



Optically controlled phased array transmitter with a controllable main lobe and null

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Abstract: Phased array transmitters often operate in contested electromagnetic environments. To achieve secure transmission and low probability of intercept operation, flexible beam control and generating a null to reduce radiation toward undesired directions are critical. In this work, a wideband optically controlled phased-array (OCPA) transmitter with flexible and independent control of the main lobe and null from a system control perspective is proposed. The proposed system integrates a spatial filter module consisting of an optical true-time delay network and balanced photodetectors. Simulation results for a 16-element OCPA based on the proposed architecture demonstrate that the main lobe and null can be scanned over a range of at least $\pm 40^\circ$ while maintaining a null depth greater than 50 dB. A proof-of-concept experiment is further carried out using a 5-element OCPA transmitter. The results show that the main lobe and null can be independently steered, with a null depth exceeding 50 dB.

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1. Introduction

Phased array systems have been widely employed in modern radar and communication applications due to their capability for directional transmission and rapid beam scanning. As the electromagnetic environment becomes increasingly complex, phased array systems face growing interference. To ensure stable operational performance and survivability of radar systems, steering nulls in specific directions of the direction pattern is highly required to suppress interference and realize a low probability of intercept [1–3]. Furthermore, as the operating bandwidth of phased array systems continues to increase, higher requirements are imposed on the broadband consistency of the nulls.

In terms of null steering for phased array systems, electrical domain solutions can be divided into two categories: those based on adaptive algorithms and those based on hardware architecture design. The method in the first category obtains the required amplitude and phase weights for each array element using algorithms. Then the amplitude and phase are adjusted using phase shifters and attenuators accordingly to realize flexible control of the main lobe and nulls [4,5]. The methods in the second category realize null steering by designing antenna elements or subarrays to establish specific amplitude-phase relationships between different channels. These methods would produce directional destructive interference [6,7] and significantly reduce the real-time computational load for null steering. Overall, the electronic solution has a solid foundation in mature RF electronic components and antenna technologies, making it easy to implement and highly integrated in system design. However, traditional electronic phased array systems typically use phase shifters to control the main lobe and nulls. Since electronic phase shifters provide frequency-independent phase shifts, beam squint occurs under broadband conditions.

Meanwhile, the null would drift with frequency, making it difficult to maintain stable interference suppression at a fixed angle within broadband.

Optically controlled phased arrays (OCPAs) employ true time delay technology instead of phase shifters to provide frequency-proportional linear delays, enabling broadband beam control without beam squint [8–12], while also providing the prerequisite for achieving broadband nulls. Current null steering methods with OCPA can also be divided into two categories: algorithm-based and hardware-based. The algorithm-based null steering method for OCPA obtains amplitude and phase weights for beam and null control through algorithms while relying on an optical beamforming network to precisely adjust the delay and amplitude of each array element. This method integrates the adaptive flexibility of algorithmic control with the broadband processing capability of microwave photonics, enabling dynamic adaptation to complex interference environments [13]. For example, Li et al. used a HJ-LCMV algorithm and implemented amplitude/phase tuning through an optical beamforming network, achieving adaptive deep null steering in interference directions while maintaining the desired main lobe response [14]. However, these approaches may introduce additional system complexity, latency, and bandwidth limitations, especially when applied to wideband signals.

In parallel, hardware-based approaches have also been investigated for broadband null steering. Several studies have explored broadband null steering in OCPAs. One mainstream method is based on spectral shaping. Frankel et al. [15,16] introduced an auxiliary photonic filtering branch in parallel with the beamforming link. The auxiliary branch generates a microwave waveform in the desired null direction, which destructively interferes with the main beam in the far field, thereby forming a directional null. However, the parallel branch in this structure requires two ‘electro-optic-electro’ conversion processes, resulting in approximately 20 dB more loss than the main beam branch. Mengual et al. [17] utilized multiple wavelengths and dispersions to construct a multi-tap filter of the same array size, which achieved delay and weighting in the optical domain. In this method, null generation and control require only a single optical-to-electrical conversion process. In addition, the method can achieve the best suppression by knowing the main lobe radiation pattern in advance. Another type of method is based on array-polynomial synthesis, in which the null positions are controlled by placing the zeros of the array factor. Zmuda et al. [18,19] proposed an OCPA capable of generating multiple nulls. This architecture constructs a multi-tap microwave photonic filter using optical delay lines and employs weighted combining to achieve dynamic null steering. However, the number of required operating wavelengths increases significantly with the array scale, making this method considerable wavelength-resource consumption. In addition, when the null position is changed, this method may require an adaptive weight-adjustment mechanism, which introduces additional computational overhead and system complexity.

In this paper, we propose an OCPA transmitter that enables independent control of the main-lobe direction and the null direction from a system control perspective. The proposed system cascades an optical true-time delay beamforming network with a spatial filtering module. Compared with existing methods, the proposed approach is capable of generating nulls with minimal wavelength resources and does not require prior knowledge of the initial radiation pattern. Moreover, no adaptive algorithms are required for system control, thereby reducing system complexity and hardware cost.

The paper is organized as follows. Section II discusses the principles and architecture of the system. Section III verifies the feasibility of the system and discusses the relationship between the main lobe and the null through hardware-in-the-loop (HIL) simulation. Section IV presents a proof-of-concept experiment based on a 5-element linear array system. Finally, the concluding remarks are presented in Section V.

