations. As a result, a high-performance 64-channel aperiodic OPA was designed. Additionally, we analyzed the impact of spacing deviations on PSLL. The simulation results show that the aperiodic OPAs exhibit high robustness to spacing deviations. This study provides valuable insights into the practical applications of OPAs in LiDAR and free-space optical communication.

2. Principle of the Aperiodic OPA

A schematic diagram of a one-dimensional (1D) OPA with an aperiodically spaced antenna array is shown in Figure 1. The input laser is divided into N independent paths by a splitter network. Each optical signal is modulated by a phase shifter and transmitted to an antenna array with a fixed spacing of d . Finally, the waveguide antennas radiate the signals into free space, where they interfere at the target steering angle, forming a resolvable pattern in the far field.

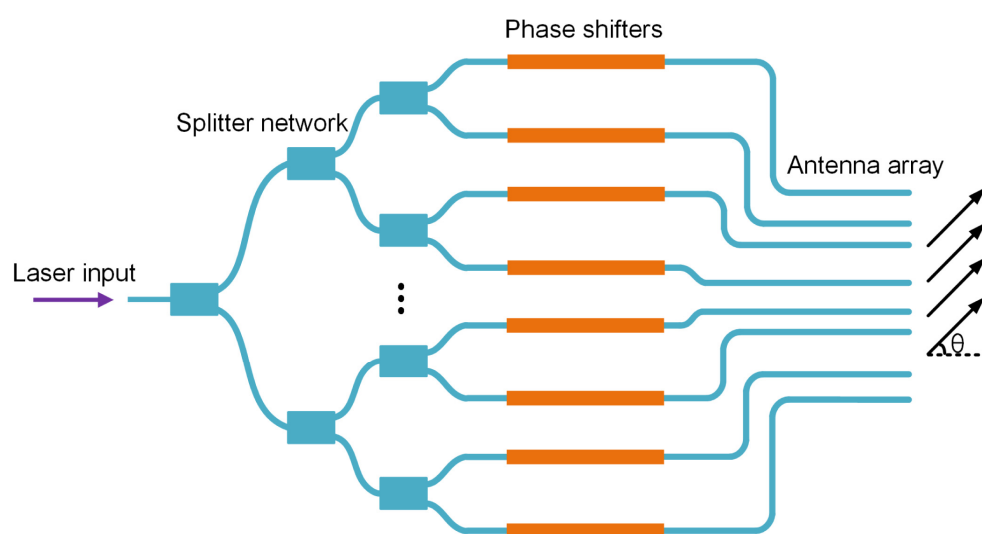


Figure 1. Schematic diagram of a 1D OPA with an aperiodically spaced antenna array.

The scanning range of a uniform OPA is determined by the position of the grating lobes. The intensity of the grating lobes becomes equal to that of the main lobe at a certain position during scanning. As the steering angle continues to increase, the grating lobe intensity surpasses the main lobe, causing the main lobe to become unrecognizable. A feasible and effective approach is to design aperiodic OPAs by disrupting the uniform antenna arrangement. As shown in Figure 2, the transition from a uniform to an irregular configuration prevents grating lobes from satisfying the conditions for coherent constructive interference, thereby suppressing unwanted grating lobes and enhancing beam scanning performance. The waveguide of each antenna is based on the silicon-on-insulator platform in this work, with a width of $0.5\ \mu\text{m}$ and a thickness of $0.22\ \mu\text{m}$. Considering the array aperture size and waveguide coupling, we set the minimum spacing $d_{\min}$ of the aperiodic OPA to $2\ \mu\text{m}$ (1.29λ) and the maximum spacing $d_{\max}$ to $5\ \mu\text{m}$ (3.23λ).

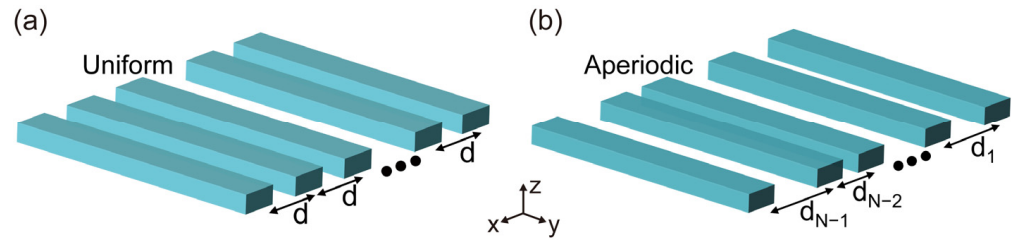


Figure 2. Schematic diagrams of (a) a uniform antenna array and (b) an aperiodic antenna array.

