Highly Directive Patch Antenna Array for FMCW Radar at Ku Band

Nikola Bošković, Branka Jokanović, Franco Oliveri, Dario Tarchi

Abstract—**We are presenting the design of a highly directive printed antenna array consisting of 420 identical patch antennas intended for FMCW radar at Ku band. The array exhibits 3 dB-beamwidths of 2° and 10° in H- and E-plane, respectively, side lobe suppression better than 20 dB and gain about 30 dBi in the frequency range 16.9 - 17.3 GHz. Excellent antenna efficiency that is between 60 and 70 % is achieved by using optimized series feeding architecture in the H-plane with both resonant and traveling-wave feed. Enhanced cross polarization suppression is obtained by anti-phase feeding of the upper and the lower halves of the antenna. Overall antenna dimensions are 31 λ_0 x 7.5 λ_0.**

Keywords—**Antenna array, patch antenna, series feeding network, radiation pattern.**

I. Introduction

Printed antenna arrays are often used in compact microwave devices with low Tx power, like FMCW radars and microwave links for fixed and mobile communications. The patch antenna is frequently used as the basic radiating element, in spite of its main drawback, the narrow bandwidth, i.e. operating range of only few per cents. To make the most of the patch antenna functionality, a great deal of care is required in designing the array feeding network. Various modifications of the patch antenna can be used to enhance the bandwidth [1]. However, they often use multilayer dielectrics or probes placed at specific places on the patch, which is very complicated in the case of an antenna array with large number of elements.

Using the patch antenna of specific impedance with an appropriate feeding network, the desired radiation characteristics can be obtained.

For feeding the printed antennas with a large number of elements, series feed is the most frequently used, because it introduces lower loss compared with corporate feed, which in turn enables wider bandwidth. Hybrid feeding networks are also used, which represent a combination of serial and a corporate feeding [2].

In this paper, we present the design of a high gain microstrip antenna with patch radiators, which has a very narrow beamwidth of 2^0 in azimuth and 10^0 in elevation, and operates in the frequency range of 400 MHz at Ku-band. Antenna is designed to have side lobe suppression better than 20 dB in H and E planes.

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II. Design of the Linear Subarray in H Plane

Design of the antenna array can be essentially divided into two phases: design of the linear subarray in H-plane and design of the E-plane feeding network which combines the H-plane arrays.

The most critical requirements are related to: (a) 3-dB beamwidth in the H plane which is supposed to be 2 degrees, which requires large number of radiators, and (b) meeting the required characteristics in the frequency range of 400 MHz.

The patch antenna was chosen as a main radiating element and its impedance is optimized to Z_{patch}=350 Ω using WIPL-D software [3]. Identical square patches are periodically placed at a distance λ_g on the substrate having ε_r = 2.17, $tg\delta$=0.0009, h=0.508 mm. To obtain the 2^0-beamwidth in H plane, it is necessary to have 42 radiating elements in a linear subarray. This very large number of elements requires the choice of a series feeding network in order to reduce losses in feeding lines. In a series fed array the input power comes to the antenna from one end of the array and therefore the main beam angle is very sensitive to the frequency change due to the progressive phase change of the series fed elements. To avoid scanning of the main beam while changing the frequency within the 400 MHz band, it was necessary to split horizontal subarray into two separate halves [4], with 21 radiating elements each. In this way it is achieved that the main lobe is always pointed in the broadside direction, regardless of frequency changes.

Feeding points of the subarray halves are not placed in their centers, but moved towards the center of the subarray, so that there are 2 x 7 central patches between the feeding points while the rest of 2 x 14 patches are placed between the feeding points and the antenna edges, as it is shown in Fig. 1. Each of the two central parts of the subarray consists of 7 patches placed at distances λ_g and connected in parallel to give 50 Ω impedance at the feeding point. It explains why the patch impedance was chosen to be 350 Ω. So, the central part of the subarray is acting like a subarray with uniform distribution and therefore contributes to the increase of the array gain. It should be noted that in this part of the subarray not every patch is matched to the line impedance, but there is matching only at the array input. By its nature, the uniform subarray is the resonant series fed array, which, in general, has a narrower bandwidth with respect to the traveling-wave array having matching at each element [5].

