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Design Investigation of Microstrip Patch and Half-Mode Substrate Integrated Waveguide Cavity Hybrid Antenna Arrays

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ABSTRACT

In this paper, two linear arrays including a linear 1×4 and a planar 2×2 of microstrip patch and half-mode substrate integrated waveguide (SIW) cavity hybrid antenna are introduced and investigated. These are simply implemented using low cost single layer printed circuit board (PCB) process. The array element consists of a rectangular microstrip patch with appropriate dimensions in the vicinity of a semi-circular SIW resonator provide a wideband hysbrid antenna. In both antenna arrays a microstrip feeding network including a quarter-wave transformer matching circuit has been used to feed the array elements. The size of 1×4 linear array is $1.58\lambda_0 \times 2.87\lambda_0$ and planar 2×2 array size is $1.57\lambda_0 \times 1.37\lambda_0$. Array structures are numerically and experimentally investigated. The measured and simulated results including reflection coefficient, radiation patterns and gain of the both arrays are reported.

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1. INTRODUCTION

In recent years, there is a great need of developing low cost, low profile and high gain antennas due to the advances of microwave wireless communication systems. Using planar structure and integrating active and passive circuits and antennas is one way to design and implement compact systems. Printed microstrip patch antenna arrays provide favorable characteristics and have been widely studied due to their easy fabrication, low-profile and compact size [1-4]. However, the limited bandwidth of these antennas is their major hurdle. Recently substrate integrated waveguides (SIW) technology has been recommended for implementing microwave circuits and antennas due to their feasibility for making microwave systems in planar form by using low cost Printed Circuit Board (PCB) process [5, 6] specially in a production line. Low profile SIW cavity backed patch antennas have been investigated in literatures [7, 8]. Cavity backed antennas present the advantages of eliminating backward radiation, reducing cross polarization levels and significantly suppressing surface waves [9]. Moreover, due to their high radiation performance, they are appropriate in array application. Two layers SIW cavity-backed patch antenna arrays have been studied in literatures [7, 8]. A 2×2 array of microstrip patch antenna demonstrates a bandwidth of 9% and 13.5 dBi gain, while its total substrate thickness is $\lambda_0/12$. A 2×2 array of E-shaped patch antenna backed by SIW cavity has been investigated in reference [10], which provides 10.5% impedance bandwidth and 13.2 dBi gain with total substrate thickness of $\lambda_0/30$. Single layer SIW cavity backed antenna array has been proposed, in which SIW structure are used for feeding network [11]. Although SIW feeding network provides low loss characteristic, but they are not flexible and occupy large area of the structure. Recently, a broadband single layer hybrid antenna consists of a patch and semi-circle SIW cavity has been investigated [12] by authors, which demonstrates 9.75% impedance bandwidth and 7.5 dBi gain with total substrate thickness of $\lambda 0/50$. Also, the effect of the microstrip patch shape on the radiation performance of the hybrid antenna was investigated in literature [13]. In this paper, using proposed hybrid antenna in reference [12], a set of array structures including a linear array of 1×4 elements and a planar

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array of 2×2 elements are studied numerically and experimentally. Array characteristics including reflection coefficient, radiation patterns and gain are reported.

2. ANTENNA STRUCTURE

2. 1. Single Element Antenna The geometry of the single element hybrid antenna is shown in Figure 1. It is made of a semi-circular SIW cavity of radius R_c and a rectangular patch length of L_p and width of W_p. These are printed on the top surface of the substrate layer, while rectangular patch is placed by distance g from the cavity. The semi-circular cavity is realized by metallic via arrays, which have been placed in half of the circumference of the circle with radius R_c. An inset 50 Ω microstrip line is used to excite the cavity at TM_{010} mode, which satisfies boundary conditions of the structure. The antenna structure is implemented by means of a single substrate of dielectric constant ε_r and height h.

2. 2. Linear Array of 1×4 Elements Figure 2 shows the proposed linear array of 1×4 elements. It consists of four elements by array spacing d_x. A simple microstrip power divider with a quarter-wave transformer is used to feed the elements with the same amplitude and phase. The feeding network is printed on the backside of the substrate to eliminate the spurious radiation.