The total electric field intensity of an aperiodic OPA is expressed as

$$E(\theta) = f(\theta) \sum_{n=1}^N A_n \exp \left[jk \sum_{i=1}^{n-1} d_i (\sin \theta - \sin \theta_s) \right] \quad (1)$$

$$f(\theta) = \frac{\sin \alpha}{\alpha} \quad (2)$$

$$\alpha = \frac{\pi a \sin \theta}{\lambda} \quad (3)$$

where $f(\theta)$ is the element factor of a single antenna, N is the number of channels, A_n is the amplitude of n -th antenna, assumed to be 1, j is the imaginary unit, $k = 2\pi/\lambda$ is the wave vector, d_i represents the spacing between the i -th antenna and the $(i+1)$ -th antenna, θ and θ_s represent the observation angle and the steering angle, respectively, a is the waveguide width of the antenna, and λ is the wavelength of the input laser. The intensity distribution is expressed as

$$I(\theta) = E(\theta) \cdot E^*(\theta) = |E(\theta)|^2 \quad (4)$$

To illustrate the grating lobe suppression effect, we use 16-channel OPAs. The aperiodic OPA uses a set of random values between $d_{\min}$ and $d_{\max}$ for the spacing arrangement, while the uniform OPA uses the average of these random values as the spacing. Thus, both OPAs have the same aperture size. The spacing distributions are shown in Figure 3a,d; the normalized far-field patterns at 0° obtained from analytical simulations in MATLAB R2021b are shown in Figure 3b,e. Subsequently, three-dimensional finite-difference time-domain (3D-FDTD) simulations were performed to obtain the 2D far-field patterns. For the simulation setup, we used an auto non-uniform mesh accuracy of 3 to discretize the simulation region. Perfectly matched layer boundary conditions were applied in the x -, y -, and z -directions. The fundamental TE mode is launched into the waveguide with an air cladding at a wavelength of 1550 nm. The numerical results are shown in Figure 3c,f. By comparison, grating lobes are significantly suppressed, and the main lobe is clearly visible across the field of view. However, the dispersed intensity of the suppressed grating lobes increases side-lobe level and background noise, which is addressed in subsequent sections. For high-precision applications, such as LiDAR systems and free-space optical communication links [20], further design optimization is needed.

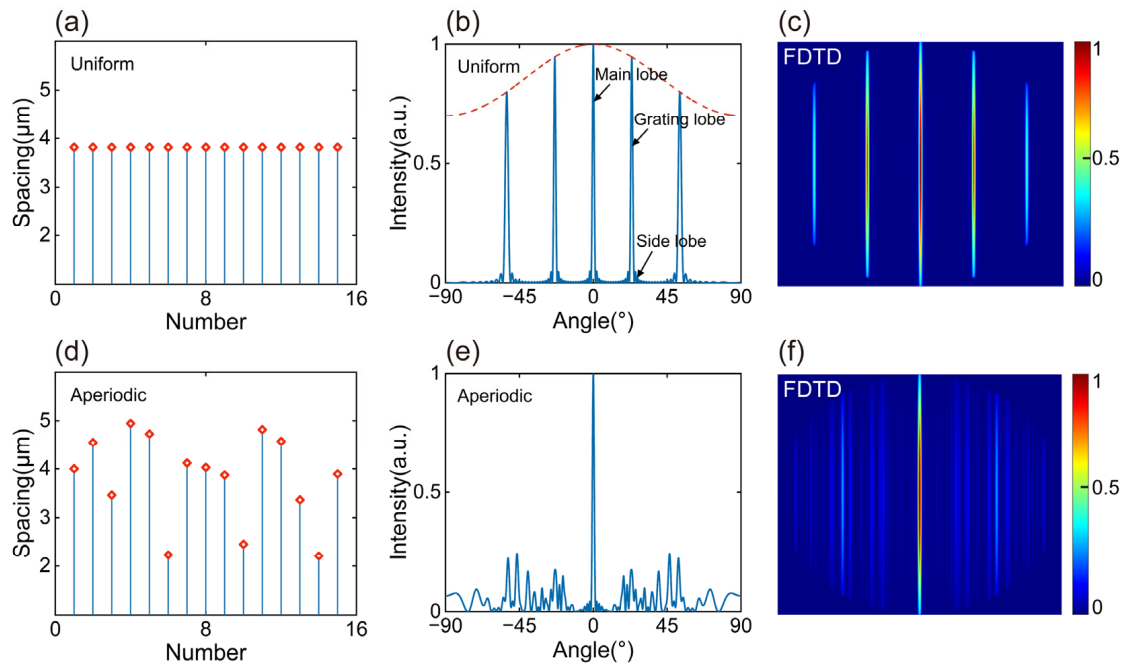


Figure 3. (a) The spacing distribution, (b) normalized far-field pattern, and (c) 2D far-field pattern of the 16-channel uniform OPA. (d) The spacing distribution, (e) normalized far-field pattern, and (f) 2D far-field pattern of the 16-channel aperiodic OPA.

3. Aperiodic Antenna Array Optimization

To effectively suppress grating lobes and side-lobe level, we use a multi-strategy enhanced PSO algorithm in MATLAB to design for the aperiodic OPAs. PSO is a typical swarm intelligence algorithm where each solution is considered a “particle” in the search space. It has the advantages of being simple to compute and easy to implement, and requires few control parameters.

