# Research on Mutual Coupling Effects in Array Antennas (Postprint)

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**Date:** 2022-05-30T10:52:27+00:00

## Abstract

Phased array feed is a receiver technology that places an array antenna at the focal plane field of a radio telescope to achieve higher gain and more flexible beam control. Given that, like array antennas, it is composed of multiple antenna elements arranged in a certain configuration, electromagnetic coupling between array elements during operation is inevitable. This paper selects helical antennas as the array elements, with an operating frequency of 1.25 GHz. After simulation and optimization of an isolated antenna, the -10 dB impedance bandwidth of this antenna is only 70 MHz. Based on this antenna element, a 5$×$5 rectangularly arranged helical antenna array model is established, with element spacings selected as 1, 0.5, 0.25, and 0.125 times the wavelength (1.25 GHz @ 0.24 m), to verify the influence of mutual coupling effects on the entire array bandwidth under different element spacings. Finally, by matching the input impedance of each array element, simulations show that at a spacing of 0.25 wavelengths, the -10 dB impedance bandwidth of the central array element can be extended to 550 MHz, and the bandwidth of the array antenna essentially characterizes the operating bandwidth when it is used as a phased array feed. The aforementioned work deepens the understanding of array antenna bandwidth characteristics and also provides possibilities for achieving wider operating bandwidths for phased array feeds in practical radio telescope systems.

## Full Text

## Research on Mutual Coupling Effects in Array Antennas

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**Abstract:** Phased array feed (PAF) is a receiver technology that places an array antenna at the focal plane of a radio telescope to achieve higher gain and more flexible beam control. Like conventional array antennas, PAFs consist of multiple antenna elements arranged in specific configurations, making electromagnetic coupling between elements inevitable during operation. This study selects helical antennas as the array elements operating at 1.25 GHz. Simulation and optimization of a single isolated antenna yield a -10 dB impedance bandwidth of only 70 MHz. Using this antenna element, a 5$\times$5 rectangular helical antenna array model was constructed with element spacings of 1, 0.5, 0.25, and 0.125 wavel = 0.24 m at 1.25 GHz) to investigate how mutual coupling affects the overall array bandwidth under different spacing conditions. By matching the input impedance of each element, simulations demonstrate that at 0.25$\lambda$ spacing, the -10 dB impedance bandwidth of the central array element expands to 550 MHz. Since the bandwidth of the array antenna essentially characterizes the operating bandwidth of the PAF, this work deepens understanding of array antenna bandwidth characteristics and provides a pathway for achieving wider operating bandwidths in PAFs for radio telescope applications.

**Keywords:** Array antenna; Phased array feed; Impedance; Coupling; Bandwidth

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## Introduction

Array antennas are constructed by arranging independent antenna elements according to specific patterns. In radio astronomy, such arrays can be employed as phased array feeds. A phased array feed places a planar array antenna in a rectangular or hexagonal configuration at the focal plane of a radio telescope, using a backend beamforming network to control the amplitude and phase of each element according to specific algorithms. This enables flexible beam shaping and scanning by combining signals from multiple elements. Currently, major radio telescope projects including the Square Kilometre Array (SKA), the Five-hundred-meter Aperture Spherical Telescope (FAST), and other large-aperture radio telescope initiatives in China are actively developing PAF technology, particularly L-band PAFs for prime focus placement. Figure 1 shows a Vivaldi PAF prototype developed for the PHAROS project (PHased Arrays for Reflector Observing Systems) [1].

For radio astronomy, which primarily detects weak celestial signals, operating bandwidth is critically important because wider bandwidth directly translates to higher sensitivity [2]. Consequently, broadband research on phased array feeds holds significant practical value. Since PAFs represent a specific application of array antennas in radio astronomy, their design follows the same fundamental principles, allowing PAF development to begin with array antenna analysis.

Compared to single antennas, array antennas can achieve higher gain and more flexible beam steering, making them widely used in microwave and communication systems [3]. Although array elements are independent antennas, different element spacings cause varying degrees of interaction between them [4]. In a transmitting array, for example, when element 1 radiates energy, a portion of that energy is received by adjacent element 2, affecting its subsequent circuitry. Simultaneously, element 2' s radiation is superimposed with this coupled energy and also transmits a portion back to element 1. This reciprocal influence among all antenna units constitutes the mutual coupling effect in array antennas [5].

Traditional array antenna design typically mitigates the adverse effects of mutual coupling by increasing element spacing ($ 0.5 $) to reduce coupling. However, recent advances in microwave antenna research have revealed that enhancing inter-element coupling can actually extend the operating bandwidth, achieving ultra-wideband characteristics [6].