2. 3. Planar Array of 2×2 Elements The 2×2 planar array of the proposed hybrid antenna is shown in Figure 3. This array is composed of two 1×2 linear arrays by spacing d_y. A compact microstrip power divider is designed to equally split power into four ways and excite each elements of the array in-phase. A 50Ω coaxial probe is centrally fed the microstrip network as shown in Figure 3(b). In the proposed 2×2 array, both radiating elements and feeding network are printed on the top surface of the substrate layer. Both proposed 1×4 array and 2×2 array antennas are implemented on a single layer substrate to provide high radiation efficiency.

3. ANTENNA ARRAY DESIGN

3. 1. Single Element Antenna A single element of the proposed hybrid antenna as shown in Figure 1, is designed at the center frequency of 8 GHz using TLY031 substrate with thickness of h = 0.787 mm and dielectric constant of ε_r=2.2. The geometrical designed parameters of the single element antenna are summarized in Table 1. The measured impedance bandwidth and gain for the single element are 9.75% and 7.5 dBi, respectively [12].

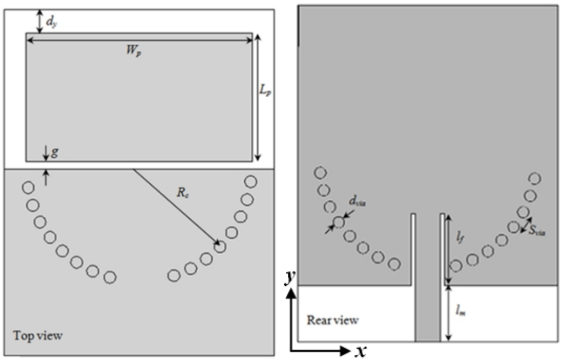
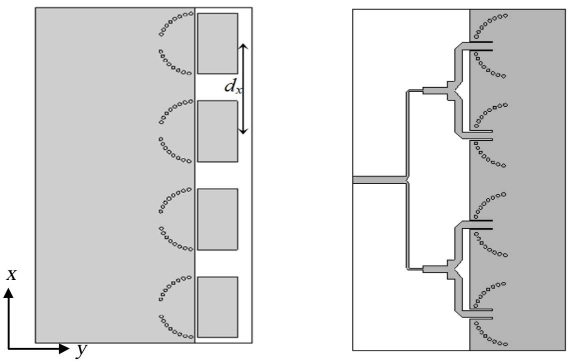
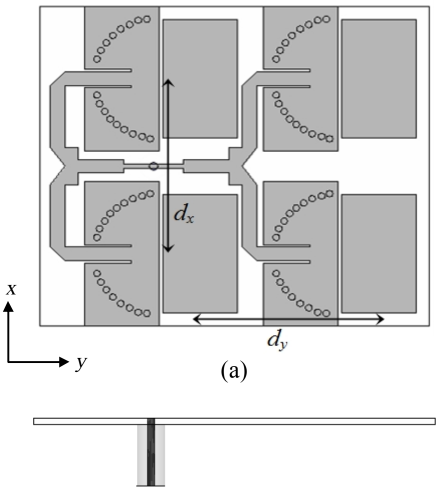


Figure 1. The top and bottom view of the single element hybrid antenna (grey color: metal, white color: dielectric).



(a) (b)

Figure 2. The geometry of the proposed 1×4 linear array: a) top view, b)rear view (grey color: metal, white color: dielectric).



(a)

(b)

Figure 3. The geometry of the proposed 2×2 planar array: a)top view, b)side view (grey color: metal, white color: dielectric).

3. 2. Mutual Coupling When two elements of the proposed hybrid antenna are placed in vicinity of each other with respect to E -(*y-z* plane) or H-plane (*x-z* plane), as shown in Figure 4, their electromagnetic fields are coupled together, and this coupling is very important in array structures.

The simulated mutual couplings between two antenna elements for different distance between them are shown in Figure 5. It can be seen for distance of $0.7\lambda_0$ mutual coupling between two elements is below -18 dB and -20 dB in E- and H-plane, respectively, which means that a very good isolation between two elements is obtained for $0.7\lambda_0$. Therefore, this can be simply extended to the array design structure.