2. Principle

The structure of the proposed OCPA transmitter and the corresponding output beam pattern are shown in Fig. 1. An RF signal to be transmitted, with an angular frequency of ω_m , is modulated onto an optical carrier at ω_c using a Mach-Zehnder modulator (MZM). Under small-signal modulation, the modulated optical signal can be expressed as:

$$E \propto A_{-1}e^{j(\omega_c - \omega_m)t} + A_0e^{j\omega_c t} + A_1e^{j(\omega_c + \omega_m)t} \quad (1)$$

where $A_i = J_i(\gamma)$ is a complex coefficient related to the modulation format, J_i is the i th-order Bessel function of the first kind, and γ is the modulation index. After passing through the optical coupler (OC), the signal is equally divided into $N-1$ paths, each carrying the same signal component. In the n th path, the first delay control module (DCM) introduces a delay difference $(n-1)T$ relative to the first path. Each path is then divided into upper and lower branches, which are fed into the corresponding second-stage DCM. The second DCM consists of a fiber and a tunable delay line (TDL) connected in parallel. The TDLs in all lower branches provide the same delay τ . Accordingly, for the n th path from DCM1, the optical signal in the upper branch of DCM2 is given by:

$$E_{up,n} \propto e^{j\omega_c[t-(n-1)T]}(A_{-1}e^{-j\omega_m[t-(n-1)T]} + A_0 + A_1e^{j\omega_m[t-(n-1)T]}), \quad (2)$$

and the optical signal in the lower branch is given by:

$$E_{low,n} \propto e^{j\omega_c[t-(n-1)T-\tau]}(A_{-1}e^{-j\omega_m[t-(n-1)T-\tau]} + A_0 + A_1e^{j\omega_m[t-(n-1)T-\tau]}), \quad (3)$$

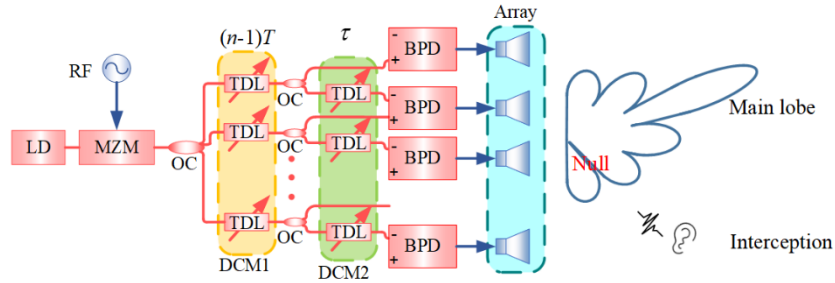


Fig. 1. Structure of the proposed OCPA transmitter and corresponding output beam pattern. LD: laser diode; MZM: Mach-Zehnder modulator; DCM: delay control module; OC: optical coupler; TDL: tunable delay line; BPD: balanced photodetector.

Next, the two branches are fed into opposite input ports of two adjacent balanced photodetectors (BPDs). For the n th path from DCM1, the upper-branch signal is delivered to the negative input port of the n th BPD, while the lower-branch signal is delivered to the positive input port of the $(n+1)$ th BPD. The resulting photocurrent from each BPD can be expressed as:

$$I \propto \text{Re} \begin{pmatrix} -e^{j\omega_m t} \\ e^{j\omega_m(t-(n-1)T-\tau)} - e^{j\omega_m(t-nT)} \\ e^{j\omega_m(t-(n-1)T-\tau)} \end{pmatrix}, \quad \begin{matrix} n = 0 \\ n = 1, \dots, N-1 \\ n = N \end{matrix} \quad (4)$$

where $\text{Re}(\cdot)$ denotes the real parts.

Finally, considering the free-space path differences, the array far-field radiation function of the array is given by:

$$F \propto \left(e^{-j\omega_m(\tau - \frac{d \sin \theta}{c})} - 1 \right) \sum_{n=0}^{N-2} e^{jn\omega_m(\frac{d \sin \theta}{c} - T)} \quad (5)$$

$$\propto \left(\cos \omega_m \left(\frac{d \sin \theta}{c} - \tau \right) - 1 \right) \frac{\sin \frac{(N-1)\omega_m}{2} \left(\frac{d \sin \theta}{c} - T \right)}{\sin \frac{\omega_m}{2} \left(\frac{d \sin \theta}{c} - T \right)}$$

where d is the spacing between adjacent elements, c is the speed of light in free space, and θ is the scanning angle. According to the above expression, the total radiation pattern of the system is the product of the null steering factor and the array factor corresponding to the main beam pattern (named sub-array array factor). The main lobe is controlled by $\theta_b = \arcsin(T \cdot c/d)$, whereas the null is controlled by $\theta_{\text{null}} = \arcsin(\tau \cdot c/d)$. Since the null steering factor influences the total radiation pattern, the position of the null is frequency-independent due to the fact that the null steering factor is equal to 0 at target direction. In this case, the direction and depth of the null remain stable throughout the entire operating bandwidth without requiring prior knowledge of the initial radiation pattern. For the peak amplitude of the main lobe in the total radiation pattern, due to the frequency response of the null steering factor, there are certain variations. However, this factor is a known function which it is easy to compensate for the amplitude variation using pre-distortion technology, ensuring the amplitude stability in the wideband scenario. Moreover, the delays used to control the main lobe and the null are independently governed by the two-stage DCMs from a system control perspective. As a result, the proposed OCPA transmitter eliminates the need for adaptive weight adjustment, thereby reducing the computational burden.