3.1. Principle of Spacing Distribution Optimization

In the process of optimizing antenna spacing distribution, PSLL is used for fitness evaluation to assess the quality of the spacing distribution, which is expressed as

$$\text{PSLL} = 10 \log_{10} \left(\frac{I_{\text{max-side-lobe}}}{I_{\text{main-lobe}}} \right) \quad (5)$$

where $I_{\text{max-side-lobe}}$ is the intensity of the maximum side lobe, and $I_{\text{main-lobe}}$ is the intensity of the main lobe. However, most reported aperiodic OPAs use the PSLL at 0° for fitness evaluation, which leads to a rapid rise in side-lobe level and an increase in background noise during scanning. In this study, we investigate the performance of spacing distributions obtained by using PSLL at different steering angles as the fitness function, which can be expressed as

$$\text{Fitness} = \text{PSLL}_{\theta_s} \quad (6)$$

where θ_s is the steering angle. The target steering range in this work is $\pm 60^\circ$, with θ_s set to $0^\circ, 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ$, and 60° , respectively. For an aperiodic antenna array with N channels, the mathematical model of the optimization problem can be expressed as

$$\begin{cases} \min \text{PSLL} \\ \text{s.t. } \min(d_1, d_2, \dots, d_{N-1}) \geq d_{\min}, \\ \quad \max(d_1, d_2, \dots, d_{N-1}) \leq d_{\max} \end{cases} \quad (7)$$

where $d_{\min}$ and $d_{\max}$ denote the minimum spacing and the maximum spacing, respectively.

3.2. Algorithm Optimization Process

The original PSO algorithm only uses the rand function for population initialization, as shown in Figure 4a. This causes an uneven population distribution, directly affecting the convergence performance and search efficiency of the algorithm. Chaotic mapping possesses characteristics such as randomness, non-repetition, and chaotic traversal, which ensure a uniform population distribution [21]. Therefore, we adopt a circular chaotic mapping strategy for population initialization [22], as shown in Figure 4b. The comparison shows that using circular chaotic mapping produces a more evenly distributed spatial arrangement, thereby enhancing the PSO algorithm's search capability.

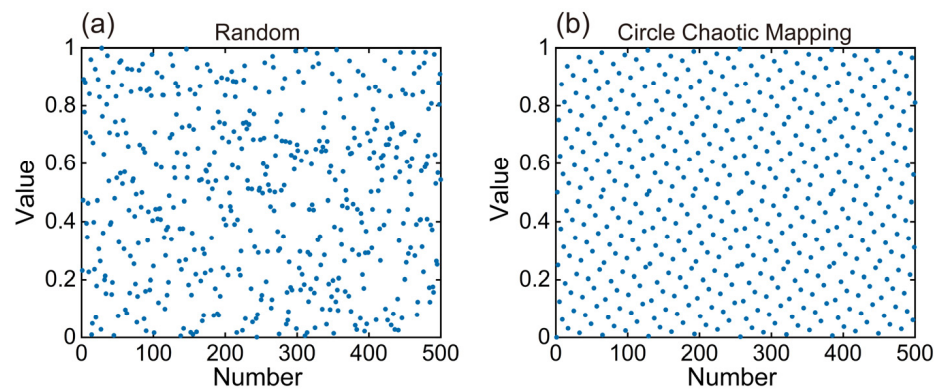


Figure 4. Initialization distribution of (a) random function and (b) circle chaotic mapping strategy.

All particles in PSO update their velocity and position based on their personal best position and the global best position identified in the population. In this step, we introduce an adaptive inertia weight ω and dynamic learning factors c_1 and c_2 , which are defined as follows:

$$\omega = \omega_{\min} + (\omega_{\max} - \omega_{\min}) \cdot \sin\left[\frac{\pi}{2} \cdot \left(1 - \frac{t}{T_{\max}}\right)\right] \quad (8)$$

$$c_1 = 2 \sin^2\left[\frac{\pi}{2} \left(1 - \frac{t}{T_{\max}}\right)\right] \quad (9)$$

$$c_2 = 2 \sin^2\left(\frac{\pi t}{2T_{\max}}\right) \quad (10)$$

where $\omega_{\max}$ and $\omega_{\min}$ represent the minimum and maximum values of ω , respectively, set to 0.9 and 0.3; $T_{\max}$ denotes the maximum number of iterations, set to 1000; and t denotes the current iteration. Figure 5 presents the values of these three parameters as functions of the iteration numbers. In the early stages, ω and c_1 are set to larger values, while c_2 is initialized with a smaller value to encourage broader exploration of the solution space and increase the probability of finding the global optimum. In the later stages, ω and c_1 are gradually reduced, while c_2 is increased to prioritize the exploitation of promising regions, thereby enhancing convergence accuracy.

The update formation is expressed as

$$V_{ij}^{(t+1)} = \omega \cdot V_{ij}^{(t)} + c_1 \cdot r_1 \cdot (pbest_{ij}^{(t)} - X_{ij}^{(t)}) + c_2 \cdot r_2 \cdot (gbest_j^{(t)} - X_{ij}^{(t)}) \quad (11)$$

$$X_{ij}^{(t+1)} = X_{ij}^{(t)} + V_{ij}^{(t+1)} \quad (12)$$

Here, $i = 1, 2, \dots, K$, $j = 1, 2, \dots, D$, where K is the population number, set to 80, and D is the dimensionality of the particles (i.e., the number of spacings). V and X represent

the velocity and position of particles, respectively, r_1 and r_2 are random numbers between 0 and 1, and pbest and gbest represent the personal best position of each particle and the global best position among all particles, respectively.