TABLE 1. The geometrical parameters of a single element antenna (units in: mm)

Parameters	Value
l_f	6.4
g	0.65
d_y	2
R_c	9.6
l_m	5
d_{via}	1
S_{via}	1.5
L_p	11.08
W_p	19.5

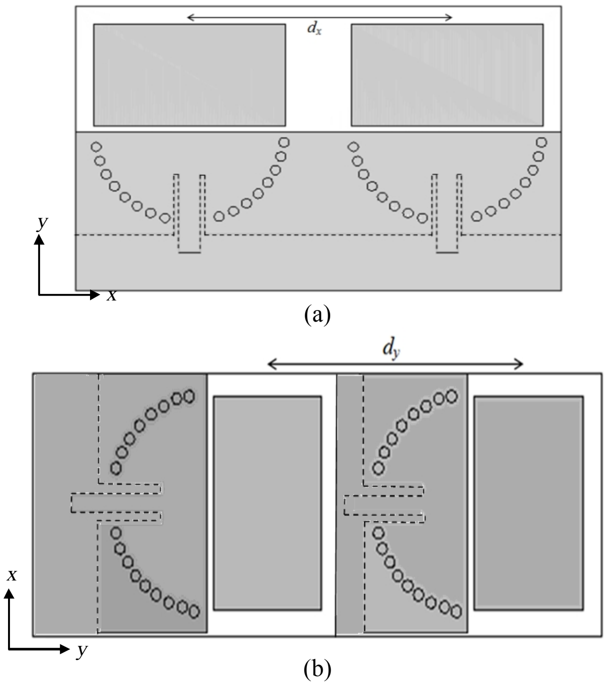


Figure 4. Two element antenna placed side by side in an array configuration: a) H-plane, b) E-plane. (grey color: metal, white color: dielectric).

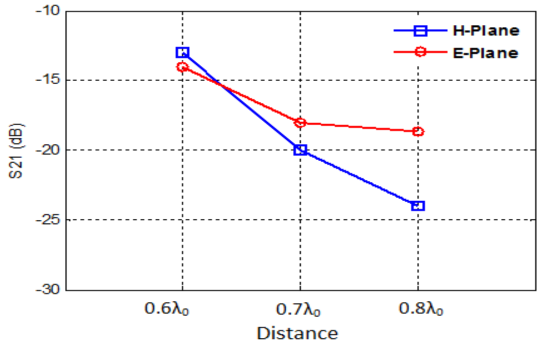


Figure 5. Impact of d_x and d_y, spacing between the two elements side by side on the coupling.

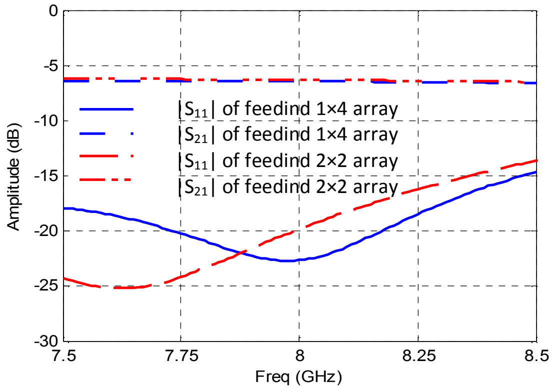


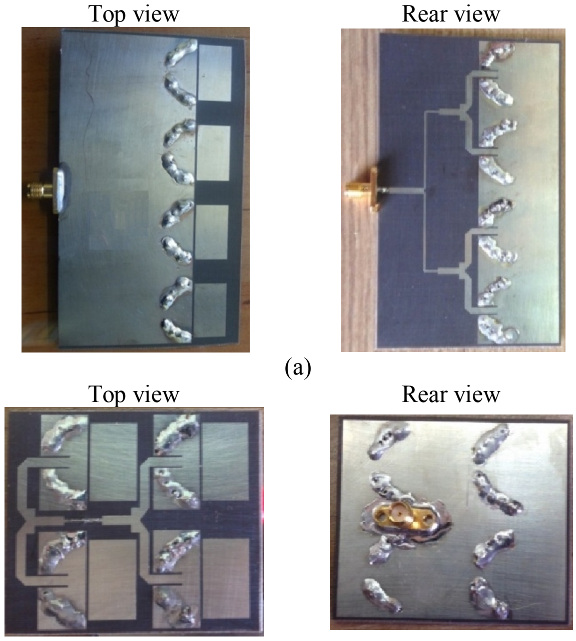
Figure 6. Simulated *S*-parameter of the feeding network of the both proposed arrays.