Furthermore, from the perspective of the total array factor, there is an inter-tuning effect between the main lobe and the nulls. The total array factor can be rewritten as $AF(u) = Z(u-v)B_M(u)$, where Z and B_M are null steering factor and the sub-array factor; $u = \omega_m d(\sin \theta - \sin \theta_b)/c$, $v = \omega_m d(\sin \theta_{\text{null}} - \sin \theta_b)/c$; θ_b and θ_{null} are point of the main lobe and null. The expanding locally around $u = 0$, the main lobe deflection angle u_p satisfies

$$u_p \approx - \frac{\frac{\partial}{\partial u} \ln |Z(u, v)|^2 \big|_{u=0}}{\frac{\partial^2}{\partial u^2} \ln |B_M(u)|^2 \big|_{u=0} + \frac{\partial^2}{\partial u^2} \ln |Z(u, v)|^2 \big|_{u=0}} \quad (6)$$

For the first-order null factor used in Eq. (5), this yields

$$u_p \approx - \frac{\cot(v/2)}{(M^2 - 1)/6 + \frac{1}{2} \csc^2(v/2)}, M = N - 1 \quad (7)$$

In summary, the null steering factor causes the actual main lobe to shift by multiplicative modulation. This shift depends on the spacing between the main lobe and the null, as well as the array size. When the space between the two is large, the main lobe peak offset caused by the null is sufficiently small, where the proposed scheme has the capability to work in a broadband. It should be noted that when the null approaches near the main lobe, local expansion is no longer applicable, and numerical solutions based on the total array factor should be used to determine the actual main lobe point.

3. Simulation results

3.1. Hardware-in-the-loop simulation

The radiation pattern of the OCPA transmitter is formed by the coherent superposition of the signals radiated from all paths. To verify the feasibility of the proposed OCPA transmitter, a

single-link-based HIL simulation is carried out. The experimental setup is shown in Fig. 2. A swept-frequency signal from 10 MHz to 40 GHz, generated by a vector network analyzer (VNA, R&S ZNA67) is applied to an MZM (FTM7980EDA) to modulate an optical carrier. The modulated optical signal is then split into upper and lower branches. The two branches are connected to opposite input ports of two adjacent BPDs (u2t-BPDV2150R-40G) through TDLs. Finally, the generated photocurrent signal is fed back to the VNA for phase measurement. By measuring the transmission response of a single path under different delay settings, the radiation pattern of the transmitter can be reconstructed.

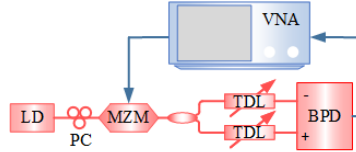


Fig. 2. Experimental setup for link response measurement. VNA: vector network analyzer.

In the experiment, one branch is disconnected from the BPD so that the transmission response of the other branch can be measured independently. The response with the TDL set to 0 ps is used as the reference. The link responses at TDL settings of 1 ps, 5 ps, and 10 ps are then measured. The phase deviations are obtained by comparing the measured results with the theoretical values, as shown in Fig. 3. The phase errors in all three cases are less than 1° , corresponding to a delay error of 0.07 ps at 40 GHz, while the phase jitter remains below 0.2° . Based on the measured delay jitter and the superposition principle, the link response for any delay corresponding to an integer multiple of the delay step can be reconstructed in simulation. Owing to the negligible transmission loss of the optical fiber, variations in the signal amplitude during propagation are ignored in this study.

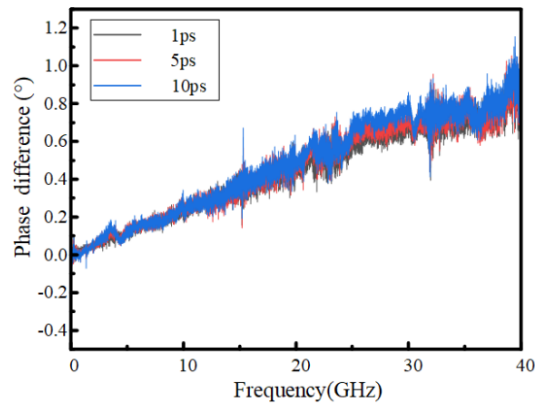


Fig. 3. Phase difference between the measured results and ideal results. Black, red, and blue lines represent the results when TDL is set to 1 ps, 5 ps, and 10 ps, respectively.

The system shown in Fig. 1 is further validated through HIL simulation. The simulated system consists of 16 array elements with an element spacing of 0.0125 m. The minimum delay step of the TDL is 1 ps. The transmitted waveform is a linear frequency modulation (LFM) signal sweeping from 8 to 12 GHz with a pulse width of 100 ns. The link response for main-lobe control is obtained as follows. First, the required time delay for each link is calculated according to the target direction and then rounded to the nearest available delay step. Next, the phase response

of each link is determined from the calculated delay. Phase jitter is then added to each link, where the jitter is generated by multiplying a random number within $(-1, 1)$ by the phase jitter measured in the experiment described above. In this way, the link response for main-lobe control is obtained. The link response for null steering is generated in the same manner.