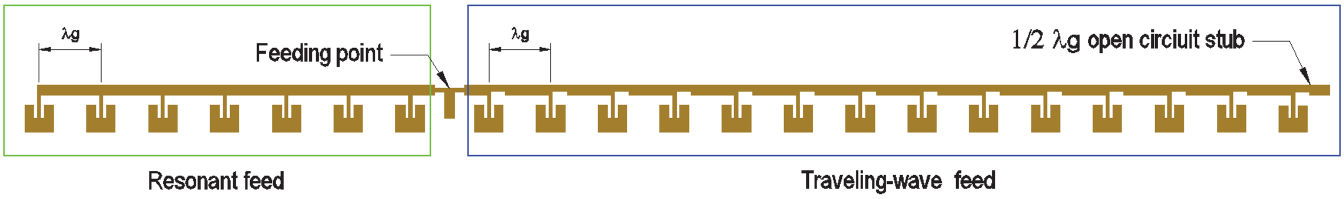


Fig. 1. Right half of the H-plane subarray with two types of series feeding

The part of the subarray between feeding points and the antenna edges is the traveling-wave array, because the impedance of the patches is not only matched to the line impedance at the feeding point, but also at every point where the patch is connected to the feeding line. Impedance of the patch (Z_{patch}=350 Ω) in parallel to the 58 Ω-impedance gives exactly the impedance of 50 Ω microstrip line. The 58 Ω impedance is obtained by transforming the feeding line impedance of 50 Ω through the quarter-wave transformer of Z_T=54 Ω as shown in Fig. 2.

Amplitude distribution in this part of the subarray has an exponential form which is designed to provide the greatest possible side lobe suppression and is given by the expression:

$$Ui = q^{i-1} + q^{2N-1}, \quad q = 6/7, \quad i = 1,\ldots 14 \qquad (1)$$

where the chosen q determines the amount of power given to the radiating element. For 350 Ω-patches fed by the 50 Ω line, q=1-Z_{50}/Z_{patch}=6/7. The second term in relation (1) comes from the power reflected from the ends of the subarray terminated with λ_g/2 open circuit stub, so that the reflected signal returns to the feeding line in phase. From (1) we can see that distribution in this subarray is exponential.

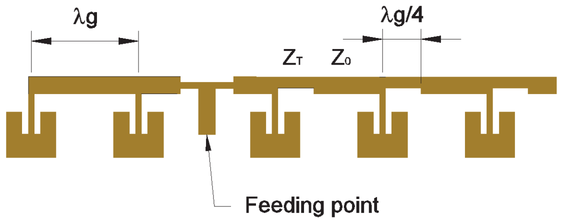


Fig. 2. Detail of the H-plane subarray near the feeding point

It should be noted that, by varying the ratio of the number of elements with uniform and non-uniform distribution in the subarrays, the trade-off between the gain and 3-dB beamwidth on one side, and side lobe suppression on the other side, can be adjusted. We have examinated three different amplitude distributions shown in Fig. 3. which contain different number of uniformly fed (5, 7, 10) and exponentially fed (16, 14, 11) elements, respectively. Each distribution is denoted with the fraction which numerator is equal to the number of elements with uniform amplitude distribution, while denominator indicates the number of elements having the exponential amplitude distribution.

