

Improved Model of the Circularly Polarized Patch Antenna Array at 24 GHz for Radar Applications

Ivana Radnovic, *Member, IEEE*, Branka Jokanovic, *Senior Member, IEEE*,
and Anatoliy Boryszenko, *Member, IEEE*

Abstract — The paper presents the improved design of the novel circularly polarized patch antenna array operating at ISM band 24.05-24.25 GHz. The antenna array consists of 24 identical truncated patches which are serially fed through the microstrip line. The antenna is a travelling-wave array with exponential power distribution which provides very good side lobe suppression of 30 dB in the entire operating band making it suitable for automotive radar applications. Simulated axial ratio is below 3dB in the range (24.06-24.26) GHz, the antenna gain is greater than 17.2 dBi, cross polarization is better than 15 dB and return loss is greater than 15 dB in the entire ISM band.

Index Terms — Antenna array, circularly polarized patch antenna, exponential power distribution, axial ratio.

I. INTRODUCTION

CIRCULARLY polarized (CP) antennas are a key technology for various wireless systems (satellite and mobile communications, wireless sensors, wireless local area networks, etc.) due to significant advantages in respect to antennas with linear polarization. Most important is that CP antennas are very effective in fighting with multi-path interference, so there is no need for strict orientation between transmitting and receiving antenna.

Printed CP antennas are very suitable for various wireless applications due to their compact size, low price, and capability of easy integration into arrays and with microwave integrated circuits [1].

Recently, a number of different antennas with circular polarization for wireless systems have been proposed. In [2], a coplanar slot antenna with circular polarization fed by

a guided wave and intended for navigation and wireless systems operating in the range of 2.2-5.2 GHz is proposed. Another type of antenna with circular polarization for wireless systems, specifically RFID and WiMAX systems is presented in [3]. Namely, an antenna array is proposed, consisting of two truncated patch antennas with an additional slot. It has been shown in [3] that this type of microstrip antenna exhibits an expanding frequency range and reducing the standing wave ratio. The modified truncated patch antenna, or the antenna truncated only at one side, instead of the two opposite sides, is presented in [4]. It is also shown that truncated patch antenna with circular polarization has about 24.6% smaller dimensions than the conventional rectangular patch antenna of the same characteristics.

Circularly polarized antennas are rarely used individually, due to a low gain. Namely, the antenna arrays with circular polarization are much more frequently applied, which are most often realized so that the number of elements for each of the two axes is the same. This way of organizing antenna arrays is conditioned by the requirement for ellipticity, which represents the ratio of the electric field components along two axes. Namely, by adding antenna elements on one of the axes, the component of the field along that axis favors and degrades the ellipticity. For this reason, almost all of the up-to-date antenna arrays are square-shaped type. Square shaped antenna arrays of 2×2 and 8×8 antennas with circular polarization operating in the Ka band were presented in [5]. Another square-shaped 8×8 antenna array with truncated circularly polarized patches for applications in the ISM (Industrial, Scientific and Medical) band at 2.4 GHz was proposed in [6]. In addition to the characteristics of the proposed array, a detailed description of the design is given. Microstrip patch antenna with circular polarization for radar systems is presented in [7]. Also, an 8×8 antenna array for radar and satellite systems operating at 29 GHz, consisting of microstrip antennas with circular polarization, is presented in [8].

Although the above mentioned squared arrays have good performances, today's emphasis is placed on linear arrays with circular polarization, which are more compact than square arrays. However, the linear arrangement of antenna elements leads to degradation of ellipticity. Therefore, a very small number of studies have been done on the subject of linear circularly polarized antenna arrays. One such array, but with only 4 elements, that is intended for applications in the Ku frequency band, is given in [9].

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Ivana Radnovic is with the Institute IMTEL Communications, Bul. Mihaila Pupina 165b, 11070 Belgrade, Serbia, e-mail: ivana@insimtel.com.

Branka Jokanovic is with the Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Pregrevica, Serbia, e-mail: brankaj@ipb.ac.rs.

Anatoliy O. Boryszenko is with the A&E Partnership, Belchertown, MA, USA, e-mail: anatoliy@ae-partnership.com.