Next, assume that the input signal power to each BPD is identical. The resulting correlation-maximum patterns (CMPs) [8] are shown in Fig. 4, where the main lobe and the null are steered to different directions. The actual directions of the main lobe and null are labeled in the figure. In addition, the inset shows a magnified view of the main lobe, and the blue arrow indicates the desired direction. Moreover, as a broadband phased array performance evaluation method, CMP can be used to analyze the consistency of the main lobe and the null over the entire operating bandwidth. The results demonstrate that the proposed system can steer the directions of the main lobe and the null in broadband scenarios. However, null steering introduces a certain deviation in the main-lobe direction, and this effect becomes more pronounced when the main lobe and null are close to each other in angle. For example, when the angular separation is approximately 40° , the main lobe deviation is less than 0.3° , whereas it increases to more than 2° when the separation is reduced to 10° . Fortunately, when the main lobe and null are steered within $\pm 40^\circ$, the desired direction remains within the effective beamwidth, i.e., the half-power beamwidth of the main lobe. For the null, a suppression depth greater than 50 dB is maintained during main lobe scanning.

3.2. Performance analysis

Based on the above results, further analyses are conducted to investigate the key factors affecting the performance of the proposed OCPA transmitter.

3.2.1. Effect of null steering on the main lobe

In this subsection, the influence of null steering on the main-lobe direction is investigated. The worst-case results obtained from multiple HIL simulation tests are used as the conservative performance evaluation for analysis in this paper. The main lobe is set to 10° , 20° , 30° , and 40° , while the null is steered from -40° to 40° .

Figure 5(a) shows that null steering affects the main-lobe direction. As the null approaches the main lobe, the main-lobe deflection increases, reaching a maximum of 3° . A similar trend is observed for the main-lobe-to-sidelobe suppression ratio (MSSR) in Fig. 5(b), where the degradation exceeds 8 dB when the null is close to the main lobe. Figure 5(c) further shows the variation in the main-lobe width caused by null steering. Although the main-lobe width decreases more rapidly as the null approaches the main lobe, its absolute variation remains below 1.5° . The above phenomenon includes the effect of spatial filter response on main lobe steering.

3.2.2. Effect of main-lobe control on null steering

This subsection analyzes the influence of main-lobe control on null steering, including its effects on both the null direction and the null depth. According to Eq. (5), the null direction is solely determined by the second term. However, phase jitter in the link and delay quantization errors can cause deviations from the ideal null direction. Therefore, the HIL simulation results are compared with the desired null-steering directions. The simulated null-direction deviations under different main lobe pointing angles are shown in Fig. 6(a), where different markers represent different main-lobe directions. The results show that the null direction deviation is less than 0.6° .

The effect of main-lobe control on the null depth is further shown in Fig. 6(b). As the main lobe approaches the null, the null-suppression capability becomes weaker. Nevertheless, even in the worst case near the steering boundary, the null depth remains approximately 50 dB. These results indicate that coupling exists between null steering and main-lobe control, leading to a trade-off between null-suppression performance and beamforming quality.

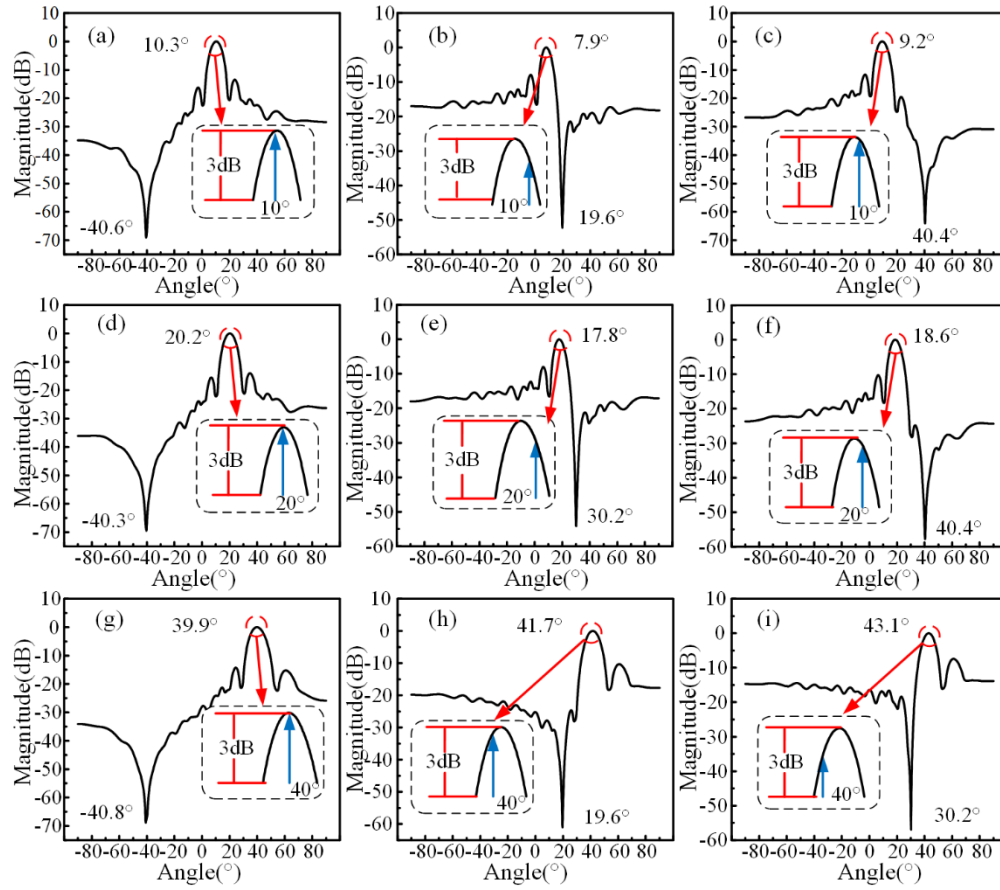


Fig. 4. CMPs of different main lobe and null. (a), (b) and (c) the main lobe is placed at 10° , while the null is placed at -40° , 20° and 40° ; (d), (e) and (f) the main lobe is placed at 20° , while the null is placed at -40° , 10° and 40° ; (g), (h) and (i) the main lobe is placed at 40° , while the null is placed at -40° , 20° and 30° . In the dotted box, magnified views of the main lobe are shown, where the blue arrows point to the target direction.