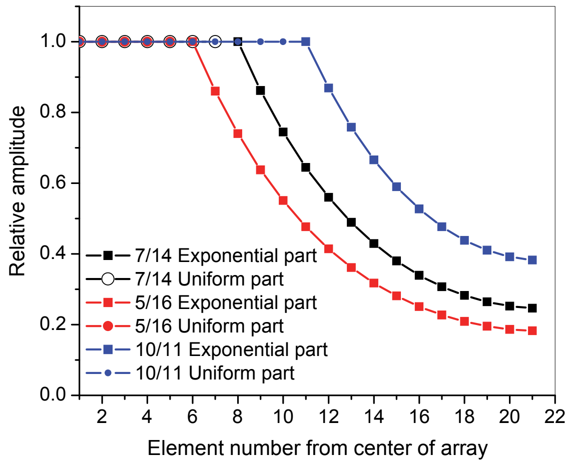
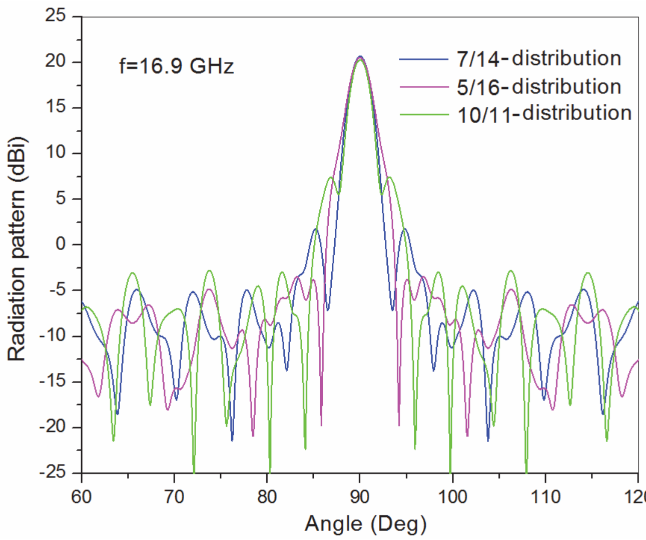


Fig 3. Different amplitude distributions for H-plane array

Simulated radiation patterns for different amplitude distributions are given in Fig. 4. It can be seen that the 10/11-distribution which contains 10 elements with uniform distribution exhibits very poor side lobe suppression of about 15 dB in the whole frequency band, while the 5/16-distribution has very good side lobe suppression of about 25 dB, but 3dB-beamwidth is 2.3^0 that is much wider than requested 2^0.



(a)

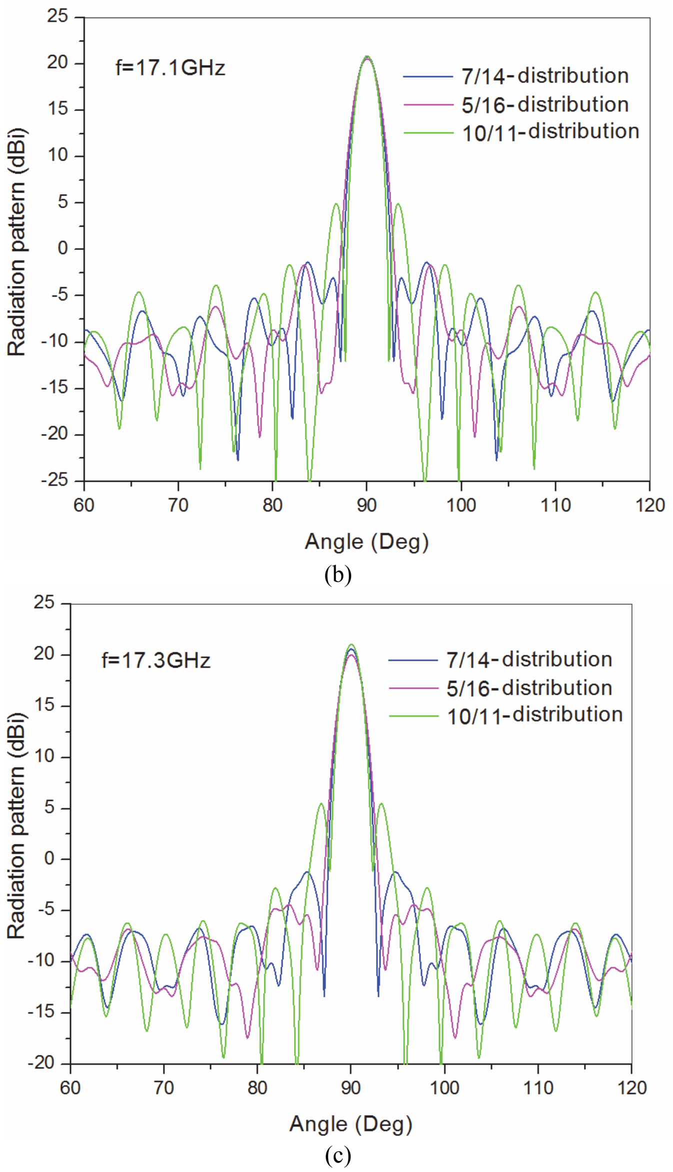


Fig. 4. Simulated H-plane radiation patterns obtained using different amplitude distributions at: (a) 17.1 GHz, (b) 17.1 GHz, (c) 17.4 GHz