This paper presents the enhanced design of the circularly polarized series-fed antenna array consisting of 24 novel truncated patch antennas operating at 24 GHz given in [10], in order to obtain fully realistic characteristics in the very narrow operating range.

II. NOVEL CIRCULARLY POLARIZED TRUNCATED PATCH ANTENNA ELEMENT

As a constituent element of the array we used the novel truncated patch antenna whose layout is presented in Fig. 1. Unlike a conventional truncated patch antenna that has two diagonal cuts (Fig. 2b), the new antenna has the square-shaped cut in only one corner. This new antenna has shown a wider axial ratio bandwidth than commonly used circularly polarized patches – with a diagonal slot or with diagonally truncated corners, Fig. 2.

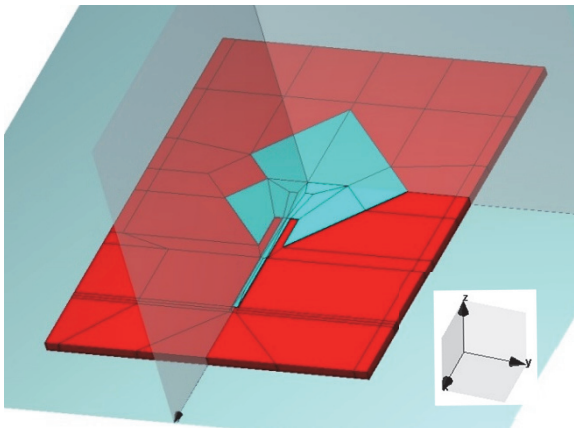


Fig. 1. Layout of the novel truncated patch used in the 24-element antenna array.

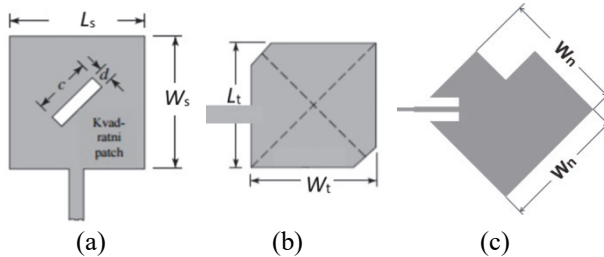


Fig. 2. (a,b): Commonly used modifications of patch antennas to obtain circular polarization (slotted patch, diagonally truncated patch), and (c): novel truncated patch.

One of the main disadvantages of patch antennas is their narrow bandwidth, so it is preferable to use dielectric substrates with higher thickness in order to improve the bandwidth.

In the first step of our investigation we have modeled and simulated a single patch antenna on the Teflon-fiberglass substrate with the dielectric constant $\epsilon_r=2.2$ and the thickness $h=0.254$ mm using 3D electromagnetic simulator based on the Method of Moments, WIPL-D [11]. Simulated ellipticity (axial ratio) was below 3 dB in the entire frequency range of interest (24.05-24.25 GHz). We carried out the analysis of the axial ratio variation with the number of elements added in series, but without the feeding network. As it was expected, the axial ratio increases even with one added element, but after the third added patch the axial ratio characteristics become stable and the obtained

results show that AR is less than 3 dB in the range (24.07-24.27 GHz) and practically don't vary with the number of elements in the array, as can be seen in Fig. 3.

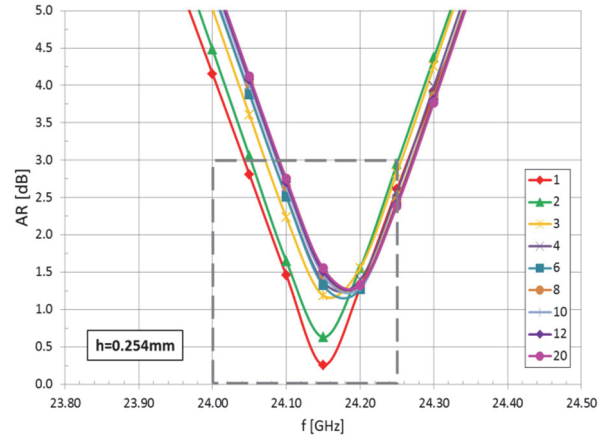


Fig. 3. Axial ratio vs. frequency for various number of radiating elements in the antenna array with uniform distribution ($\epsilon_r=2.2$, $h=0.254$ mm).