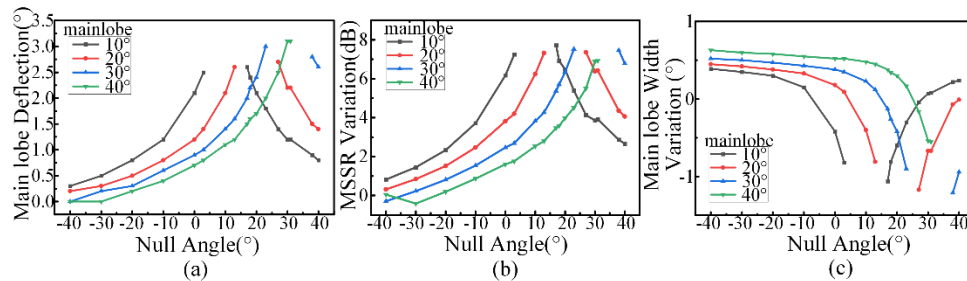


Fig. 5. (a) Deflection angle of the main-lobe direction caused by the null steering. (b) Main-lobe-to-sidelobe suppression ratio (MSSR) variation caused by the null steering. (c) Variation in main lobe width caused by the null steering. The four curves with different markers correspond to main-lobe 10° , 20° , 30° , and 40° , respectively.

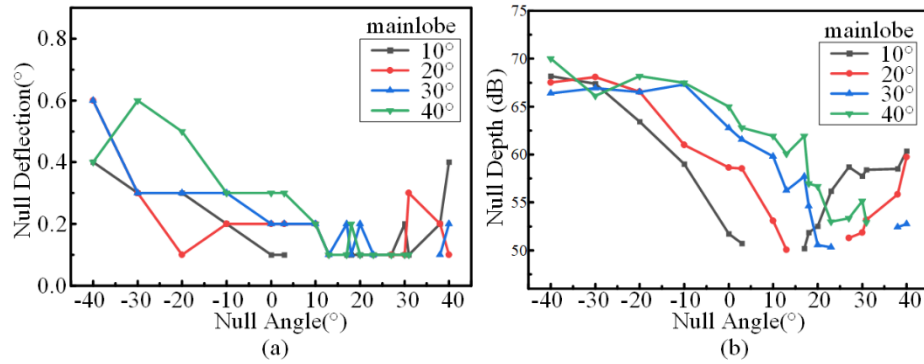


Fig. 6. (a) Deflection angle of the null direction for different main lobe pointing directions. (b) Null depth for different main lobe pointing directions. The four curves with different markers correspond to main-lobe 10°, 20°, 30°, and 40°, respectively.

3.2.3. Effect of array size on the main lobe and nulls

The above results indicate that coupling exists between main-lobe control and null steering. When the null direction is too close to the main lobe, the null depth deteriorates rapidly. To mitigate this interaction, increasing the array size is considered, since it can narrow the main-lobe width and reduce the overlap between the main lobe and the null. Therefore, the system performance under different array sizes is investigated. The numbers of array elements are set to 32, 48, and 64. Under the 50-dB null-depth boundary condition, the critical angle and the main lobe width are recorded for both the simulated and ideal jitter-free cases, as listed in Table 1. The results show that, as the array size increases, the simulated performance gradually approaches the jitter-free case. For the 48-element array, the critical angle of the system is only 3° wider and the main-lobe width is 0.2° wider than those of the jitter-free cases.

Table 1. Impact of array size on performance

Array size	16×	32×	48×	64×
Critical angle (°)	15	12	9	8
Main lobe width (°)	7	4	2.7	2.1
Critical Angle (Ideal) (°)	9	7	6	6
Main lobe width (Ideal) (°)	6.8	3.5	2.5	1.9

Taking the 20° main-lobe pointing case as an example, the impact of array size is further analyzed. Figure 7(a) shows the main lobe deflection angles for different array sizes. For arrays with 48 elements or more, the deflection angle is generally less than 0.4°. Although the deflection angle tends to increase near the critical angle, it remains below 0.8°. Figure 7(b) shows the corresponding MSSR. As the array size increases, the influence of null steering on the MSSR becomes weaker. This effect becomes more pronounced as the null direction approaches the critical angle. Compared with the 32-element array, the MSSR at the corresponding critical angle is improved by 1.43 dB and 2.48 dB for the 48- and 64-element arrays, respectively.

Furthermore, the effect of array size on null-steering performance is evaluated. The null directions obtained from the HIL simulations are compared with the desired null directions, and the corresponding deflections are shown in Fig. 8(a). The results indicate that the null deviation is less than 1° in all considered cases. Figure 8(b) further shows the null depth for different array sizes. It can be observed that the null depth increases as the array size increases. However, near the critical angle, increasing the array size provides only marginal improvement in the null depth.