The 5/16-distribution is clearly the best of three concerning the side lobe suppression, because of the largest exponential subarray containing 16 elements. The 10/11-distribution is the best considering 3dB-beamwidth that is 1.9^0, but it exhibits the worst side lobe suppression. As a compromise the 7/14-distribution is chosen for the design of H-plane subarray because it satisfies both requirements. The side lobe suppression is around 20 dB and 3-dB beamwidth is 2.1^0 in the whole frequency range.

III. Design of the E Plane Feeding Network

To obtain the required beamwidth of 10 degrees in the E plane, it is necessary to use ten H plane subarrays: the top five arrays contain patches placed on one side of the feeding line while the other five arrays have patches on the opposite side, in order to reduce unwanted cross polarization radiation. Due to anti-symmetry of lower and upper antenna halves, they must be fed in anti-phase in the whole operating band.

Main purpose of the E plane feeding network is to provide high side lobe suppression in the E plane with satisfactory gain. Modified Taylor distribution was chosen, which enables side lobe suppression of more than 30 dB at central frequency. Amplitude distribution coefficients are calculated by means of LINPLAN software [6]. The obtained relative amplitude coefficients are given in Table I, with the same notation as in Fig. 3. The given distribution was implemented by using different line impedances of the microstrip line [7] i.e. quarter-wave transformers.

TABLE I
AMPLITUDE COEFFICIENTS OF THE E PLANE DISTRIBUTION

U_1	U_2	U_3	U_4	U_5
1	0.909	0.614	0.295	0.114

One of four identical E-plane feeding networks is shown in Fig. 5. It can be seen that corresponding signal levels at the left and right hand sides are identical, although they feed different numbers of patches: 7 patches at the central part of the array and 14 patches at the edge part. The impedance values are given in Table II.

TABLE II
IMPEDANCES OF THE E-PLANE FEEDING NETWORK IN Ω

Z_1	Z_2	Z_3	Z_4	Z_5	Z_{12}	Z_{23}	Z_{34}, Z_{45}
115	100	89.8	79.2	70.7	63.6	86.8	134

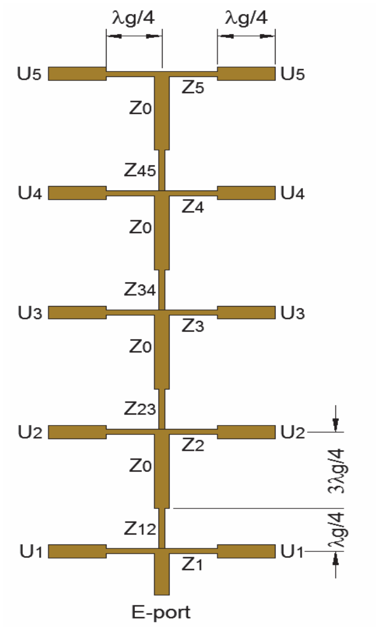


Fig. 5. One of four identical E-plane feeding networks

IV. Measured Antenna Characteristics

The antenna is designed using WIPL-D software. Using the options *Symmetry* and *Anti-Symmetry* available in the WIPL simulator, only a quarter of the antenna is simulated. For the complete antenna simulation, the number of unknown variables was 138156. Antenna simulation is accelerated tenfold by using GPU card TESLA K40C, but the duration of the simulation is 120 minutes at each frequency, which is still rather long.