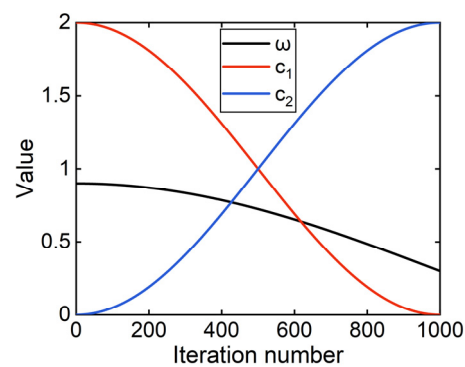


Figure 5. Adaptive inertia weight and dynamic learning factors as functions of the iteration numbers.

The process of the enhanced PSO for antenna spacing distribution is illustrated in Figure 6, and the steps are described as follows:

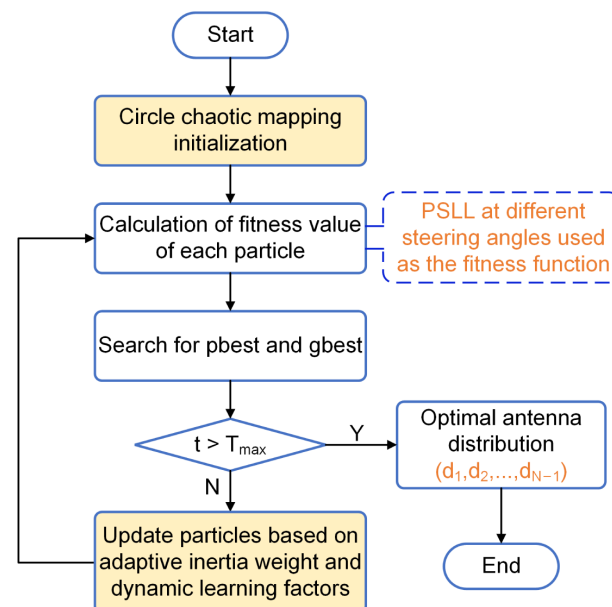


Figure 6. Optimization process of antenna spacing distribution based on the enhanced PSO algorithm.

Step 1: Set the population numbers K and the maximum number of iterations $T_{\max}$. Generate initial particles based on the minimum spacing $d_{\min}$, maximum spacing $d_{\max}$, and number of channels N . In this work, we study antenna arrays with $N = 32$ and $N = 64$.

Step 2: Calculate the fitness values of particles. In this study, the PSLL at different steering angles is used as the fitness function (Equation (7)) where particles with smaller fitness values are considered better.

Step 3: Determine pbest and gbest. The historical best solution found by each particle is considered its individual optimal solution, referred to as pbest. Then, the best solution among all individual optimal solutions is selected as the global optimal solution, referred to as gbest.

Step 4: Update particles based on Equations (11) and (12). At the final iteration, the optimal spacing distributions $(d_1, d_2, \dots, d_{N-1})$ of the 32- and 64-channel aperiodic OPAs are determined.

3.3. Optimization Results

According to Equation (7), we use the PSLL at seven different steering angles as the fitness function, resulting in seven distinct spacing distributions. For 32- and 64-channel aperiodic OPAs, the PSLL variations during scanning from 0° to 60° for these solutions are shown in Figure 7a,b, respectively. As shown in Figure 8, for all solutions, PSLL decreases as the steering angle increases. Notably, as the optimized steering angle increases, there is a degradation in PSLL at small steering angles but an improvement at large steering angles. For the 32- and 64-channel aperiodic OPAs, when the optimized steering angles are 20° and 40° , respectively, compared to 0° , the PSLL slightly decreases at small steering angles but shows significant improvement at larger angles.

