Antenna Arrays for Tactical Communication Systems: A Comparative Study

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Abstract. *In this paper, we give a comparative study of several planar antenna concepts for reliable long range links in a tactical environment. The antenna elements are studied in terms of their electrical properties (bandwidth, reflection coefficient and radiation characteristics) and construction (robustness and material consumption). First, we model single antenna elements to investigate if they meet the requirements. Second, we arrange the elements with the best features into 2×2 arrays. Computer simulations of the arrays are verified by measurements. Finally, we formulate recommendations for large array (8×8 or 16×16 elements) synthesis to achieve the required properties.*

Keywords

Planar antenna array, tactical communication systems, aperture-fed antenna, stacked-patch antenna, E-shaped patch antenna, U-slot patch antenna, feeding network.

1. Introduction

An antenna array for reliable long range links in tactical (i.e. military) environment faces to many contradictory requirements. On one hand, it should excel in high gain, low side lobes, good front-to-back ratio and low reflection coefficient. On the other hand, the antenna should have compact size and easy and robust construction.

Planar antenna arrays are able to satisfy the requirements on the construction. Unfortunately, in many cases, they suffer from narrow bandwidth. In this work, we will investigate selected types of planar antennas with simple construction and wide bandwidth. After completing them into arrays with appropriate number of elements, the requirements listed in Tab. 1 should be satisfied.

The organization of this paper is as follows. In a first step, we study four different planar antenna elements: an aperture-fed antenna, a stacked patch antenna, an E-shaped stacked-patch antenna with washer, and a U-slot patch antenna. The antenna elements are optimized to reach the required properties. In a second step, the antenna elements with the best features are grouped into 2×2 arrays. We model the arrays by a numerical tool and verify the simulations by experiments. The achieved results are compared and recommendations for the design of planar antenna arrays for long range links of tactical communication systems are drawn in summary and discussion.

Bandwidth	4.4 to 5.0 GHz
Input impedance	50 Ω
Total gain	≥ 20 dB
$20\log\|S_{11}\|$ in operation band	≤ −14 dB
Polarization	Linear
3 dB beamwidth, E-plane	15°± 2°
3 dB beamwidth, H-plane	15°± 2°

Tab. 1. Technical requirements for the planar antenna array.

2. Antenna Elements

We describe here the single antenna elements investigated in terms of impedance matching and radiation characteristics. All computer simulations were done in CST Microwave Studio (CST MWS).

2.1 Aperture-fed Antenna

The first studied antenna is the aperture-fed microstrip antenna [1], [2] with air substrate: a metallic patch is placed and fixed by dielectric spacers above a dielectric substrate with a feed line on the one side and with a ground plane on the other side. The metallic patch is excited by a radiating slot (aperture) etched into the ground plane, see Fig. 1.

Because of the feeding technique, the aperture-fed microstrip antenna excels in operation bandwidth (typically 10 %) and clean radiation patterns (the radiating patch and the feeding network are spatially divided by the ground plane). We used a thin dielectric substrate with low permittivity to achieve strong coupling between the microstrip and the slot and also to keep the feeding line wide and make fabrication easy and low-cost.

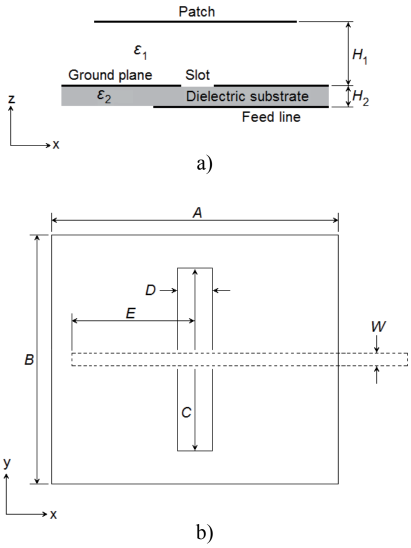


Fig. 1. Schematics of the aperture-fed antenna: side view (a), top view (b).

For larger bandwidth, we increased the length of the coupling slot. When the length of the aperture becomes comparable to the wavelength, the aperture begins to resonate together with the metallic patch. This dual-resonant effect leads to considerable expansion of the bandwidth of the antenna. Since the aperture behaves as a magnetic dipole, it radiates both into the upper and the lower hemisphere separated by the ground plane, and results in high side lobe level and poor front-to-back ratio [1].

Values of parameters of the antenna from Fig. 1, optimized for frequency band 4.4 GHz ÷ 5.0 GHz, are summarized in Tab. 2. The simulated reflection coefficient and co-polar radiation patterns are shown in Fig. 2 and Fig. 3, respectively (due to inaccurate cross-polarisation calculation in the CST MWS, we do not present these results). The obtained total antenna efficiency in the considered frequency interval is very near to 100 % and the gain changes from 8.4 dB up to 8.7 dB, see Tab. 3.

The aperture-fed antenna has excellent reflection coefficient ($20\log|S_{11}| \leq -21$ dB, i.e. VSWR ≤ 1.20) and sufficient gain. However, back radiation of the coupling slot results in increased side lobes and weak front-to-back ratio.

A [mm]	21.78
B [mm]	19.13
C [mm]	17.59
D [mm]	1.77
E [mm]	2.72
W [mm]	0.70
H_1 [mm]	8.00
ε_1 [–]	1.00
H_2 [mm]	0.25
ε_2 [–]	2.55

Tab. 2. Parameters of the aperture-fed antenna.