3. 3. Microstrip Feed Network A microstrip power divider with quarter-wave transformer is used to feed the antenna elements with the same phase and amplitude. For the linear array, a one to four divider circuit is designed and simulated. Simulated *S* paramers of the divider are ploted in Figure 6. It can be seen that the reflection coefficient of the divider is less than -17 dB and insertion losses of each branch are around 0.4 dB. In caes of planar array, a microstrip binary feed network to direct the signal with the same phase and amplitude from the central feed to the antenna element is designed. Simulated $|S_{11}|$ and $|S_{21}|$ plots are also shown in Figure 6 which shows that reflection coefficient is less than -15 dB and insertion losses of each branch are less than 0.25 dB.

4. RESULTS AND DISCUSSIONS

The 1×4 and 2×2 arrays are designed and fabricated on a single layer TLY031 substrate of thickness of 0.787 mm and ε_r=2.2 and a standard SMA connector is used in launching the signal to the both arrays. Photos of the fabricated arrays are shown in Figure 7. The array spacing in 1×4 array is $d_x = 0.7\lambda_0$ and in 2×2 array are $d_x = 0.75\lambda_0$ and $d_y = 0.77\lambda_0$, in which λ_0 is wavelength in free space at 8 GHz. The whole size of the arrays are $1.58\lambda_0 \times 2.87\lambda_0$ and $1.57\lambda_0 \times 1.37\lambda_0$ for linear and planar array, respectively.

4. 1. Linear Array Figure 8 shows the simulated and measured results of reflection coefficient of the proposed linear antenna. Simulated results show fractional impedance bandwidth of 10.75% for $|S_{11}|$<-10 dB. The measured results at lower resonant frequency have good agreement with that obtained by simulation but there is a disagreement at higher band. This is may be due to fabrication imperfections and also coupling between adjacent elements. The simulated gain and radiation efficiency including measured gain versus frequency are plotted in Figure 9. It can be seen that measured peak gain is around 12.15 dBi. Also, simulated radiation efficiency in operating bandwidth is at least 90%. Radiation patterns have been measured at 7.7 GHz in two principle cut planes; H- (*x-z* plane: φ=0°) and E-plane (*y-z* plane: φ=90°). The simulated and measured normalized radiation patterns are shown in Figure 10. It can be seen that the H-plane pattern has narrower beamwidth than that of the E-plane. This is confirmed by considering half power beamwidth (HPBW) of both patterns, which are 103° and 17° in E- and H-plane, respectively. Measured cross polarization level (CPL) within HPBW in E- and H-plane is less than -19.7 dB and measured Front to Back Ratio (*FBR*) is 20 dB.



(b)

Figure 7. Photos of the fabricated arrays: a) linear array, b) planar array

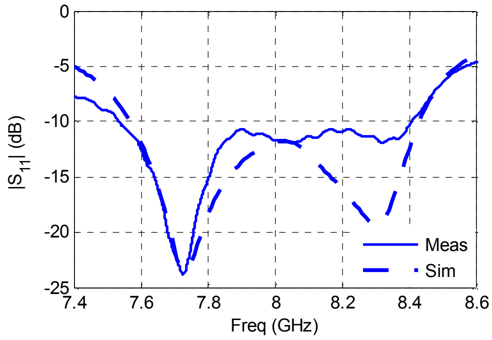


Figure 8. The simulated and measured reflection coeffient of the linear array.

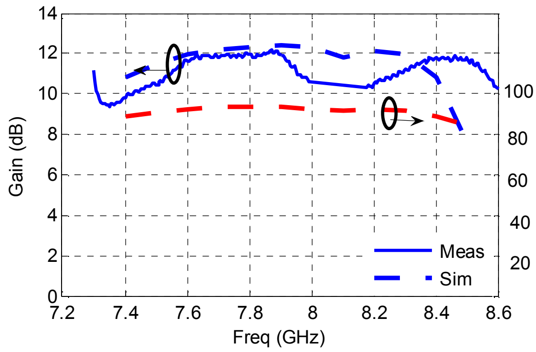
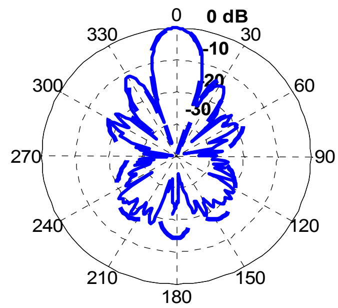
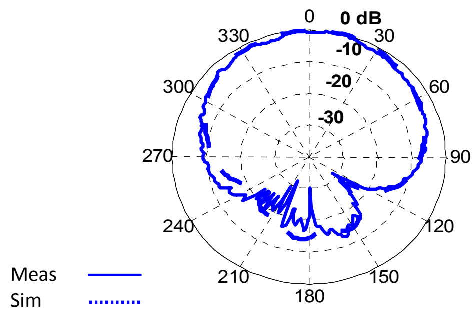


