Probe-fed dipole antenna with parasitic patches for wideband and wide-scanning planar phased arrays

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Abstract
A probe-fed dipole antenna with parasitic patches is proposed in this study as the element for wideband and wide-scanning planar-phased arrays. Parasitic patches are used to realize wideband performance by significantly reducing the active input impedance. The printed dipole antenna with parasitic patches is directly matched with the subminiature version A (SMA) connector through the modified probe structure. The cell size is $0.5 \times 0.5 \times 0.145 \lambda_{\text{high}}$. The planar and low-profile characteristics make it suitable for modular phased array applications. It is shown that the infinite array simulation results achieve 45.2% bandwidth (7.86–12.45 GHz) with active voltage standing wave ratio (VSWR) $< 2$ at broadside, 60° scans in $E_\perp$, $D$-planes and 50° scan in $H$-plane. An 8 × 8 prototype array has been manufactured and measured to validate the proposed design and the active element patterns agree well with simulation results.

1 | INTRODUCTION

A broadband wide-scanning phased array is extensively used in the modern communications and radar systems to satisfy multi-bands and multiple-beams requirements [1,2]. Furthermore, planar-phased arrays with a low profile are more popular, thanks to their compact size, conveniences in fabrication and modularization. Previous wideband wide-scanning phased array antennas use Vivaldi [3-6], bunny-ear [7,8], balanced antipodal Vivaldi antenna [9] and horn antenna [10] as their radiating element to achieve a wide bandwidth at the cost of the array profile. They are inconvenient in modern systems due to high profile and fabrication difficulty.

Patch array is a common planar array for phased array application. Decoupling structures such as electromagnetic band-gap (EBG) structure and defected ground structure (DGS) are widely used to decrease interaction effect between patch antennas. Due to the narrow bandwidth of EBG and DGS, the wide-scanning performance is obtained in a narrow band [11-13]. Therefore, there is high interest in the development of broadband patch-phased array. One effective way is to increase the antenna profile. In [14], Awida et al. employed a cavity-backed patch antenna to achieve scanning to ±60° with 12% relatively wide bandwidth. Arand et al. designed a patch antenna adopting metal wall to reduce mutual coupling, the patch array is capable of scanning to ±65° in $E$-plane and ±60° in $H$-plane while the bandwidth is 20% with VSWR < 2 [15]. The bandwidth of patch arrays is enhanced but sacrifices low profile performance.

For ease of integration with RF modules, an appropriate back-feeding structure is required in planar-phased array. A cavity-backed slot array in triangular lattice with coaxial feeding structure was proposed in [16], which achieved 12% bandwidth in the broadside. In [17], Xia et al. designed a cavity-backed slot antenna element with coaxial feeding structure. Obviously, it is quite difficult to integrate coaxial lines into the substrate. Over the past decade, a great deal of effort has been devoted to realizing low-cost wideband array apertures using printed circuit board (PCB) [18-22]. Non-printed external baluns [18], Wilkinson power dividers [19,20] and vertically matching networks [20-22] are commonly used. The adoption of complex feed structure...
requires additional support structure, which will increase the system complexity and assembly difficulty, and reduce system structural strength. Most of them cannot be integrated with printed antennas on single-layer PCB, and extra insertion loss will be attached, reducing antenna efficiency and degrading system noise figure.

In this study, we propose a probe-fed dipole antenna with parasitic patches for wideband and wide-scanning planar-phased arrays. The proposed element uses a single layer printed dipole antenna to obtain stable radiation patterns. Different from the method of loading wide-angle matching layer [17,18] and segmenting periodic element [19,20], we load parasitic patches on the dipole antenna to reduce the active input impedance. A modified probe structure integrated in a single layer PCB is designed to connect the dipole antenna to the SMA connector. The proposed design presents wideband, wide-scanning performances with the advantages of low profile, low cost and easy integration.

This study continues in Section 2 by introducing the evolvement of the proposed antenna. The influence of parasitic patches and modified probe structure on active reflection coefficient is analysed. Section 3 provides an experimental demonstration using a 64-element (8 × 8) array prototype, and Section 4 concludes the study.

2 INFINITE ARRAY DESIGN AND PERFORMANCE

The unit cell geometry of the proposed antenna is illustrated in Figure 1. A dipole with a pair of parasitic patches is etched on the top of the substrate. The substrate in this design is FR4 (\(\varepsilon_r = 2.55, \tan \delta = 0.0015\)). A probe structure that contains one inner probe and two outer vias is designed to feed dipole antenna. The inner probe connects the SMA connector and one arm of dipole antenna, while the other arm connects to the ground plane through two outer vias. The proposed antenna has a compact size and very low profile (0.145 \(\lambda_{\text{high}}\), \(\lambda_{\text{high}}\) is the wavelength corresponding to the highest operating frequency) which can be implemented as a planar-phased array. There are more details shown in Figure 1(b). This element was created and analysed using the EM software HFSS.