Frequency [GHz]	4.4	4.7	5.0
Gain [dB]	8.4	8.7	8.7

Tab. 3. Gain of the aperture-fed antenna.

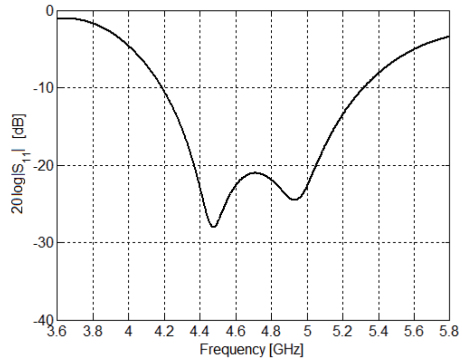


Fig. 2. Reflection coefficient of the aperture-fed antenna.

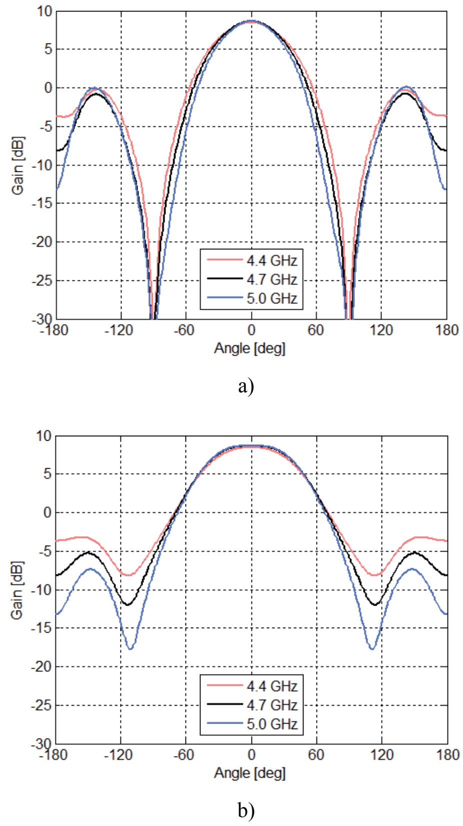


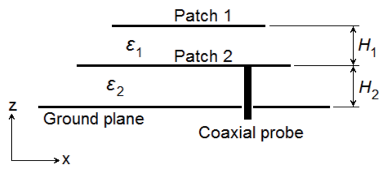
Fig. 3. Radiation patterns of the aperture-fed antenna: E-field (a), H-field (b).

2.2 Stacked-patch Antenna

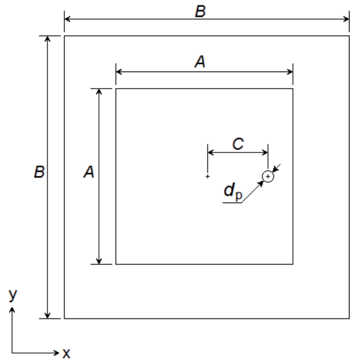
The second investigated antenna is the stacked patch antenna with one parasitic element, see Fig. 4. In this case, a lower patch is driven by a coaxial probe whereas an upper parasitic patch is in capacitive coupling with the lower one. The two patches resonate at slightly different frequencies and ensure large bandwidth (up to 20 % instead of 3 % of conventional probe-fed patch antennas without parasitic elements), [1].

The stacked-patch antenna from Fig. 4 was optimized for frequency band 4.4 GHz ÷ 5.0 GHz. Values of parameters are summarized in Tab. 4.

Based on simulation results (Fig. 5, Fig. 6 and Tab. 5), the antenna exhibits the desired co-polar radiation patterns with low side lobe level and good front-to-back ratio. However, we suppose that the square patches could cause higher cross-polarization level than in the previous case. The calculated total antenna efficiency is above 98 %. The gain of the antenna is considerably larger than in the case of the aperture-fed one: its value changes from 9.0 dB to 10.2 dB, see Tab. 5. Unfortunately, the reflection coefficient of the antenna ($20\log|S_{11}| \leq -13$ dB, i.e. VSWR ≤ 1.58) does not meet the requirements, thus some modifications of the original concept are investigated in the next section to improve the antenna performance.



a)



b)

Fig. 4. Schematics of the stacked-patch antenna: side view (a), top view (b).

A [mm]	24.13
B [mm]	30.16
C [mm]	13.95
d_p [mm]	1.27
H_1 [mm]	3.47
ε_1 [–]	1.00
H_2 [mm]	3.53
ε_2 [–]	1.00

Tab. 4. Parameters of the stacked-patch antenna.

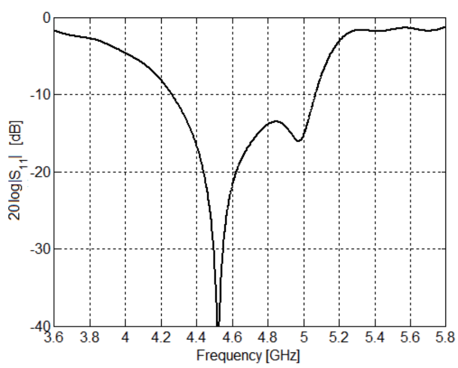
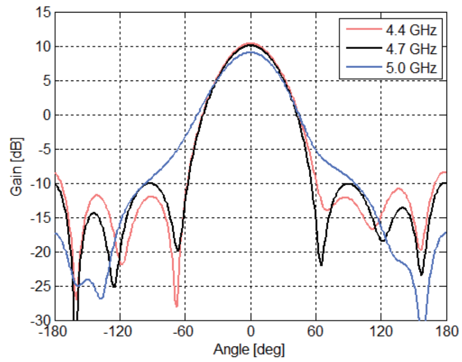
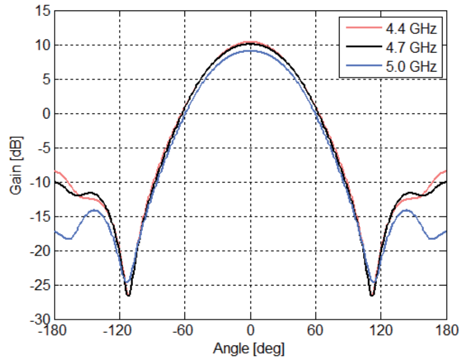


Fig. 5. Reflection coefficient of the stacked-patch antenna.



a)



b)

Fig. 6. Radiation patterns of the stacked-patch antenna: E-field (a), H-field (b).