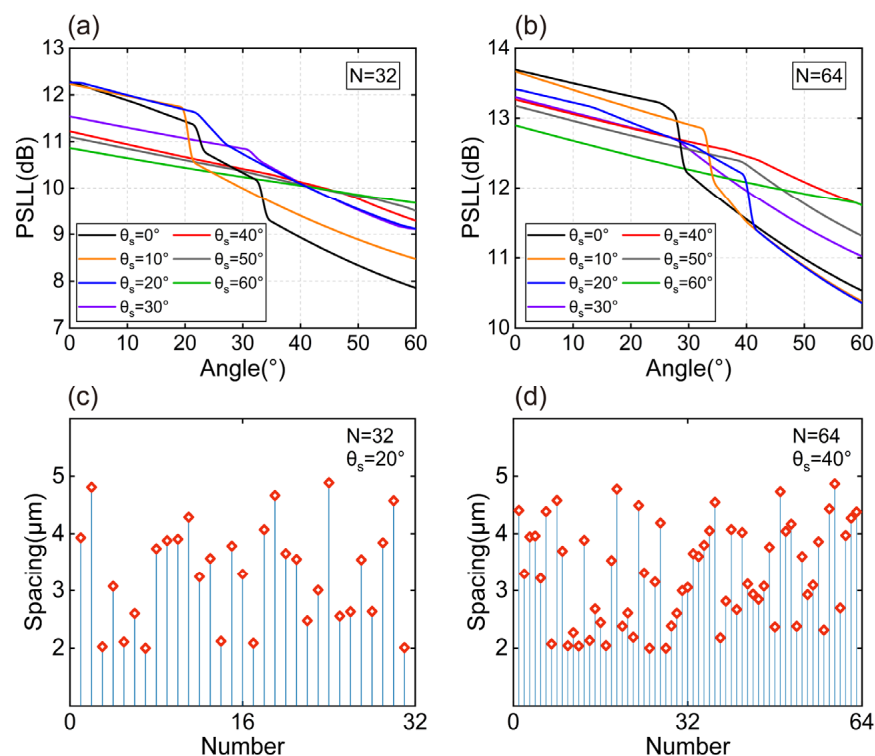


Figure 7. PSLL versus steering angle for the (a) 32- and (b) 64-channel aperiodic OPAs optimized with different steering angles. (c) Spacing distribution for the 32-channel aperiodic OPA optimized at the steering angle of 20° . (d) Spacing distribution for the 64-channel aperiodic OPA optimized at the steering angle of 40° .

For ease of expression, we define Fitness_{0° , $\text{Fitness}_{20^\circ}$, and $\text{Fitness}_{40^\circ}$ as the fitness functions corresponding to optimized steering angles of 0° , 20° , and 40° , respectively. A comparison between the results for the 32-channel OPA using Fitness_{0° and $\text{Fitness}_{20^\circ}$ shows that $\text{Fitness}_{20^\circ}$ reduces the PSLL by only 0.03 dB near 0° but increases the PSLL by approximately 1.2 dB from 35° to 60° . Similarly, for the 64-channel OPA, $\text{Fitness}_{40^\circ}$ decreases the PSLL by about 0.36 dB from 0° to 28° , but significantly increases the PSLL by more than 1 dB from 40° to 60° . These comparisons show the reduction in the side-lobe level and the improvement in PSLL achieved by the proposed design. The antenna spacing distributions of the 32- and 64-channel aperiodic OPAs are shown in Figure 7c,d, respectively. Both OPAs have an average spacing of $3.3 \mu\text{m}$ (2.13λ), with aperture sizes of $103 \mu\text{m}$ and $208 \mu\text{m}$ for the 32- and 64-channel OPAs, respectively.

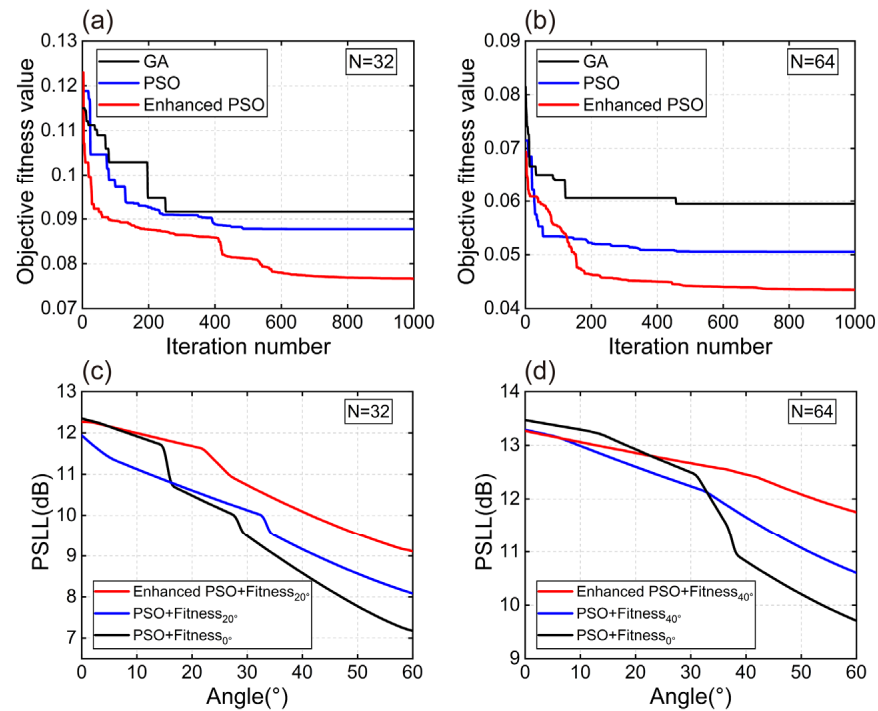


Figure 8. Objective function values for (a) 32- and (b) 64-channel aperiodic OPAs. PSLL versus steering angle for the (c) 32- and (d) 64-channel aperiodic OPAs.