The evolvement of the proposed antenna is shown in Figure 2. The periodic boundary condition (PBC) is used for simulation [10], all results are obtained at broadside scanning, and all parameters are the same as in Figure 1. A fan-shaped dipole is simulated as Antenna 1. Antenna 1 has a resonant frequency of 11.8 GHz, and the peak resistance of the active input impedance is about 175 \(\Omega\), as shown in Figure 3. It is very difficult to match 175–50 \(\Omega\) in the case of low profile. To decrease the resistance, we add open-loaded parasitic patches orthogonal to the Antenna 1 and obtain an Antenna 2. Figure 3 shows the difference between Antenna 1 and Antenna 2. The resonant frequency moves from 11.3 to 9.1 GHz and the peak resistance of the active input impedance decrease from 175 to 70 \(\Omega\), while the imaginary part approximating 0 in broadband. It is obvious that Antenna 2 is easier to match with 50 \(\Omega\) than Antenna 1. For easily connecting to the SMA connector, we try twin-wire feeding structure and obtain Antenna 3. The distance between two parallel wires is 0.3 mm. However, there is a serious mismatch between Antenna 3 and the input port. Although reducing the distance between two parallel wires can relieve the mismatch, it will greatly increase the fabrication difficulty. To solve this problem, a modified probe structure is designed, which contains one inner probe.
and two outer vias. The comparison of the two feeding structure is presented in Figure 4(a). The diameter and spacing of the twin-wire feeding structure are 0.51 and 0.81 mm, respectively, and the diameter and spacing of the modified probe structure are 0.51 and 1.05 mm, respectively. The transmission performance of the two structures is simulated; the characteristic impedance of the two wave ports is shown in Figure 4(a). Obviously, the modified probe structure achieves good transmission performance by properly configuring the diameter and spacing. Finally, the modified probe structure is used as a balun to match the antenna to 50 $\Omega$. Figure 4(b) shows the difference between Antenna 3 and Antenna 4, the active input impedance of Antenna 3 is very high due to the high characteristic impedance of twin-wire structure; for Antenna 4, two resonances appear around 8.5 and 12.5 GHz, the real part of active input impedance is floating around 50 $\Omega$ and the imaginary part of active input impedance is floating around 0. Finally, Antenna 4 perfectly match to 50 $\Omega$ in broadband. The simulated active reflection coefficient of Antennas 1–4 is depicted in Figure 5. The port $Z_0$ is 50 $\Omega$ for all antennas. The Antenna 4 achieves a 48% (7.86–12.84 GHz) $−10$ dB bandwidth.

**Figure 4** (a) Comparison of two feeding structures. (b) The simulated active input impedance of Antennas 3 and 4

**Figure 5** Active reflection coefficient of different antennas

**Figure 6** Simulated active VSWR of the unit cell in different cases

**Figure 7** Simulated active VSWR of the unit cell varies with $R$
The VSWR of infinite arrays under broadside and scanned conditions are plotted in Figure 6. The difference between two dipoles with and without parasitic patches is obvious. Good wide-scanning property is attributed to the parasitic patches. The parasitic patches effectively decrease the imaginary part of active input impedance while array scanning. The proposed design achieves about 45.2% bandwidth (7.86–12.45 GHz) with VSWR < 2 when scanning to ±60° in E- and D-planes, ±50° in H-plane. The D-plane is defined as the diagonal plane (φ = 45°). Simulated active VSWR of the unit cell which varies with R is depicted in Figure 7. The value of R determines the transmission performance of the modified probe structure and affects the VSWR of the antenna. As shown in Figure 7, the active VSWR in E-plane and H-plane has the opposite trend; thus, the choice of R depends on the compromise of antenna performance between the E-plane and H-plane. As can be seen from Figure 7, R = 1.05 mm is optimal. The total radiation efficiency of the infinite array unit cell is depicted in Figure 8. The efficiency is beyond 90% at broadside and all scanning angles over the band of 7.86–12.45 GHz.

The comparison between the proposed arrays and arrays in the existing publication is shown in Table 1. All the designs we selected present wideband and wide-scanning performance. While the design in [14] has a lower profile, the proposed

![Figure 8](image_url) Simulated total efficiency of the unit cell in different cases

| Design          | Bandwidth       | Scan range     | Unit cell size          | Fabrication   | Extra support mechanisms |
|-----------------|-----------------|----------------|------------------------|---------------|--------------------------|
| This work       | 45.2% (7.86-12.45 GHz) | H-50°, E-60°, D-60° | 12 × 12 × 3.5 mm³ (0.5 × 0.5 × 0.145 λ_{high}) | Single layer PCB | No                       |
| [14]            | 12% (9.4-10.6 GHz)  | H-60°, E-60°, D (N/A) | 15 × 15 × 3.175 mm³ (0.53 × 0.53 × 0.11 λ_{high}) | Single layer PCB | No                       |
| [15]            | 20% (N/A)       | H-60°, E-60°, D (N/A) | N/A (0.61 × 0.53 × 0.22 λ_{high}) | Mechanical processing | No                       |
| [17]            | 43.4% (7.4-11.5 GHz) | H-60°, E-60°, D (N/A) | 11.5 × 10 × 7 mm³ (0.45 × 0.39 × 0.27 λ_{high}) | Mechanical processing | No                       |
| [18]            | 43.9% (8-12.5 GHz) | H-60°, E-70°, D (N/A) | 8 × 8 × 11.6 mm³ (0.33 × 0.33 × 0.48 λ_{high}) | Single layer PCB | Yes                      |
| [22]            | 136% (3.5-18.5 GHz) | H-45°, E-70°, D (N/A) | 8.1 × 8.1 × 10.18 mm³ (0.5 × 0.5 × 0.63 λ_{high}) | Multilayer PCBs | Yes                      |
| [26]            | 100% (6-18 GHz)  | H-60°, E-60°, D (N/A) | 7.78 × 7.78 × 5.75 mm³ (0.47 × 0.47 × 0.34 λ_{high}) | Single layer PCBs | Yes                      |