Frequency [GHz]	4.4	4.7	5.0
Gain [dB]	10.2	10.1	9.0

Tab. 5. Gain of the stacked-patch antenna.

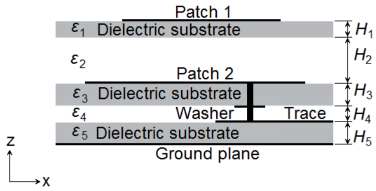
2.3 E-shaped Stacked-patch Antenna with Washer

The E-shaped stacked-patch antenna with washer was published by Ooi [3]. The structure differs from the conventional stacked-patch antenna (Fig. 4) both the shape of the lower patch and the presence of a washer, see Fig. 7. The small circular washer beneath the lower patch aids to cancel reactance of a coaxial probe and produces better matching condition [3].

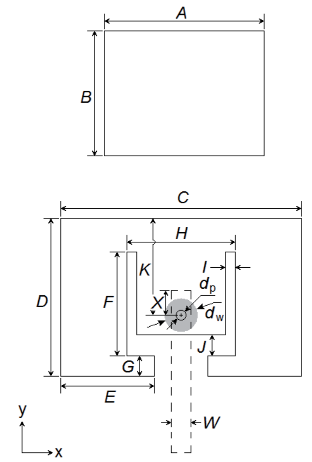
In our design, we placed the metallic patches on dielectric substrate Taconic TLX-8 with thickness 0.51 mm and relative permittivity 2.55. The antenna is fed by a microstrip transmission line, which is connected to a 50 Ohm SMA connector. The washer is placed on the reverse side of the substrate with the E-shaped patch.

We optimized the antenna to achieve the best impedance matching in the band from 4.4 GHz to 5.0 GHz. The optimal values of parameters are summarized in Tab. 6. Fig. 8 and Fig. 9 show the calculated reflection coefficient and co-polar radiation patterns, respectively. For antenna gain, see Tab. 7.

Unambigously, the E-shaped stacked-patch antenna meets the requirements on reflection coefficient in the operation band ($20\log|S_{11}| \leq -21$ dB, i.e. VSWR $\leq$ 1.20). The calculated total antenna efficiency is close to 100 %. Radiation patterns show a slightly deflected main lobe in E-plane (effect of the feeding line) but also sufficient suppression of side lobes and good front-to-back ratio.



a)



b)

Fig. 7. Schematics of the E-shaped stacked-patch antenna with washer: side view (a), top view – the upper patch and the lower patch (b).

A [mm]	20.02
B [mm]	18.89
C [mm]	39.73
D [mm]	21.95
E [mm]	13.57
F [mm]	15.76
G [mm]	4.09
H [mm]	10.36
I [mm]	0.27
J [mm]	0.87
K [mm]	15.76
X [mm]	3.68
W [mm]	1.5
d_p [mm]	1.2
d_w [mm]	3.16
H_1 [mm]	0.51
ε_1 [–]	2.55
H_2 [mm]	3.46
ε_2 [–]	1
H_3 [mm]	0.51
ε_3 [–]	2.55
H_4 [mm]	2.79
ε_4 [–]	1
H_5 [mm]	0.51
ε_5 [–]	2.55

Tab. 6. Parameters of the E-shaped stacked-patch antenna with washer.

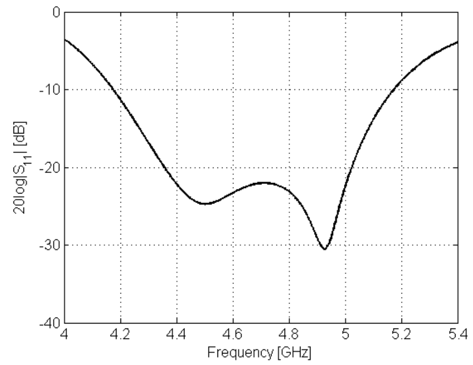
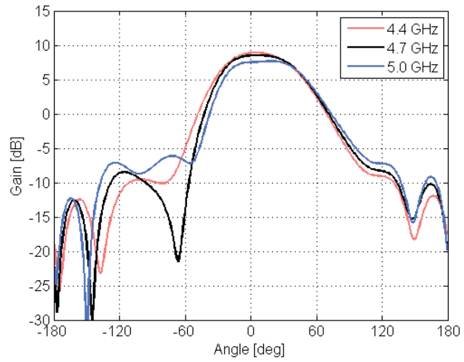
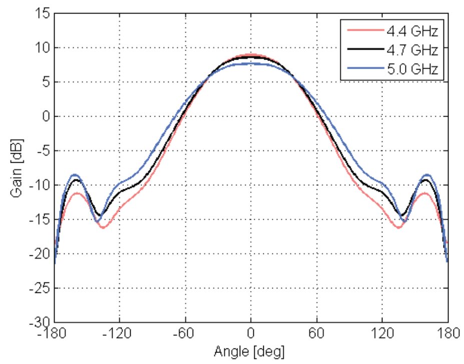


Fig. 8. Reflection coefficient of the E-shaped stacked-patch antenna with washer.



a)



b)

Fig. 9. Radiation patterns of the E-shaped stacked-patch antenna with washer: E-field (a), H-field (b).