Figure 9. The simulated and measured gain and simulated radiation efficiency of the linear array



(a)



(b)

Figure 10. The simulated and measured radiation patterns of the linear array at 7.7 GHz: a) H-plane b) E-plane.

4. 2. Planar Array Figure 11 shows the simulated and measured results of reflection coefficient for planar array versus frequency. Simulated -10 dB bandwidth is 9.75%. In case of measured results, the two resonant frequencies have been not merged enough to exhibits a broad impedance bandwidth. Figure 12 shows the simulated and measured gain including simulated radiation efficiency of the planar array versus frequency. It can be seen that measured results show antenna gain at lower and upper resonant frequencies are nearly 12.4 dBi and 11.4 dBi, respectively. Also, measured peak gain is around 12.93 dBi. Moreover, simulated radiation efficiency of the proposed planar array is at lest %90 over the entire operating bandwidth.

The simulated and measured radiation patterns at lower resonant frequency of the planar array in two principle cut planes E- and H-planes are illustrated in Figure 13. It can be concluded that in E- and H-plane patterns, measured *SLL* is less than 7 dB and 13.5 dB, respectively. It can also be seen that E-plane pattern are asymmetricm which is due to asymmetric array design at this radiating plane. Moreover, both E- and H-plane patterns are narrower than the patterns of the single element antenna. This is obviously established by considering HPBW of both patterns, which are 33°and 36°in E- and H-plane, respectively . The measured and simulated performance of the both linear and planar antenna arrays including the radiation properties of the single element antenna are summarized in Table 2. Apart from the disagreement between the simulated and measured results for S_{11}, there is a good agreement between the other radiation characteristics of the planar array. This disagreement might be due to fabrication imperfections, and the effect of feeding network. Also, simulation studies confirm that radiation patterns, gain and radiation efiiciency of both arrays are not changed significaltly versus frequency over the operating bandwidth.

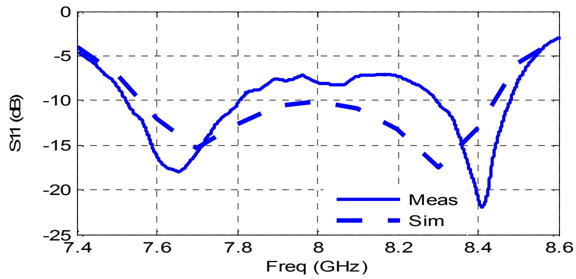


Figure 11. Simulated and measured reflection coeffient of the proposed planar array.

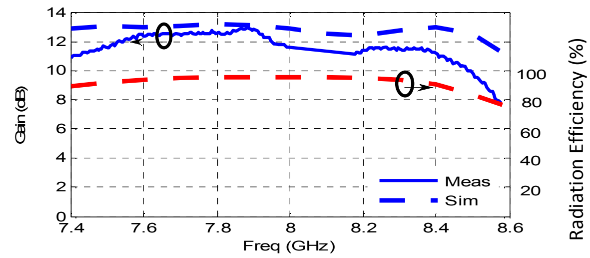
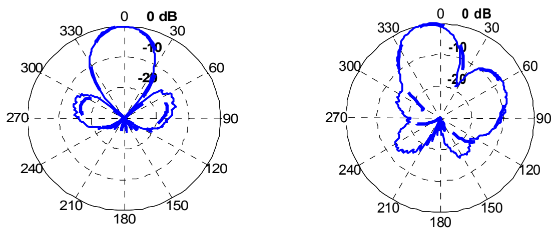


Figure 12. The simulated and measured gain and simulated radiation efficiency of the planar antenna array.



(a) (b)

Figure 13. Radiation patterns of the planar antenna array at lower resonant frequency: a) H- plane, b) E-plane.

TABLE 2. Summary of the measured and simulated radiation characterestics of the single elements and antenna arrays.