The reason why we decided to use the thinner substrate is the fact that microstrip line becomes narrower with the substrate height decrease, thus the main feed line realized on the common dielectric plate with radiating elements will not much affect and degrade radiating characteristics (axial ratio, gain and side lobe suppression) of the array, as it does in [12] resulting in the increase of side lobe levels.

III. CONCEPT AND DESIGN OF THE 24-PATCHES ARRAY

The antenna array consists of 24 series-fed identical patches with an appropriate matching network, as presented in Fig. 4 and Fig. 5. The input impedance of the patch, Z_p at the resonant frequency (24.15 GHz) is around 250 Ω . Patches are matched to the 100 Ω -feeding line through the parallel connection with the input impedance of the $\lambda/4$ -transformer Z_{in} . Therefore, the characteristic impedance of the transformer Z_T is equal to the square root of the product of its input impedance Z_{in} and the characteristic impedance of the feeding line $Z_0=100$ Ω . The simple analytical expression for the amplitude distribution along the antenna array is based on the ratio of the impedance of the feeding line Z_0 and the impedance of the patch antenna Z_p and is given by:

$$|a_i| = \left(1 - \frac{Z_0}{Z_p}\right)^{i-1} + \left(1 - \frac{Z_0}{Z_p}\right)^{2N-i} \quad i=1, \dots, N \quad (1)$$

where $2N$ is the total number of elements in the array.

It is well-known that the array with a travelling wave has to be terminated by a load to absorb the power left after the last radiating element. In our case, instead of the load, a half-wavelength open-circuited line reflecting a part of the leftover power and radiating it through patches is used, Fig. 5. As the patches are at the mutual distance of λ_g (wavelength in the dielectric), the wave is reflected from the open line in phase with a direct travelling wave, so the energy loss is very small.

The second term in the expression (1) originates from the power reflected from the open-circuited line at the end of the array.

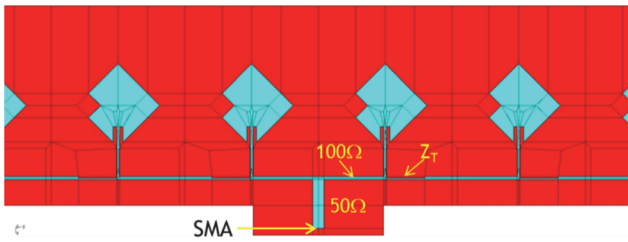


Fig. 4. Central elements of the antenna array with the main feed line and impedance transformers.

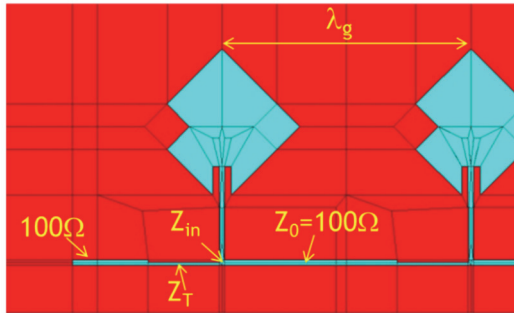


Fig. 5. End element of the antenna array with the matching network and the open-circuited 100 Ω-line.

IV. IMPROVEMENT OF THE BASIC MODEL OF THE ANTENNA ARRAY AND RESULTS OF THE SIMULATION

In the previous section we have introduced the model of the 24-elements antenna array that is optimized by use of WIPL-D electromagnetic simulator. In order to speed up the simulations, in this basic model [10] only the dielectric loss ($\tan\delta=9\times 10^{-4}$) was included, while the metallization thickness ($t=17\mu\text{m}$) and losses in the copper were not taken into account. Also, *normal* accuracies of the integrals and currents expansion were the input parameters in simulations.

After we have modeled the antenna structure which implied the copper thickness, and increased the order (accuracy) of the numerical integration as well as of the current expansion (set to *enhanced 1* and *enhanced 2*, respectively), the shift of about 25-30 MHz of the axial ratio characteristic toward lower frequencies has occurred, that is around 15% of the entire operating range of the antenna, Fig. 6. Since the presented antenna array covers quite a narrow bandwidth (200 MHz) in terms of the axial ratio ($\text{AR}\leq 3\text{ dB}$), this frequency shift could be critical in some applications.