Frequency [GHz]	4.4	4.7	5.0
Gain [dB]	8.9	8.5	7.7

Tab. 7. Gain of the E-shaped stacked-patch antenna with washer.

2.4 U-slot Patch Antenna

Broadband characteristic of a conventional probe-fed patch antenna can be obtained by a U-shaped slot etched in a patch. In this case, the U-slotted patch antenna has two resonance frequencies and the relative bandwidth increases up to 30 % [4], [5].

Geometry of the U-slot antenna is shown in Fig. 10. A rectangular patch is separated from a ground plane with an air substrate. The U-slot is located in the centre of the rectangular patch and is fed by a coaxial probe along the y-direction.

Tab. 8 lists the physical parameters of the optimized U-slot patch antenna. Fig. 11 shows the simulated reflection coefficient ($20\log|S_{11}| \le -22$ dB, i.e. VSWR ≤ 1.17 in the operation band). The calculated total antenna efficiency is near to 100 %. Asymmetry of the rectangular patch with the U-slot results in slight deflection of main lobe in E-plane, see Fig. 12. The gain of the antenna is above 9.3 dB, see Tab. 9.

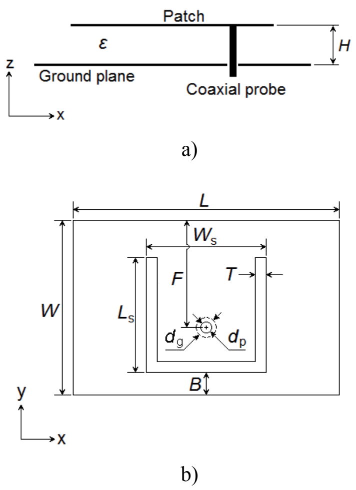


Fig. 10. Schematics of the U-slot patch antenna: side view (a), top view (b).

L [mm]	37.50
W [mm]	24.30
L_s [mm]	18.90
W_s [mm]	11.40
F [mm]	13.00
B [mm]	2.90
T [mm]	2.00
d_p [mm]	1.20
d_g [mm]	4.32
H [mm]	5.50
ε [–]	1.00

Tab. 8. Parameters of the U-slot antenna.

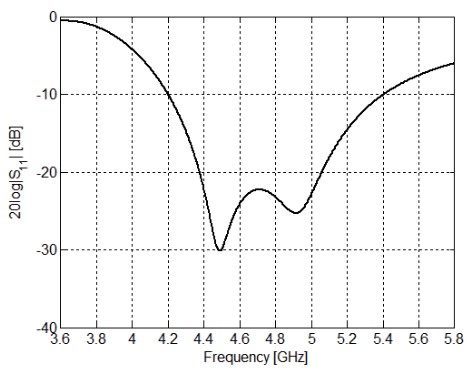


Fig. 11. Reflection coefficient of the U-slot patch antenna.

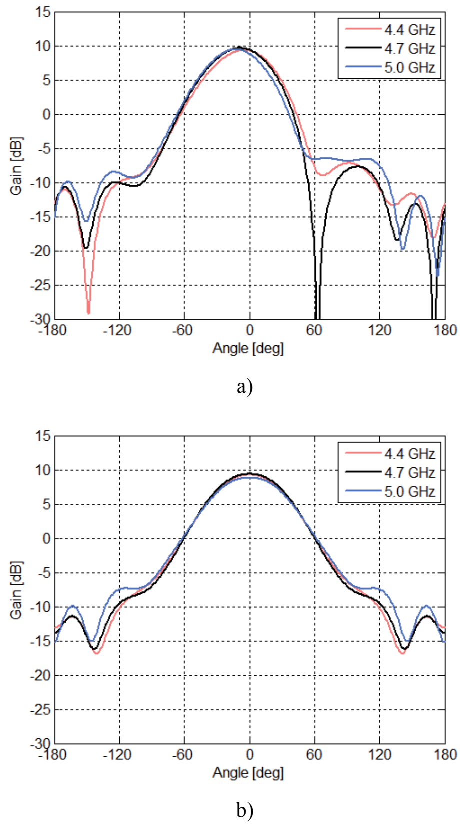


Fig. 12. Radiation patterns of the U-slot patch antenna: E-field (a), H-field (b).

Frequency [GHz]	4.4	4.7	5.0
Gain [dB]	9.3	9.6	9.4

Tab. 9. Gain of the U-slot patch antenna.

3. Small Antenna Arrays

To achieve higher gain, we arranged the single antenna elements with the best features (E-shaped stacked-patch antenna with washer and U-slot patch antenna) into small arrays consisting of 2×2 patches. Both the arrays were completed with a dielectric radome (acrylonitrile-butadiene-styrene – ABS).