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## 1. Array Element Selection

To construct the array antenna model, the first step is selecting appropriate array elements. Various antenna types can serve as array elements, including dipole antennas, slot antennas, loop antennas, and tapered slot antennas. Helical antennas, constructed from wire conductors wound in a spring-like spiral structure, are traveling-wave antennas with simple structures that are easy to fabricate, making them common choices for array elements.

A typical helical antenna features a cylindrical design whose radiation characteristics primarily depend on the ratio of helix diameter to wavelength ($D/\lambda$). This ratio determines three operational modes: when $D/\lambda < 0.18$, maximum radiation occurs in the plane perpendicular to the helix axis; when $D/\lambda$ is between 0.25 and 0.46, maximum radiation aligns with the helix axis—this axial mode is commonly referred to as a helical antenna; when $D/\lambda$ increases further, the pattern becomes conical. Generally, only the first two modes are utilized [7].

For rapid validation of array antenna performance in mutual coupling studies, we selected a structurally simple axial-mode end-fire helical antenna as the array element. The antenna was designed for operation at f = 1.25 GHz (L-band). After optimization, the final parameters were: helix diameter $D = 0.426\lambda$, pitch $s = 0.25\lambda$, number of turns $n = 3.5$, and ground plane radius $r = 0.375\lambda$, as shown in Figure 3.

Figure 4 presents the simulated return loss of this helical antenna across 0.7–1.8 GHz. At the design frequency of 1.25 GHz, the return loss reaches 33.64 dB, with $S_{11}$ remaining below -10 dB only within the narrow band of 1.21–1.28 GHz, confirming the 70 MHz impedance bandwidth.

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## 2. Array Design

Array antenna design primarily considers arrangement geometry, array size, and element spacing. Common configurations include linear arrays (elements along a line) and planar arrays (elements on a plane). For radio astronomy applications, planar arrays are more prevalent, so this design adopts a planar configuration. Within planar arrays, rectangular and hexagonal arrangements dominate. Since many tightly coupled arrays employ rectangular layouts, we selected a 5$×$5 rectangular arrangement, as illustrated in Figure 5.

Array size depends on element spacing, which represents the most critical design parameter and the direct cause of mutual coupling effects. To investigate array performance under coupling influence, we established 5$×5*rectangulararraysusingthehelicalantennaelementwithfourtypicalspacings*(1 , 0.5 , 0.25 , *and*0.125 $) to study coupling effects under different design scenarios.

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### 3.1 S-Parameters

Using the 5$×5*rectangularhelicalantennaarraymodelwithelementspacingsof*1 , 0.5 , 0.25 , *and*0.125 $ at 1.25 GHz, we analyzed array symmetry by selecting the central element (#5) and its neighbors along the E-plane (#6, #10) and H-plane (#8, #11). With uniform amplitude and phase excitation across all elements, we solved for the return loss of element #5 and its coupling to adjacent elements under mutual coupling conditions. Table 1 summarizes the simulation results.

**Table 1. S-parameters at Different Element Spacings**

| Spacing | $-S_{5,5}$ (dB) | $-S_{5,6}$ (dB) | $-S_{5,10}$ (dB) | $-S_{5,8}$ (dB) | $-S_{5,11}$ (dB) |
|---|---|---|---|---|---|
| $1\lambda$ | | | | | |
| $0.5\lambda$ | | | | | |
| $0.25\lambda$ | | | | | |
| $0.125\lambda$ | | | | | |

As the central element, #5 approximates an element in an infinite array. Table 1 shows that its return loss ($-S_{5,5}$) improves as spacing decreases, reaching optimum at $0.25\lambda$, with slight degradation at $0.125\lambda$ but still better than $1\lambda$ and $0.5\lambda$ spacings. Coupling between element #5 and its E-plane and H-plane neighbors ($-S_{5,6}$, $-S_{5,10}$, $-S_{5,8}$, $-S_{5,11}$) generally weakens with increasing spacing, with H-plane coupling being weaker than E-plane coupling at corresponding positions.

Across 0.7–1.8 GHz with uniform amplitude-phase excitation (all ports at 50 Ω), we simulated the return loss of central element #5. Figure 6 shows that at $1\lambda$ and $0.5\lambda$ spacings, $S_{5,5}$ exceeds -10 dB at the 1.25 GHz operating point, whereas at $0.25\lambda$ and $0.125\lambda$ spacings, $S_{5,5}$ falls below -10 dB. Since the typical design requirement is $S_{5,5}$ < -10 dB, the 0.25$\lambda$ and 0.125$\lambda$ spacings initially meet specifications.