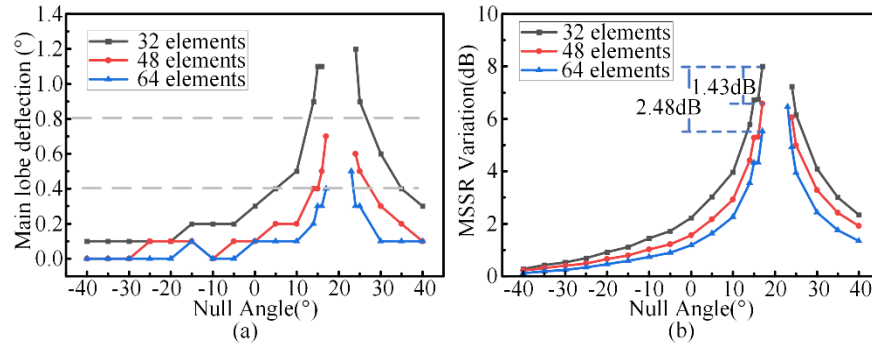


Fig. 7. (a) Deflection of the HIL-simulated main lobe caused by different null directions for different array sizes. (b) Variation in the HIL-simulated MSSR relative to that of the system without null steering for different array sizes. The three curves with different symbols represent cases when the array size is 32, 48 and 64.

When the null is far from the critical angle, the null depth is improved by approximately 10 dB compared with that of the 16-element array. These results indicate that increasing the array size can effectively improve the null depth, especially when the null is sufficiently separated from the critical angle. In conclusion, increasing the array size constitutes an effective solution for improving the overall performance of the system. Additionally, predistortion techniques can be leveraged to compensate for main lobe and null deflection.

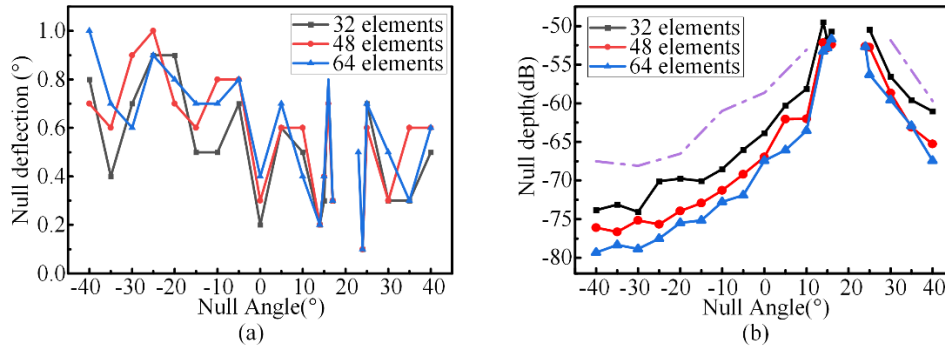


Fig. 8. (a) Deflection of the HIL-simulated null directions from the desired null directions for different array sizes. (b) Null depth for different array sizes. The three curves with different markers represent cases when the array size is 32, 48 and 64. The dash dot line in (b) represent 16-element system.

3.2.4. Comparison of the two schemes

Here, we selected the broadband null control system based on microwave photonic filter spectral shaping. (previous) as the main comparative approach. Consider a 16-element uniform linear array with an element spacing of 0.0125 m, an operating bandwidth of 8–12 GHz with the same main lobe and null settings, 20° and 0°. Under the assumption of the ideal system, the two-dimensional frequency-angle responses are shown in Fig. 9, exhibiting similar performance.

To further compare the differences between the two schemes, the normalized radiation patterns of 16-element and 64-element phased array systems are compared at a bandwidth center frequency of 10 GHz, as shown in Fig. 10. It can be seen that under ideal conditions, when the number

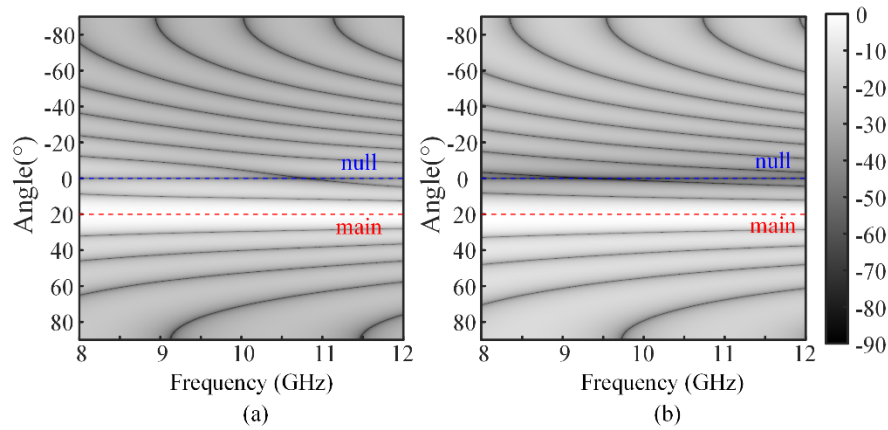


Fig. 9. 2-D frequency-angle response of (a) previous schemes, (b) proposed schemes. Main lobe and the null point to 20° and 0°.

of array elements is 16, the difference between the two schemes is mainly reflected in the main lobe and MSSR. Compared with the previous scheme, the proposed scheme shifts the main lobe outward by 1.2° and reduces the MSSR by 2.7 dB. When the array size increases to 64, the main lobe shift is approximately 0.1° while the MSSR decreases by about 1.06 dB, which can be neglected. In comparison, the proposed scheme still delivers suppression capability around the null. In summary, the proposed scheme features a wider null, while the other performs similarly to the previous scheme. The difference becomes smaller as the array element size increases.