Therefore, we had to carry out further optimizations with all previously mentioned improving parameters included. By introducing the metallization thickness in the basic antenna model the number of elements has increased from 12360 to 17788 while the number of unknowns increased from 21924 to 49811. Along with enhancements of the numerical integration and current expansion the running time at one frequency for the 24-patches array is raised from ~600 sec. to ~7200 sec. Simulations were performed on the PC with the processor Intel(R) Core(TM) i5-3470 CPU @ 3.20 GHz and 16 GB of RAM.

We carried out a thorough convergence study by testing various combinations of the reference frequency value

(increased for 25%, 50% and 75%) and order of the numerical integration as well as of the current expansion, and came to the conclusion that, except for the less time needed for the program execution, none of them did perfectly converge to the solution obtained with previously mentioned accuracy input parameters (*enhanced 1* and *enhanced 2* for the numerical integration and the current expansion, respectively).

However, to save the CPU time the optimizations were accomplished with the 4-element array, as the analysis presented in section II showed that the axial ratio stabilizes after adding the third element in the array, and practically doesn't depend on the number of further added radiating elements. New dimensions of the patch obtained in these optimizations are implemented into 24-element array and satisfactory results are achieved. The difference between dimensions of the improved antenna model and the basic one is quite slight – it ranges from -1% (length of the patch and the length of the square-shaped cut) to +8% (width of the patch input microstrip line), but obviously has a significant effect on the characteristics of such a narrowband antenna. Consequently, the manufacturing of the proposed antenna has to be accomplished carefully.

Minimum of the simulated axial ratio is at $f_c=24.15\text{ GHz}$ while its bandwidth is within (24.06-24.26) GHz, as shown in Fig. 6.

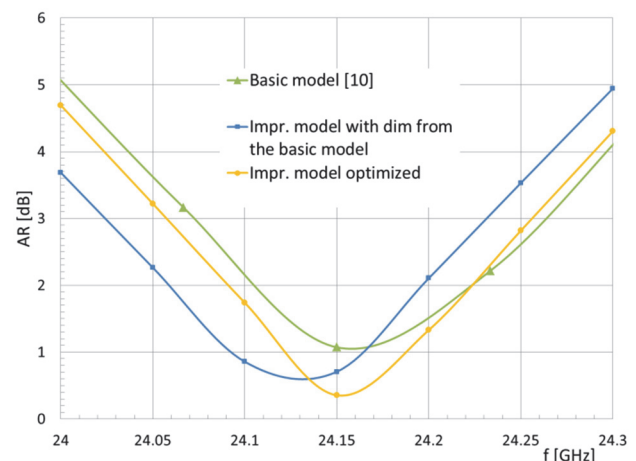


Fig. 6. Axial ratios of the basic and the improved model of the proposed antenna array at $\theta=90^\circ$, as a function of frequency.

In order to introduce the contribution of the metallic surfaces roughness to all losses, we entered the diminished value of copper conductivity – 20 MS/m instead of usually used 48 MS/m.

The diagrams in Figs. 7-9 display the H-plane (yOz) co- and cross-polarization radiation patterns (with indicated maximum power levels) of both basic and improved antenna array model (with dimensions from the basic model and after the optimization) at the center and edge frequencies of the range in which the axial ratio is less than 3 dB. According to the maximum levels of the co-polarization gains, the improved model of the antenna exhibits about 0.6-0.8 dB lower gain in the range of interest, comparing to the basic model with only losses in the dielectric substrate included. If the copper surface