Note: N/A—means the corresponding datum is not provided in the reference.
Abbreviation: PCB, printed circuit board.
*The VSWR is below 3.
design has a wider bandwidth (more than 3.7 times). Unlike other designs that require mechanical processing or extra support mechanisms, the proposed design can be fabricated as a low-cost single-layer PCB which has the advantages of low cost and lightweight. It can be seen that our design has wideband, wide-scanning performances with the advantages of low profile, low cost and easy integration.

3 | FINITE 8 × 8 ARRAY EXPERIMENT RESULTS

As shown in Figure 9, an 8 × 8 planar array was fabricated for measurement to validate the proposed design. The substrate of F4B (εr = 2.55, tan δ = 0.0015) is used in this example. The substrate is installed on the top of the metal board through plastic screws, and the SMA connectors are installed on the bottom of the metal board through metal screws. The SMA connector used has a metal probe with a diameter of 0.51 mm, passes through the metal board and substrate to the antenna. The probe is welded to the printed antenna on the top of the substrate.

The S-parameters $S_{ij}$ between 37th element and other elements were measured using vector network analyzer with all other elements matched. The active VSWR of the 37th element

![Image](a)

**FIGURE 9** Photo of the fabricated 8 × 8 array. (a) Top view, (b) bottom view and (c) side view

![Image](b)

**FIGURE 10** Measured and simulated active VSWR of the 37th element in different cases

![Image](c)

**FIGURE 11** The measured active element patterns of the 37th element at 12 GHz. (a) E-plane and (b) H-plane
is calculated via a summation of the measured $S_{21}$ with proper phased weight at different scan angles [23]. The measured and simulated active VSWR of the 37th element in finite $8 \times 8$ array at different scan angles are depicted in Figure 10. In the frequency band of 7.86–12.45 GHz, the measured active VSWR is below 2 at broadside and below 3 at the scanning angles of $60^\circ$ in $E$-plane and $50^\circ$ in $H$-plane. It is shown that the measured finite array results agree well with the simulated ones. The discrepancies are mainly caused by the errors in assembling, such as the gaps between the substrate and the metal board which cause a decrease in the effective permittivity. Additional efforts could be taken to treat finite array edge effects, such as making the array larger [24].

It is well known that the embedded element pattern is a good indication of the scan performance in a large array. Each antenna element is measured, while other antenna elements are matched. All the active element patterns are combined together with uniform weighting to form the overall radiation pattern. The scanning array patterns can be calculated as a post-processing step by assigning appropriate phase excitations for beam scanning [23,25]. The measured active element patterns of 37th element at 12 GHz are shown in Figure 11. The measured element patterns show good agreement with the simulated ones in $E$-plane. The results in $H$-plane show a slight difference which is caused by assembly errors. The cross-polarization levels remain below $-15$ dB in most ranges. The measured realized gain at 12 GHz of the array is presented in Figure 12. The peak realized gain at broadside, $60^\circ$ scan in $E$-plane and $50^\circ$ scan in $H$-plane is 22.4, 19.8 and 19.4 dBi, respectively. Due to the finite array aperture, the array cannot be accurately scanned to desired angles, though each element is ideal phased, especially at large angles.

4 | CONCLUSION

A planar dipole antenna is proposed for wideband and wide-scanning phased arrays. Modified probe structure design and parasitic patches design are employed. The proposed array achieves wideband, wide-scanning performances with the advantages of low profile, low cost and easy integration. Infinite array simulations show that it achieves nearly 45.2% bandwidth (7.86–12.45 GHz) with active VSWR < 2. The radiation efficiency (including reflection loss) is higher than 90% when scanning to $60^\circ$ in $E$, $D$-plane and $50^\circ$ in $H$-plane. An $8 \times 8$ prototype array is fabricated for experimental validation. This prototype array experimentally obtains more than 45.2% bandwidth (7.86–12.45 GHz) for VSWR < 2 at broadside and VSWR < 3 at $60^\circ$ scan in $E$, $D$-plane and $50^\circ$ scan in $H$-plane. Active element patterns at 12 GHz are measured and array scanning patterns are computed accordingly. Measured and simulated active element pattern results show good agreement.

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