Comparing the broadband $S_{5,5}$ performance, the 0.125$\lambda$ spacing exhibits discontinuous passbands below -10 dB, while the 0.25$\lambda$ spacing shows multiple continuous passbands below -10 dB in the high-frequency region, with the widest passband approaching 150 MHz—the best broadband performance among the four configurations. Although the 1$\lambda$ and 0.5$\lambda$ spacings have limited passbands meeting the requirement, the 0.5$\lambda$ spacing demonstrates better high-frequency performance than 0.125$\lambda$. These results suggest that appropriately reducing element spacing to enhance coupling can extend array bandwidth, though the improvement is limited and depends on the specific element design.

Figure 7 compares the return loss of central element #5 at 0.25$\lambda$ spacing for both the isolated array and the array integrated with a reflector. When combined with a 25-meter reflector having a focal ratio of 0.3 [8], the return loss (-$S_{5,5}$) of the PAF remains essentially identical to that of the isolated array, with only minor differences. This confirms that the array' s bandwidth fundamentally characterizes the PAF bandwidth when used with a reflector.

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### 3.2 Impedance

The broadband return loss simulations revealed that merely adjusting element spacing cannot achieve a sufficiently continuous and wide operating bandwidth. Since reducing spacing affects the input impedance of each antenna element through mutual coupling, we selected the two most promising configurations—0.5$\lambda$ (conventional design) and 0.25$\lambda$ (demonstrating wider bandwidth potential)—for further impedance analysis. With uniform amplitude-phase excitation, we simulated the input impedance (in ohms) of each array element, as shown in Figure 8.

Due to mutual coupling, different spacings cause significant variations in element input impedance, which substantially differs from the nominal 50 Ω assumption used in previous simulations. The impedance mismatch is more pronounced at 0.5$\lambda$ spacing, resulting in poorer return loss compared to the 0.25$\lambda$ case.

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### 3.3 Array Bandwidth After Impedance Matching

Using the impedance values from Figure 8, we modified the input impedance of each element accordingly for both 0.5$\lambda$ and 0.25$\lambda$ spacings. With uniform amplitude-phase excitation across 0.7–1.8 GHz, we resimulated $S_{5,5}$ for the central element. Figure 9 shows the return loss before and after impedance optimization.

After impedance matching, both spacings exhibit improved $S_{5,5}$ performance.

Notably, the 0.25$\lambda$ spacing achieves return loss below -10 dB across most of the 0.7–1.8 GHz band, particularly delivering a valuable 550 MHz continuous bandwidth from 0.8–1.35 GHz.

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## 4. Conclusion

This paper presents simulation and optimization of a standalone helical antenna operating at 1.25 GHz, achieving 33.64 dB return loss at the design frequency with a -10 dB impedance bandwidth of 70 MHz. Using this element, we constructed a 5$\times 5 rectangular helical antenna array model for PAF applications with element spacings of 1 , 0.5 , 0.2 to investigate mutual coupling effects on PAF bandwidth.

Simulations showed that only 0.25$\lambda$ and 0.125$\lambda$ spacings met the -10 dB return loss requirement at the operating frequency, with 0.25$\lambda$ spacing demonstrating the greatest broadband potential across 0.7–1.8 GHz. After impedance matching based on the coupled input impedances, significant improvement was achieved across the entire band. The 0.25$\lambda$ spacing configuration realized a continuous 550 MHz -10 dB impedance bandwidth, confirming that array bandwidth fundamentally characterizes PAF bandwidth when integrated with a reflector.

Future work will focus on further optimization of array elements and spacing, combined with comprehensive PAF array design considering edge illumination of radio telescope focal planes, to continue exploring broadband characteristics for phased array feeds.

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*Funding: National Natural Science Foundation of China (11973078); Xinjiang Uygur Autonomous Region Key Laboratory Open Project (2020D04014); Chinese Academy of Sciences "Western Light" Talent Training and Recruitment Program (2020-XBQNXZ-018); Shanghai Cooperation Organization Science and Technology Partnership Program and International Science and Technology Cooperation Program (2020E01041); Chinese Academy of Sciences Astronomical Observatory Equipment Update and Major Instrument Operation Special Fund.*

*Received date: Revised date:*

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*Note: Figure translations are in progress. See original paper for figures.*