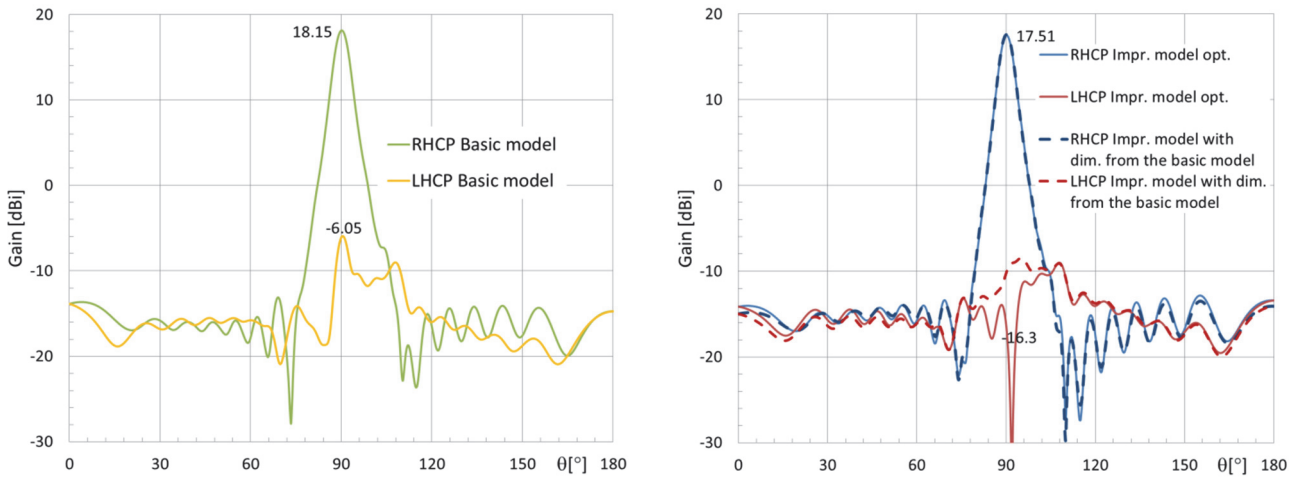


Fig. 7. H-plane radiation patterns: RHCP (co-pol) and LHCP (cross-pol) of the basic and the improved model of the proposed antenna array at $f_c=24.15$ GHz.

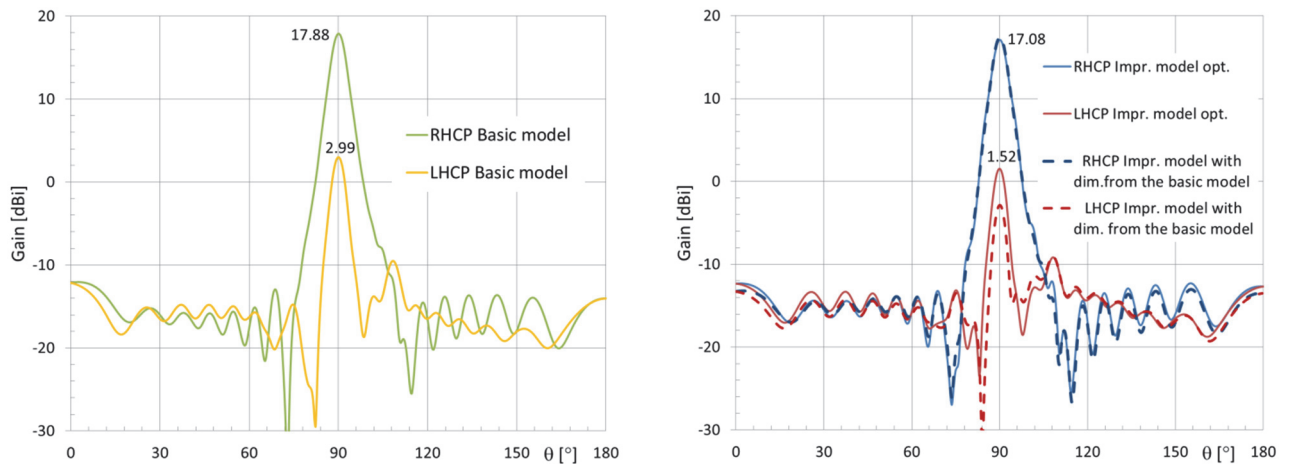


Fig. 8. H-plane radiation patterns: RHCP (co-pol) and LHCP (cross-pol) of the basic and the improved model of the proposed antenna array at the lower edge frequencies of the operating range.