Antenna array is manufactured using photo lithographic procedure with tolerances of ±20 microns that is very good result since the overall antenna length is about 600 mm. Antenna is mounted on 6 mm-thick aluminum honeycomb panel which is low weight (3.2 kg/m^2) in order to keep antenna weight at minimum. On the opposite side of aluminum panel the printed circuit of the Tx/Rx canceller which provides simultaneous transmitting and receiving antenna operation. Antenna is connected with the canceller by 6 mm long coaxial cable.

Photograph of the manufactured antenna array is given in Fig. 6. Overall antenna dimensions are 600 mm x 170 mm and weight is around 0.5 kg.

Measured normalized antenna radiation patterns at H- and E-planes are given in Fig. 7. Measured antenna gain is about 30 dBi, with a variation of 0.85 dB in the whole band. Average 3dB-beamwidth in H-plane is 2.2°and side lobe suppression is around 20 dB in the whole band. The side lobe levels in E- plane are considerably lower, first of all due to the possibility of more flexible control. Hence the side lobe level is suppressed more than 25 dB in respect to the main lobe, while the 3-dB beamwidth is around 10.4°. Measured cross polarization of the array in H- plane is between 31 and 39 dB below the main lobe.

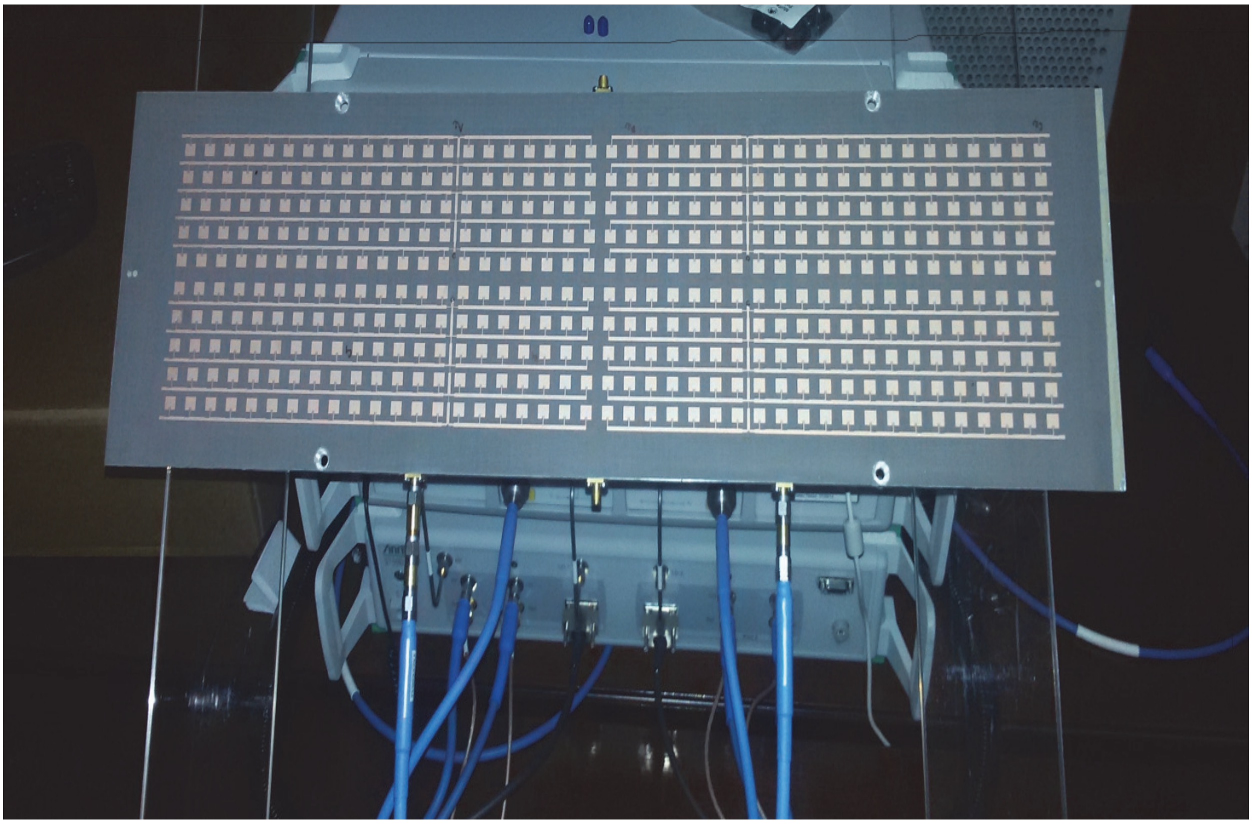
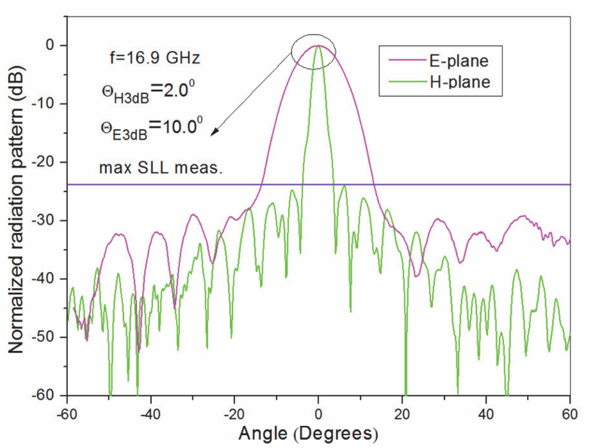
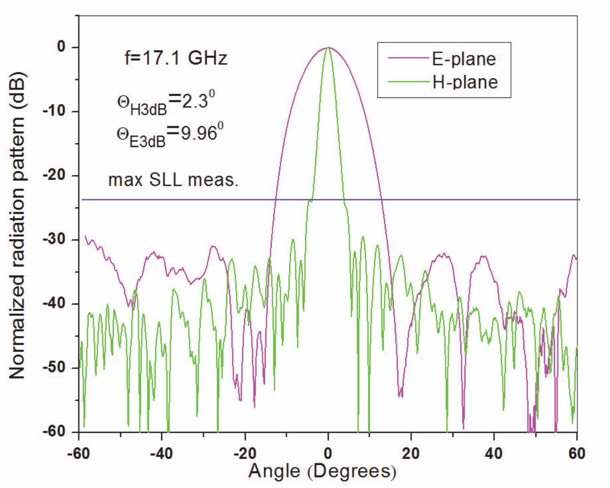