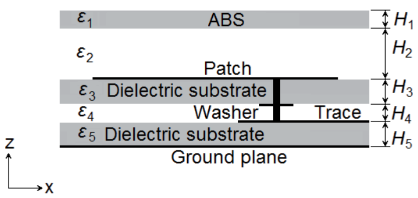
3.1 Array with E-shaped Patches and Washer

Placing the ABS over the E-shaped stacked-patch antenna with washer, we observed a significant deterioration of the impedance matching. After we removed the upper parasitic patch (Fig. 13), we re-tuned the antenna for the best reflection coefficient in the required frequency band. Next, we composed the single antenna element into a small array with 2×2 patches. Due to a tilted main lobe of the single antenna element, opposite patches are fed with phase difference of 180 deg, see Fig. 14.

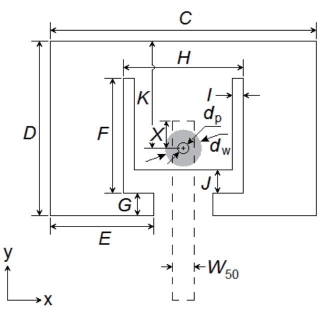
Values of the antenna array and the feeding network are summarized in Tab. 10. Photograph of the fabricated prototype is shown in Fig. 15. The antenna array is fed by a 50 Ohm SMA connector mounted on the bottom of the structure. Overall dimensions are 150 mm × 150 mm. Both the array of patches and the feeding network are realized on dielectric substrate Taconic TLX-8 with thickness 0.51 mm and relative permittivity 2.55. Plastic components such as spacers are made from polyamide.

C [mm]	45.90
D [mm]	23.90
E [mm]	15.27
F [mm]	19.25
G [mm]	2.50
H [mm]	15.51
I [mm]	0.24
J [mm]	0.80
K [mm]	18.32
X [mm]	2.28
d_p [mm]	1.04
d_w [mm]	2.99
H_1 [mm]	5.00
ε_1 [-]	2.77
H_2 [mm]	33.10
ε_2 [-]	1.00
H_3 [mm]	0.51
ε_3 [-]	2.55
H_4 [mm]	2.00
ε_4 [-]	1.00
H_5 [mm]	0.51
ε_5 [-]	2.55
D_{ant} [mm]	50.90
W_{50} [mm]	1.50
W_{70} [mm]	0.96
W_{100} [mm]	0.35
L_q [mm]	11.49
L_f [mm]	13.50
L_{90} [mm]	11.49
m [-]	0.50

Tab. 10. Parameters of the array with E-shaped patches and washer.

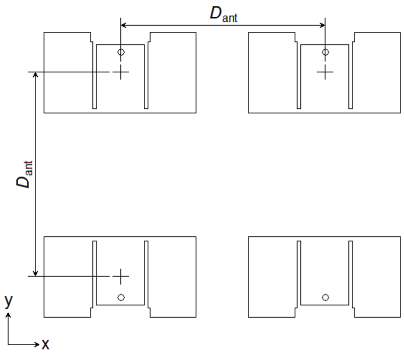


a)

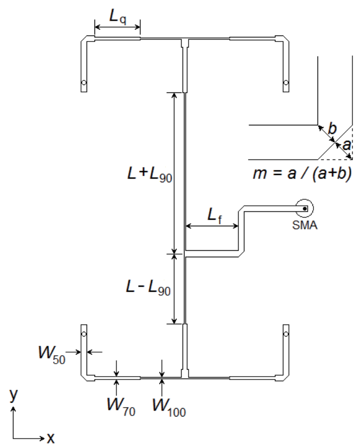


b)

Fig. 13. Schematics of the E-shaped patch antenna with washer and ABS: side view (a), top view (b).



a)



b)

Fig. 14. Schematics of the array with E-shaped patches and washer: top view (a), feeding network (b).

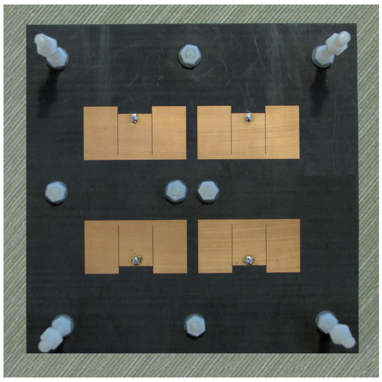


Fig. 15. Photograph of the fabricated array with E-shaped patches and washer (the radome was removed).

The simulated and measured reflection coefficient of the array with E-shaped patches and washer, completed with the ABS, are depicted in Fig. 16. Obviously, the measured results show $20\log|S_{11}| \leq -18$ dB (VSWR ≤ 1.29). The simulated total antenna efficiency is greater than 98 %. Radiation patterns (Fig. 17 and Fig. 18) indicate low side lobe level and good front-to-back ratio. The cross-polarization level does not exceed −6 dB. Due to the phase-opposite feeding technique, deflection of main lobe becomes negligible. The antenna gain extends from 14 dB up to 16 dB, see Tab. 11.

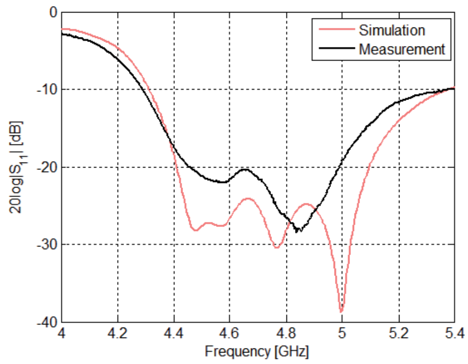
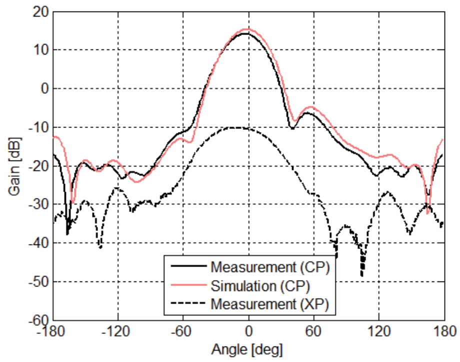
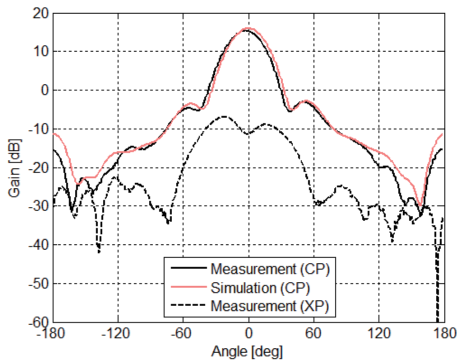