We compared the optimization results of 32- and 64-channel aperiodic OPAs using the multi-strategy enhanced PSO algorithm, the traditional PSO algorithm [4,13–18], and the GA [8,10–12]. These algorithms were tested under the same conditions, with the maximum iteration number set to 1000. For the 32- and 64-channel OPAs, these algorithms used $Fitness_{20^\circ}$ and $Fitness_{40^\circ}$ as the fitness functions, respectively. The optimization results over 1000 iterations are shown in Figure 8. For the 32-channel OPA, the traditional PSO algorithm and GA converged at the 480th and 255th iterations, respectively, while the enhanced PSO algorithm converged at the 700th iteration, producing a significantly better solution. As shown in Figure 8c, the 32-channel OPA optimized by the enhanced PSO maintains a higher PSLL during scanning, with a 1.04 dB improvement at 60° compared to the traditional PSO algorithm. For the 64-channel OPA, the traditional PSO algorithm and GA converged at the 460th and 457th iterations, respectively, while the enhanced PSO algorithm converged at the 730th iteration. However, by the 150th iteration, the enhanced PSO had already outperformed the best solutions of the traditional PSO and GA. As shown in Figure 8d, the 64-channel OPA optimized by enhanced PSO shows a 1.3 dB improvement in PSLL at 60° compared to the traditional PSO algorithm. Therefore, the multi-strategy enhanced PSO algorithm shows superior search capabilities.

We simulated the 32- and 64-channel aperiodic OPAs using the traditional PSO and $Fitness_{0^\circ}$, with the results of the PSLL variations during scanning shown in Figure 8c,d, respectively. It can be observed that for the 32-channel OPAs, our method improves the PSLL by 1.94 dB at 60° , and with an improvement of 2.05 dB at 60° for the 64-channel OPA, indicating a significant increase in PSLL across the wide-angle steering range.

Taking the 64-channel aperiodic OPAs as an example, the far-field intensity distribution patterns obtained at 60° are shown in Figure 9. A comparison reveals that the FWHM remains nearly the same, while the prominent high-intensity side lobes are effectively suppressed, resulting in a reduction in the overall side-lobe level. This indicates that our method effectively suppresses the rapid deterioration of PSLL during scanning.

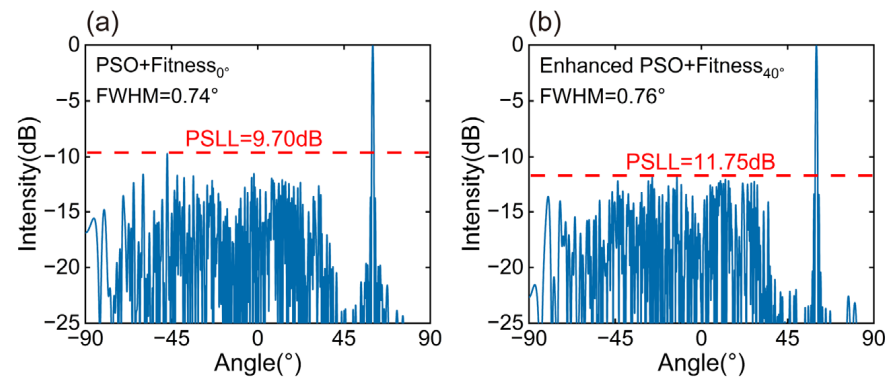


Figure 9. The far-field patterns of 64-channel aperiodic OPAs: (a) with the traditional PSO algorithm and Fitness_{0° and (b) with the enhanced PSO algorithm and $\text{Fitness}_{40^\circ}$.

Figures 10 and 11 present the far-field patterns from analytical and numerical simulations for the 32- and 64-channel aperiodic OPAs, respectively. It can be observed that the numerical simulation results at 0° outperform the analytical simulations, with the PSLL of both OPAs being about 0.3 dB higher. At the large steering angle of 60° , the PSLL decreases by 1.83 dB and 2.04 dB for the 32- and 64-channel OPAs, respectively. This discrepancy is due to the idealized handling of far-field interference in the analytical simulations. However, the analytical and numerical simulation results show good agreement with key metrics such as the main lobe position, full width at half maximum (FWHM), and far-field intensity distribution. For these two aperiodic OPAs, the FWHM ranges from 0.74° to 1.46° and from 0.39° to 0.76° , respectively, maintaining a high resolution and beam directivity during scanning. Moreover, increasing the number of channels can further reduce the FWHM, thereby achieving higher resolution.