Fig. 6. Photograph of the manufactured patch antenna array. The antenna footprint is 31 λ_0 x 7.5 λ_0



(a)



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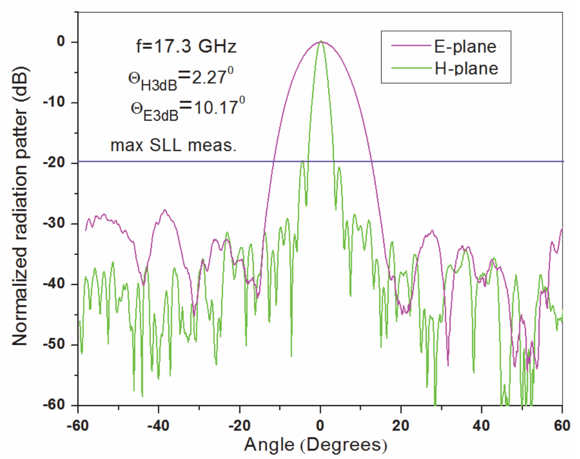

(c)

Fig. 7. Measured radiation patterns for H- and E-plane at: (a) 16.9 GHz, (b) 17.1 GHz, (c) 17.3 GHz

V. Conclusion

This paper presents the detailed design procedure of the high gain microstrip antenna array containing 420 patches, and operating in the frequency range of 400 MHz at 17 GHz. The array is extremely directive in H-plane, with the 3-dB beamwidth of just 2°, and therefore is more difficult for controlling the H-plane side lobe levels, while it is easy to achieve a very high side lobe suppression of more than 25 dB in the E-plane. The antenna exhibits an extremely good efficiency, between 60 and 70% in the operating band, due to the series feeding that is applied along the H-plane subarray.

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