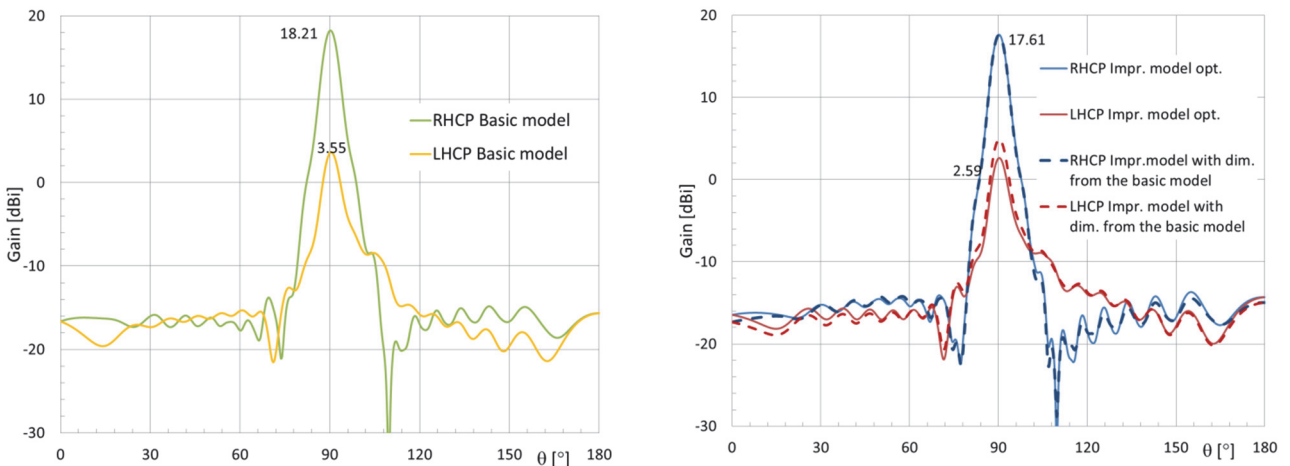


Fig. 9. H-plane radiation patterns: RHCP (co-pol) and LHCP (cross-pol) of the basic and the improved model of the proposed antenna array at the upper edge frequencies of the operating range

roughness was neglected this discrepancy would be on the average 0.3 dB, as shown in Fig. 10. The simulated gain of the proposed CP antenna array is greater than 17.2 dBi in the entire observed ISM range while the axial ratio is less than 3 dB from 24.06 GHz to 24.26 GHz, displayed in Fig. 10 and Fig. 6, respectively. The side lobe suppression is better than 30 dB in the same

frequency range. The half power beamwidth (HPBW) in H-plane ($y0z$) is around 4.5° , whereas in E-plane ($x0z$) is 104° . The 3D radiation pattern plotted at the center frequency (24.15 GHz) is shown in Fig. 11.

The overall dimensions of the antenna model are (235×30) mm.

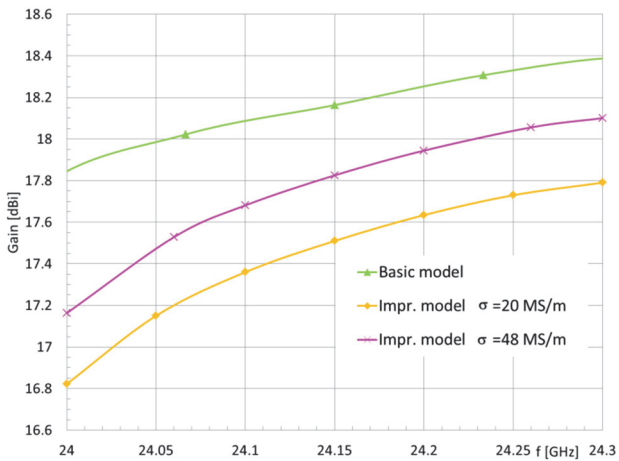


Fig. 10. Total gain of the basic and the improved model (for two values of copper conductivity) of the proposed antenna array, as a function of frequency.

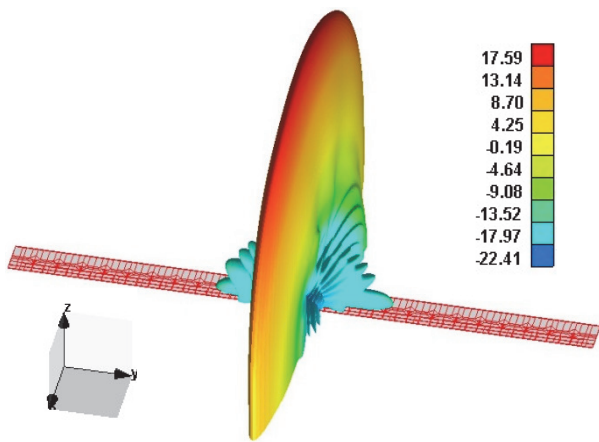


Fig. 11. 3D radiation pattern of the improved model of the proposed antenna array at $f_c=24.15$ GHz.