Fig. 16. Reflection coefficient of the array with E-shaped patches and washer.



a)



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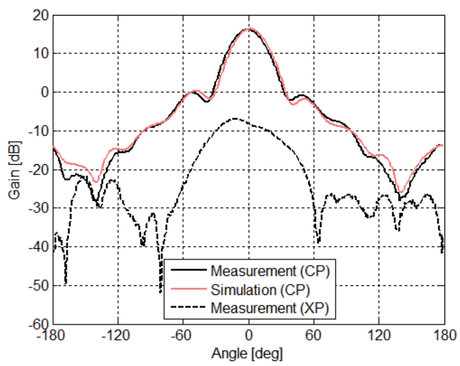
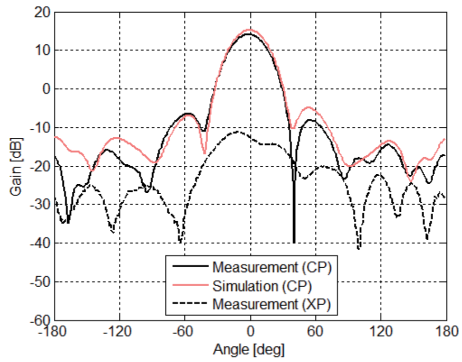
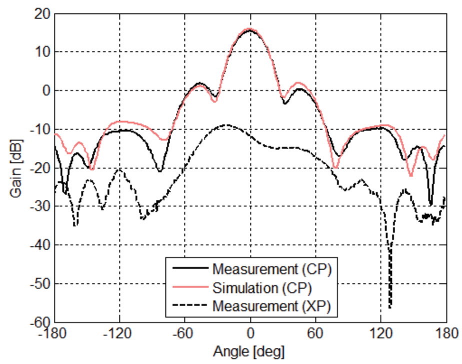


c)

Fig. 17. Radiation patterns (E-field) of the array with E-shaped patches and washer: 4.4 GHz (a), 4.7 GHz (b), 5.0 GHz (c).



a)



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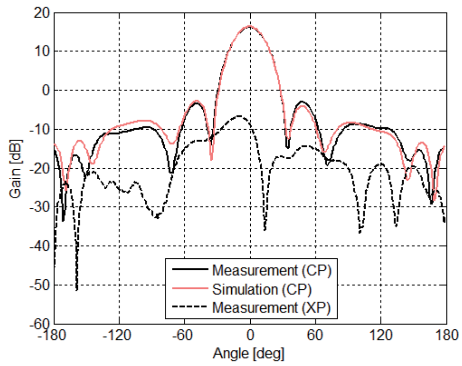


c)

Fig. 18. Radiation patterns (H-field) of the array with E-shaped patches and washer: 4.4 GHz (a), 4.7 GHz (b), 5.0 GHz (c).

Frequency [GHz]	4.4	4.7	5.0
Gain – simulated [dB]	15.3	15.9	16.3
Gain – measured [dB]	14.2	15.4	16.2

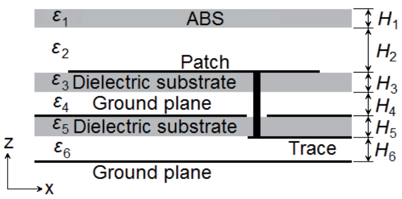
Tab. 11. Gain of the array with E-shaped patches and washer.

3.2 Array with U-slot patches

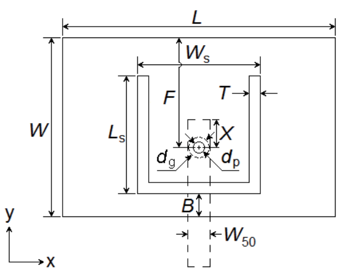
To compose the single U-slot patch presented in section 2.4 into small antenna array, we made some modifications of the original concept: the U-slot patch was placed on dielectric substrate Taconic TLX-8 with thickness 0.51 mm and relative permittivity 2.55; the microstrip line replaced the coaxial feeding and it is situated under the ground plane on dielectric substrate Taconic TLY-5 with thickness 0.79 mm and relative permittivity 2.2. The ABS was included too, see Fig. 19. The array with U-slot patches uses in-phase feeding network (Fig. 20). In order to minimize the parasitic radiation of the feeding network, we put it into a shielding box. Tab. 12 summarizes dimensions of the antenna elements and the feeding network.