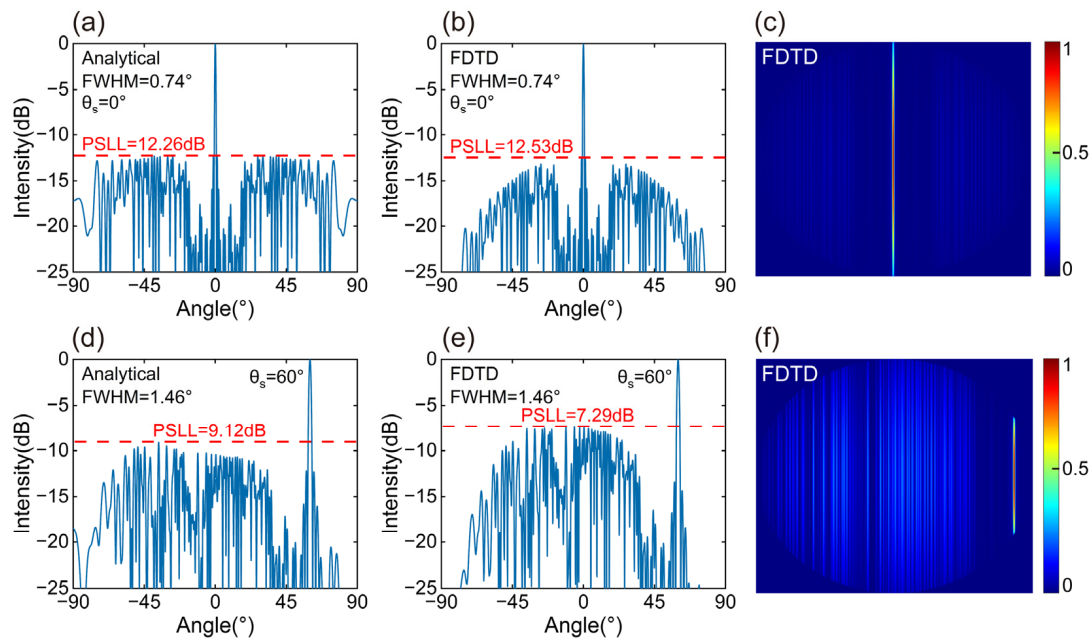


Figure 10. The far-field patterns of the 32-channel aperiodic OPA at 0° for (a) the analytical results and (b) the numerical results. (c) The 2D far-field pattern of the 32-channel aperiodic OPA at 0° . The far-field patterns of the 32-channel aperiodic OPA at 60° for (d) the analytical results and (e) the numerical results. (f) The 2D far-field pattern of the 32-channel aperiodic OPA at 60° .

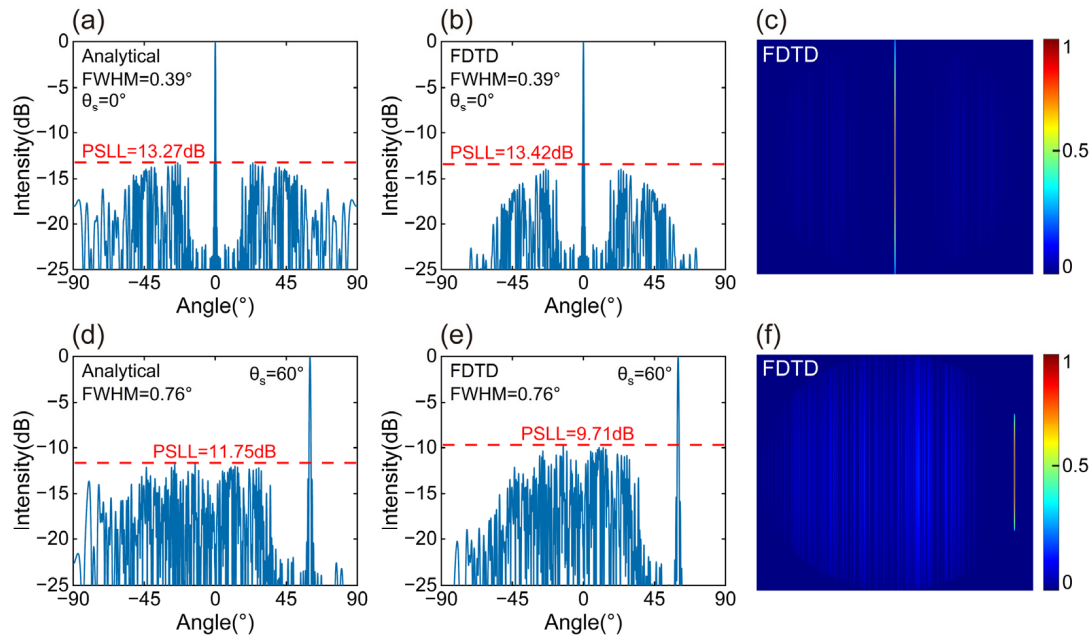


Figure 11. The far-field patterns of the 64-channel aperiodic OPA at 0° for (a) the analytical results and (b) the numerical results. (c) The 2D far-field pattern of the 64-channel aperiodic OPA at 0° . The far-field patterns of the 64-channel aperiodic OPA at 60° for (d) the analytical results and (e) the numerical results. (f) The 2D far-field pattern of the 64-channel aperiodic OPA at 60° .

Two-dimensional beam scanning includes horizontal beam scanning and vertical beam scanning. For 1D OPAs, horizontal beam scanning is achieved by changing the phase difference between adjacent antennas. In contrast, vertical beam scanning is achieved by changing the wavelength of the input laser, thereby adjusting the emission angle of the antennas. Therefore, the sensitivity of the scanning performance of 1D aperiodic OPAs to wavelength variations is also an important factor to consider. For the 32- and 64-channel aperiodic OPAs, the PSLL variations were tested at steering angles of 0° , 30° , and 60° with wavelength changes from 1500 nm to 1600 nm in 10 nm increments, as shown in Figure 12a,b, respectively. It can be observed that the PSLL of both the 32- and 64-channel OPAs remains almost unchanged at 0° and 30° , while at 60° , within a 100 nm bandwidth, the variations are approximately 0.25 dB and 0.19 dB, respectively. Therefore, the designed OPAs combined with wavelength tuning can maintain high stability.