The reflection coefficient S_{11} is less than -15 dB in the entire ISM range. Certainly, better matching can be achieved by a variation of the main feed line length.

The efficiency of the improved antenna model, shown in Fig. 12 along with the total antenna gain, is better than 74% in the entire operating range, whereas the efficiency of the basic model (with only dielectric loss included) is around 93%.

In addition to the precedent analysis it should be noticed that in the presented case of the narrowband antenna, simulated on the dielectric substrate with $\epsilon_r=2.2$ and $h=0.254$ mm, even a small variation of the dielectric constant (which is within tolerances declared by the manufacturer) produces the frequency shift of the axial ratio characteristic, displayed in Fig. 13, which has to be taken into consideration as well.

V. CONCLUSION

A novel circularly polarized truncated patch antenna array consisting of 24 elements is presented. According to the simulated results the antenna is very convenient for radar systems, especially for automotive radar applications operating in the ISM band around 24 GHz. The paper presents precise modeling with enhanced

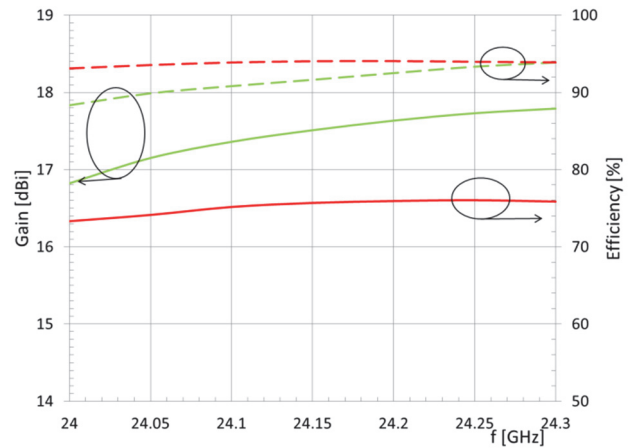


Fig. 12. Simulated antenna array efficiency (red line) and the total gain (green) of the improved (solid line) and the basic model (dashed) as a function of frequency.

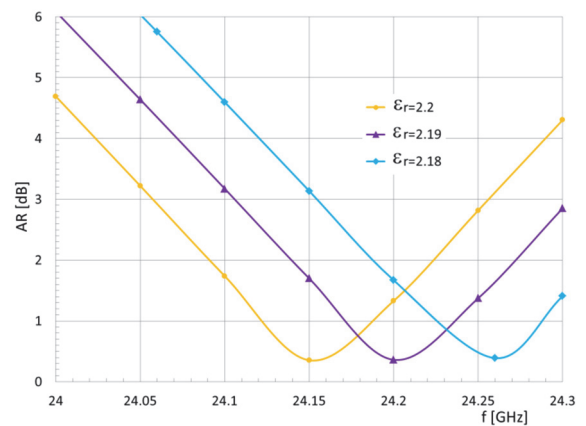


Fig. 13. Effect of the dielectric substrate constant variation on the axial ratio of the proposed antenna array.

simulation accuracy of the CP patch antenna array that is necessary to obtain realistic values of the antenna characteristics in the very narrow operating frequency range around 24 GHz. Design of the antenna array requires the exact value of the dielectric substrate permittivity as well as the enhancements of the numerical integration and current expansion to be taken into account in the simulations. By introducing these improvements into the previously simulated basic model the shift of 25-30 MHz toward lower frequencies (that is about 15% of the entire operating range) of the axial ratio was produced, therefore further optimizations were needed.

The novel truncated patch design with a square-shaped cut in only one corner does not complicate the manufacturing process comparing to commonly modified CP patches as it is performed by use of a standard photolithographic procedure that makes it simple and cost effective as well.

The presented array exhibits the side lobe suppression better than 30 dB thus making it suitable for radar applications, gain greater than 17.2 dBi, and axial ratio less than 3 dB in the range (24.06-24.26) GHz.

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