L [mm]	31.20
W [mm]	24.90
L_s [mm]	16.40
W_s [mm]	11.80
B [mm]	2.40
T [mm]	2.40
F [mm]	13.95
X [mm]	1.15
d_p [mm]	1.20
d_g [mm]	4.20
H_1 [mm]	5.00
ε_1 [-]	2.77
H_2 [mm]	7.00
ε_2 [-]	1.00
H_3 [mm]	0.51
ε_3 [-]	2.55
H_4 [mm]	4.00
ε_4 [-]	1.00
H_5 [mm]	0.79
ε_5 [-]	2.20
H_6 [mm]	10.00
ε_6 [-]	1.00
D_{ant} [mm]	37.00
W_{50} [mm]	2.40
W_{70} [mm]	1.40
W_{100} [mm]	0.65
L_q [mm]	10.30

Tab. 12. Parameters of the array with U-slot patches.



a)

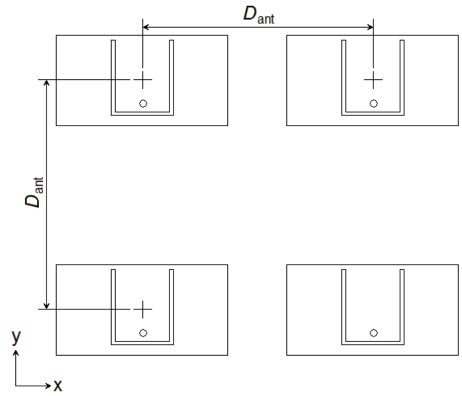


b)

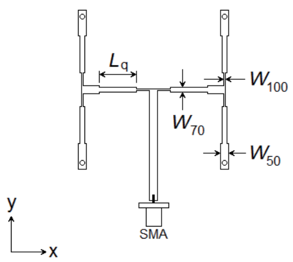
Fig. 19. Schematics of the U-slot patch antenna with ABS: side view (a), top view (b).

Photograph of the fabricated U-slot patch antenna is depicted in Fig. 21. The overall dimensions are 150 mm × 150 mm. The antenna array is fed by a 50 Ohm SMA connector mounted on the side of the structure. Plastic components are made from polyamide.

Simulated and measured reflection coefficient of the antenna is shown in Fig. 22. For better impedance matching, we tuned the SMA-microstrip transition by a capacitive stub, see Fig. 21.b. Due to the stub, we achieved the reflection coefficient $20\log|S_{11}| \leq -22$ dB (VSWR ≤ 1.17). The calculated total antenna efficiency is larger than 98 %. Just above the operation band, parasitic resonance of the shielding box is obvious. On the other hand, due to the metallic box covering the feeding network, good front-to-back ratio of the antenna was obtained (Fig. 23 and Fig. 24). The cross-polarization level is under −11 dB. Unfortunately, with growing frequency the side lobe level increases and reaches about 0 dB in H-plane at 5.0 GHz. The measured antenna gain extends from 11 dB up to 13 dB, see Tab. 13.

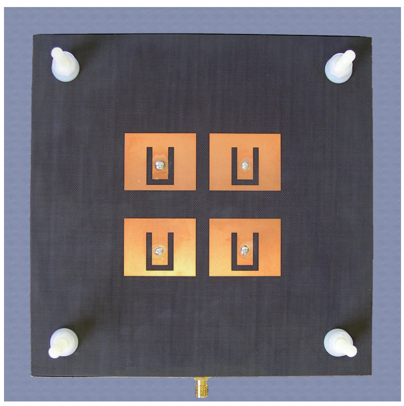


a)

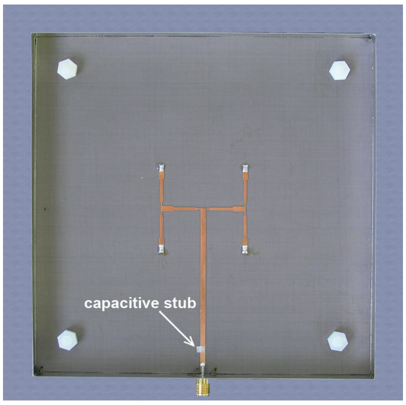


b)

Fig. 20. Schematics of the array with U-slot patches: top view (a), feeding network (b).



a)



b)

Fig. 21. Photograph of the fabricated array with U-slot patches: top view - the radome was removed (a), feeding network - the top shield of the metallic box was removed (b).

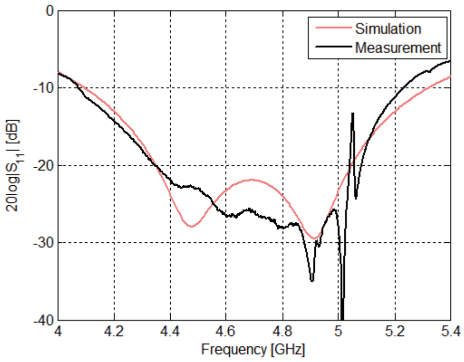
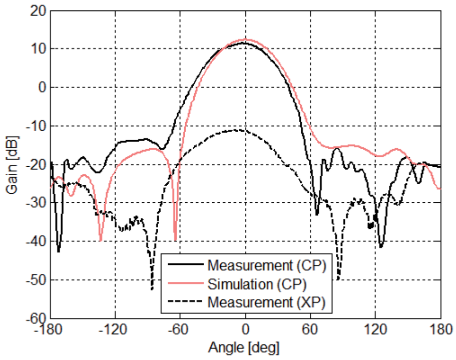
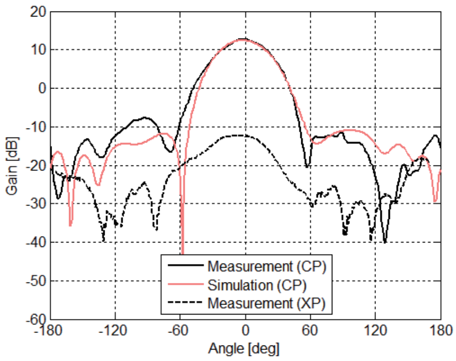