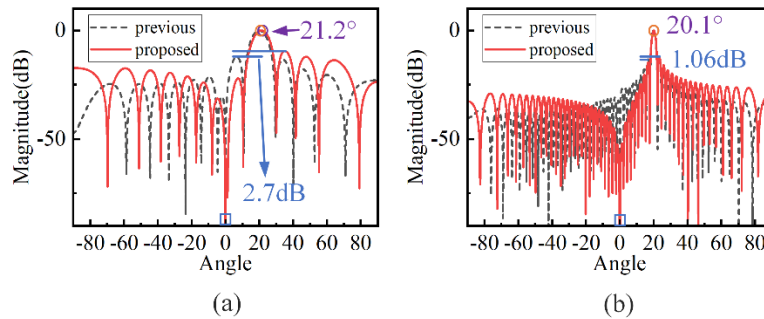


Fig. 10. Normalized radiation pattern at 10 GHz of two schemes. (a) 16-element array system, (b) 64-element array system.

4. Experiments and discussions

To further validate the feasibility of the proposed scheme, a simplified experimental system is established. A five-element beamforming system is constructed, as shown in Fig. 11. The system consists of two layers. The lower layer, shown in Fig. 11(b), contains the main optical components, including a narrow linewidth laser operating at 1550 nm, a 40-GHz intensity modulator (iXblue), a modulator bias controller, OC links indicated by the white box, and a TDL (YXODL-1550PM-1-150-0-FA). The TDL has eight channels, among which the first four channels act as primary DCMs for main-lobe control, while the remaining four channels serve as the secondary DCMs for null control. Through adjustable attenuators, the eight TDL outputs are connected to the upper layer. The upper layer, shown in Fig. 11(a), consists of five BPDs

(GD45235R) and five low-noise amplifiers (LAL-1112) of the same type, which are connected to the antenna array via RF cables. The radiation pattern of the system is measured in a microwave anechoic chamber. In the chamber test system, a VNA (PNA-L N5235A) is used for signal generation and far-field reception.

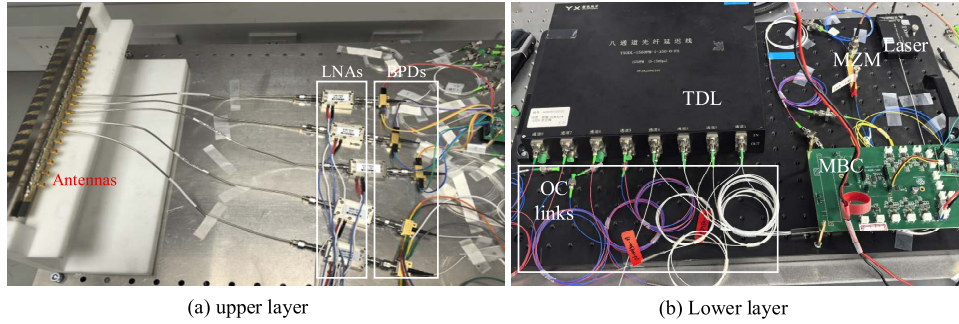


Fig. 11. Photos of the proposed 5-element OCPA transmitter. The (a) upper layer is the frontend structure, while the (b) lower layer is the main component of the system. LNAs: low-noise amplifiers, MBC: modulator bias controller.

First, the null-control capability of the system is verified. The VNA is configured to generate a 9-GHz RF signal. The null is then steered while the main lobe is fixed at -32° . The results are illustrated in Fig. 12(a), where the legend indicates the desired null direction. It can be observed that the null can be steered from 17° to 39° , with a null depth exceeding 50 dB. In addition, the scenario in which the main lobe is steered while the null remains fixed is also tested. As shown in Fig. 12(b), the nulls are directed at 29.5° , while the main lobes (fitted values) are pointed to -24.4° , -28.4° and -31.6° . These results are presented to better illustrate the capability of main-lobe steering. Moreover, the radiation pattern at 11 GHz is measured, as shown in Fig. 13. The blue dashed curve represents the radiation pattern of a conventional four-element linear array at 11 GHz. The black and red curves represent the radiation patterns of the proposed OCPA transmitter when the main lobe is fixed at -32° and the nulls are set to 20.7° and 24.3° , respectively. These experimental results demonstrate that the proposed OCPA transmitter can independently control the main lobe and null at different operating frequencies.

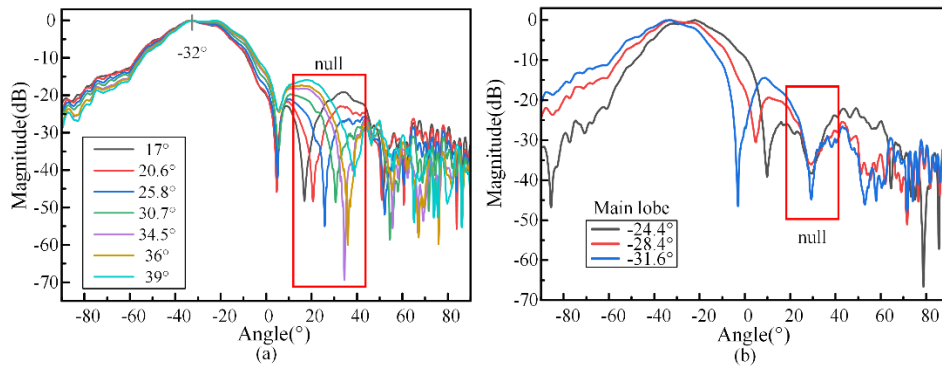


Fig. 12. Radiation patterns of the proposed OCPA transmitter at an RF frequency of 9 GHz. (a) The null is steered from 17 to 39° , while the main lobe is fixed at -32° . (b) The main lobe is steered while the null is set to 29.5° .