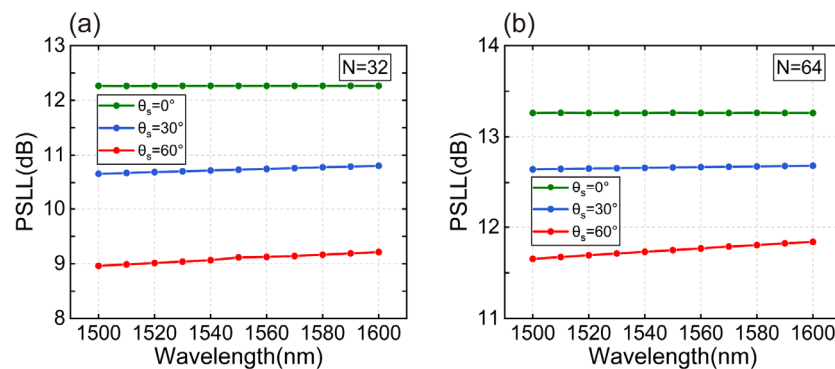


Figure 12. PSLL versus the wavelength at steering angles of 0° , 30° , and 60° for the aperiodic OPAs with (a) 32 channels and (b) 64 channels.

4. Error Analysis

This paper assumes that the optimized and actual spacings are completely consistent. However, unavoidable manufacturing errors [2,9,23] always lead to antenna position deviations. Therefore, it is crucial to analyze the effects of spacing deviations on PSLL.

In practical fabrication, spacing deviations typically occur in one direction, resulting in either an increase or a decrease in all spacings. For the antenna spacing d_i ($i = 1, 2, \dots, N - 1$), we use Δd_i as the spacing error of d_i , following a uniform distribution. Thus, the actual antenna spacing is $d_i + \Delta d_i$. The antenna spacing deviation is defined as Δd . When $\Delta d < 0$, Δd_i is uniformly and independently distributed in $[\Delta d, 0]$, whereas when $\Delta d > 0$, Δd_i is uniformly and independently distributed in $[0, \Delta d]$.

To ensure reliability, we conducted 300 tests for each spacing deviation and averaged the results. The results are shown in Figure 13. As Δd decreases from 0 to -100 nm, for the 32-channel OPA, when $\Delta d > -40$ nm, the PSLL remains almost unchanged, and when $\Delta d = -100$ nm, the PSLL decreases by 0.54 dB. For the 64-channel OPA, when $\Delta d > -20$ nm, the PSLL remains almost unchanged, and when $\Delta d = -100$ nm, the PSLL decreases by 0.45 dB. As Δd increases from 0 to 100 nm, the PSLL generally exhibits a decreasing trend. For the 32-channel OPA, when $\Delta d < 30$ nm, the PSLL remains almost unchanged, and when $\Delta d = 100$ nm, the PSLL decreases by 0.72 dB. For the 64-channel OPA, when $\Delta d = 100$ nm, the PSLL decreases by 0.61 dB. Comparisons show that the impact of spacing increases is greater than that of spacing decreases. The above analysis shows that our design exhibits high robustness to spacing deviations.

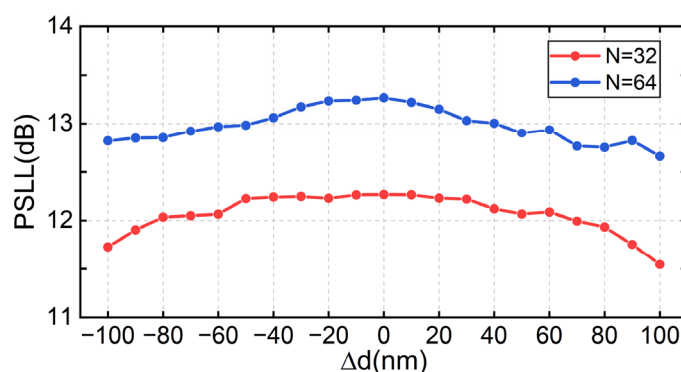


Figure 13. Influence of spacing deviations on PSLL.

5. Conclusions

To conclude, we have proposed a multi-strategy enhanced PSO algorithm, which exhibits stronger global search capability compared to the traditional PSO algorithm and the GA. We used the PSLL at different steering angles as the fitness function to optimize the antenna spacing distributions for 32- and 64-channel aperiodic OPAs. Through this design method, we effectively suppress grating lobes and mitigate the rapid degradation of the PSLL during beam steering. Within a scanning range of $\pm 60^\circ$, for the 32-channel OPA, the PSLL ranges from 12.26 to 9.12 dB, with the FWHM varying from 0.74° to 1.46° ; for the 64-channel OPA, the PSLL ranges from 13.27 to 11.75 dB, and the FWHM varies from 0.39° to 0.76° . In addition, the numerical simulation results obtained using 3D-FDTD are in good agreement with the analytical results. The variation in PSLL remains below 0.72 dB within a 100 nm spacing deviation range, indicating the robustness of the antenna arrays. Therefore, our OPAs meet the requirements for various applications such as LiDAR, free-space optical communication, and other fields.

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