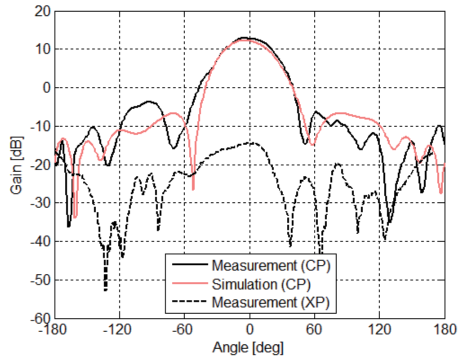
Fig. 22. Reflection coefficient of the array with U-slot patches.



a)

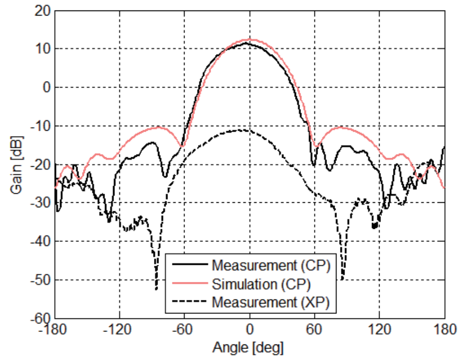


b)

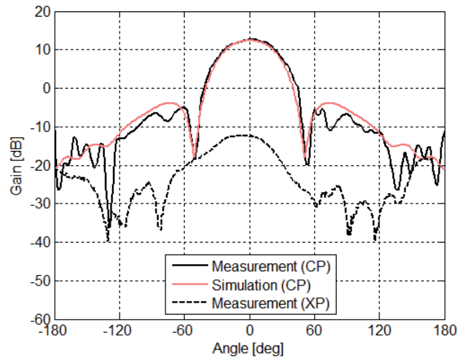


c)

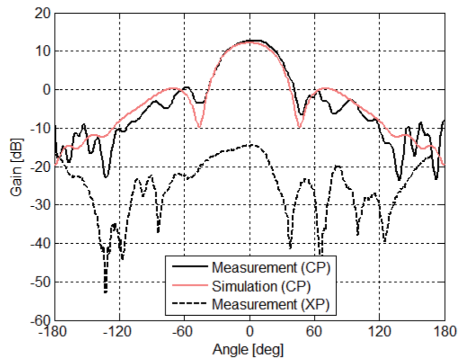
Fig. 23. Radiation patterns (E-field) of the array with U-slot patches: 4.4 GHz (a), 4.7 GHz (b), 5.0 GHz (c).



a)



b)



c)

Fig. 24. Radiation patterns (H-field) of the array with U-slot patches: 4.4 GHz (a), 4.7 GHz (b), 5.0 GHz (c).

Frequency [GHz]	4.4	4.7	5.0
Gain – simulated [dB]	12.2	12.4	12.2
Gain – measured [dB]	11.4	12.7	12.9

Tab. 13. Gain of the array with U-slot patches.

4. Summary and Discussion

In the paper, we focused on practical aspects of the design of wideband planar antenna arrays. We considered the influence of a selected microwave substrate, radome, plastic spacers, and other construction components of antenna arrays. Experience with the design and construction were described to provide guidelines for antenna designers.

First, four types of wideband planar antennas (aperture-fed antenna, stacked-patch antenna, E-shaped stacked-patch antenna with washer and U-slot patch antenna) were investigated in terms of impedance matching and radiation characteristics. We put the main emphasis on low reflection coefficient in the operation band (4.4 GHz – 5.0 GHz), low side lobe level, good front-to-back ratio and sufficient antenna gain. The antennas with the best performances (E-shaped stacked-patch antenna with washer and U-slot patch antenna) were then completed with radome and arranged into small arrays consisting of 2×2 elements. The designed arrays were fabricated and measured.

In the case of the array with E-shaped patches and washer, measurement shows reflection coefficient in operation band $20\log|S_{11}| \leq -18$ dB (VSWR $\leq$ 1.29). Radiation patterns of the antenna indicate an almost undeflected main lobe, sufficient suppression of side lobes and front-to-back ratio about 30 dB. The antenna gain reaches up to 16 dB at 5.0 GHz. The main disadvantage of the proposed concept is that a feeding network and an array of patches are not divided by a ground plane: at larger structures deformation of directivity patterns due to the parasitic radiation of microstripes can appear.

The array with U-slot patches excels in low reflection coefficient: after compensation of reactance of an SMA connector by a capacitive stub, $20\log|S_{11}| \leq -22$ dB (VSWR $\leq$ 1.17) was achieved. On the other hand, radiation patterns show an increased side lobe in comparison with the array with E-shaped patches and washer. The measured front-to-back ratio is approximately 30 dB. The antenna gain is up to 13 dB at 5.0 GHz. In the proposed construction, radiating patches and feeding network (hidden into a metal box) are completely divided from each other.

Clearly, both the designed small antenna arrays satisfy the requirements on reflection coefficient and basic radiation properties. Compounding the elements into larger antenna arrays, requirements on a final structure listed in Tab. 1 can be achieved.

Acknowledgements

The research of the antennas described in the paper was financially supported by the grant of the Czech Ministry of Industry and Trade FR-TI2/039 “The Set of Antennas”. The support of the project CZ.1.07/2.3.00/20.0007 WICOMT, financed from the operational program Education for competitiveness, is also gratefully acknowledged.

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