Parameters	Single element		Linear Array		Planar Array	
	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
Bandwidth (%)	10	9.6	10	10.75	3.5,2.1	9.75
Gain (dB)	7.5	7.6	12.15	12.41	12.93	13.2
FBR (dB)	13.2	21.47	20	14.5	27	36
HPBW in H-plane	82°	72°	17°	17°	36°	32°
HPBW in E-plane	71°	76°	103°	102°	33°	36°
SLL in H-plane (dB)	-	-	13	13.2	13.5	14
SLL in E-plane (dB)	-	-	-	-	7	7.5

TABLE 3. Performance comparison of the proposed planar array with recently published ones

Parameters	This work	SIW cavity-backed microstrip patch array [7]	SIW cavity-backed E-shaped patch antenna [10]	Slotted substrate integrated cavity antenna [14]
Elements Number	2×2	2×2	2×2	3×3
Bandwidth (%)	9.75	10	10.5	4.7
Gain (dBi)	13.2	13.6	13.2	13.6
Type	Single-layer	Two-layer	Two-layer	Single-layer
Size	$1.55\lambda_0 \times 1.37\lambda_0$	$1.58\lambda_0 \times 1.58\lambda_0$	$1.73\lambda_0 \times 1.6\lambda_0$	$1.6\lambda_0 \times 1.6\lambda_0$

A comparison study between simulated results of the proposed planar antenna array with the results of the recently published planar SIW antenna array is presented in Table 3. It can be seen that the proposed planar antenna array in this paper has smaller size and due to single layer structure has simpler fabrication process, while it nearly provide identical impedance bandwidth and gain to that of other reported planar SIW arrays.

4. CONCLUSION

In this paper, two hybrid antenna arrays including a linear 1×4 and a planar 2×2 array are introduced. The elements of both arrays consists of a half-mode SIW semi-circle cavity in conjunction with a rectangular microstrip patch, which forms a wideband hybrid antenna. A simple appropriate microstrip feeding circuit consisting the required power dividers and quarter wavelength transformers are used to provide impedance matching condition.

Both antenna arrays are implemented using a single layer PCB process to facilitate planar integration with passive and active circuits and also, to simplify applying SMA connector. Each element of both arrays is uniformly excited with same amplitude and phase. Both antenna arrays have been designed for operating frequency of 8 GHz with total size of $1.58\lambda_0 \times 2.87\lambda_0$ and $1.57\lambda_0 \times 1.37\lambda_0$ for linear- and planar array, respectively.

Simulated and measured results including reflection coefficient, radiation patterns and gain are presented and for planar array, they are compared with those which recently published in literature.

Apart from small difference between measured and simulated results for S_{11} of planar array, there is a very good agreement with other obtained results. It is believed that this disagreement on S_{11} is might be due to the effect of feeding networks and fabrication imperfections. Measured results exhibit peak gain of 12.15 dBi and 12.93 dBi for linear array and planar array, respectively.

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چکید

در این مقاله دو آرایه شامل یک آرایه خطی ۱×٤ و یک آرایه صفحهای ۲×۲ با استفاده از آنتن ترکیبی پچ مایکرواستریپ و محفظه نیم- مود موجبر مجتمع شده در زیر لایه (SIW) معرفی و ارائه می شود. این ساختارها به سادگی روی یک زیرلایه با فرآیند مدار چاپی پیاده‌سازی می‌شوند. عنصر آرایه ها از یک پچ مستطیلی با ابعاد مناسب در کنار یک حفره تشدید نیم دایره ای تشکیل شده است که یک آنتن ترکیبی پهن باند را به وجود می‌آورند. در هر دو آنتن آرایه ای از شبکه تغذیه مایکرواستریپی با مبدل ربع موج به عنوان مدار تطبیق برای تغذیه عناصر آرایه استفاده شده است.آرایه خطی ۱×٤ به ابعاد نسبی ۱/۵۸λ_0×۲/۸۷λ_0 و آرایه صفحه ای ۲×۲ به ابعاد نسبی ۱/۵۷λ_0×۱/۳۷λ_0 طراحی و ساخته شده و با روش عددی و آزمایشگاهی بررسی شده اند. نتایج اندازه گیری و شبیه‌سازی ضریب انعکاس، الگوی تشعشع و بهرهٔ آرایه ها گزارش شده است.

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