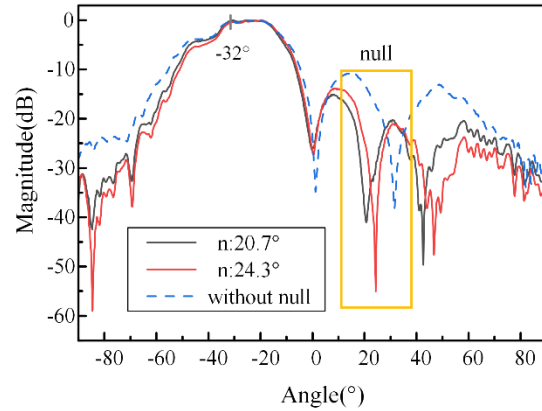


Fig. 13. Radiation patterns of the proposed OCPA transmitter at an RF frequency of 11 GHz. The main lobe is fixed at -32° , while the null is set to 20.7° and 24.3° . The blue dashed curve shows the pattern of a conventional 4-element linear array.

Furthermore, the broadband performance of the proposed scheme was verified through swept frequency test from 8 to 9 GHz. The results are shown in Fig. 14, where the main lobe and the null are set at -20° and 30° , respectively. Moreover, as a reference, the test results from a conventional 4-element line array (dashed line) is used operating at 9 GHz with the main lobe pointing at -20° . The experimental results show that each frequency component can form main lobe and null as expected. Although the errors cause variations in the main lobe and null across different frequency components, the main lobe waveforms are relatively consistent, while suppression is achieved in the target null region, which demonstrates the broadband operating capability of the proposed scheme.

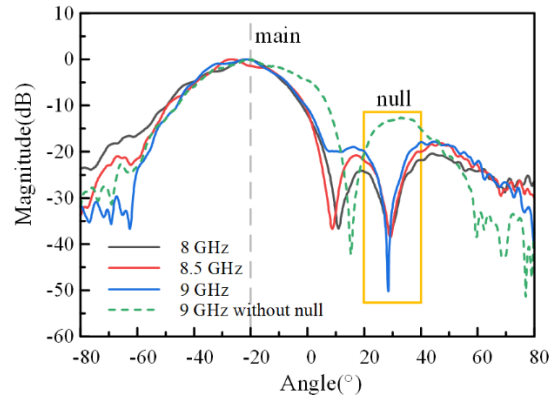


Fig. 14. Radiation patterns of the proposed OCPA transmitter swept from 8 to 9 GHz, when the main lobe and the null are set to -20° and 30° . The dashed line represents the test results of 4-element linear array at 9 GHz.

Due to experimental constraints, the array size used in the proof-of-concept system is relatively small. Therefore, significant coupling exists between the main lobe and the null, as discussed in Section III. Increasing the number of array elements is an effective approach for optimizing the radiation pattern. Furthermore, in the experiment, when adjusting the main lobe and the null, the output optical power of the link was coarsely calibrated via manual variable optical

attenuator, yielding observable results. Therefore, incorporating array element responses such as amplitude/phase errors, mutual coupling, and frequency-dependent element patterns into the link transmission model, along with system calibration and pre-distortion compensation, can achieve better performance to a certain extent.

Finally, this paper aims to simplify the structure of a broadband phased array system with controllable main lobe and the null. The proposed structure employs BPD to implement a single-stage differential network, thus enabling only one controllable null. In future work, we will design multi-stage differential networks based on broadband phase shifters to achieve multiple null steering.

5. Conclusion

In this work, we propose an OCPA transmitter capable of independently controlling the main lobe and null direction from a system control perspective. Based on a conventional optical beamforming network, the proposed scheme incorporates a spatial filtering module composed of an optical delay network and BPDs. This architecture enables null steering without prior knowledge of the original beam pattern or the need for adaptive computation. A 16-element OCPA is verified and analyzed through HIL simulations. The results show that both the main lobe and the null can be steered over a range of at least $\pm 40^\circ$. A critical angular region is observed around the main lobe, where the worst-case performance occurs near the critical angle. Even under this condition, a null depth exceeding 50 dB is achieved, while the MSSR remains higher than 6 dB. Meanwhile, the peak main lobe deflection is less than 3° , and the beamwidth variation is within 2° . Similarly, main-lobe control has little influence on null steering, with the null direction deviation remaining within 1° and the null depth maintained at an acceptable range. In addition, a 5-element null-steering OCPA transmitter is constructed to experimentally validate the proposed approach. The experimental results demonstrate that, at 9 GHz, the main lobe and null can be steered from -22° to -33.6° and from 17° to 39° , respectively, with a null depth exceeding 50 dB. Overall, this work provides an effective solution for null control in OCPA transmitters.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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