Original scientific paper

Stepped Printed Dipole Antenna Array Element

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***Abstract* — In this paper presents the design and radiation characteristics of a stepped printed dipole antenna array element. The array element is designed to operate in the 5G millimeter wavelength (mm-Wave) range (from 24.25 to 27.50 GHz). In the required frequency band, the value of the VSWR does not exceed 1.30. The value of the realized gain ranges from 4.53 to 5.59 dB. The overall dimensions (width × depth × height) are 6 mm × 6 mm × 2 mm. Based on it, a model of a 4 ×4 antenna array was developed. Its radiation characteristics were compared with the characteristics of the arrays of the differently shaped dipole antennas (a horizontal flat, a horizontal flat with matching inserts, a vertical flat, and a volumetric). It is shown that the stepped shape of the dipole makes it possible to obtain the best characteristics.**

***Keywords* — 5G communications, antennas, broadband antennas, dipole antennas, microwave antennas, millimeter waves.**

I. INTRODUCTION

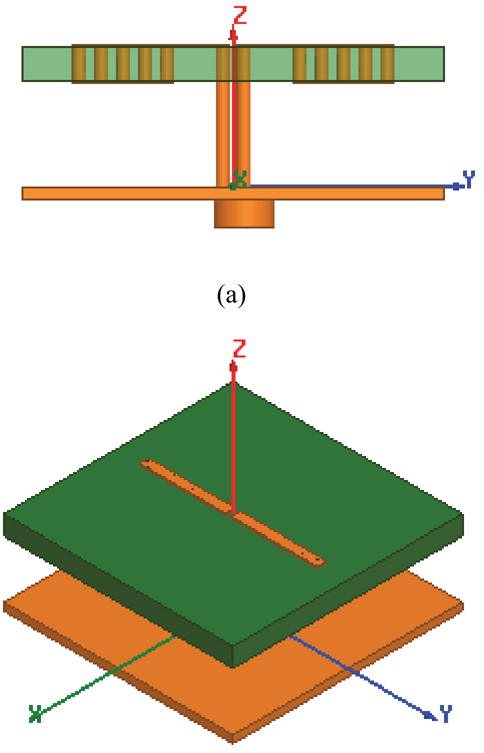
The printed dipole antenna is one of the most common types of antennas, which is used in the mm-Wave range. In the mm-Wave range, as a rule, such a design is used in which transverse radiation occurs as in the strip (patch) antennas. I.e., the maximum of the radiation pattern is directed along the normal to the plane with the antenna conductors [1] – [9]. On the one hand, this is a consequence of a trend towards a modular design. On the other hand, this is due to the great difficulties of mounting vertically oriented antennas with small geometric dimensions into a two-dimensional array. However, the printed dipole antennas, as well as the Vivaldi antennas with longitudinal radiation, are used in linear arrays [10] – [16].

The analysis of the publications shows that the printed dipole antennas, as a rule, consist of a dipole, matching elements, and a feed line. The feed line can be connected directly to the dipole [1], [6], [10], by a capacitive feed [8] or slot [2] – [5], [7]. The matching elements can be either flat on one layer or distributed between the layers, including those connected by a plated-through hole. The arms of the dipole have a different configuration, but as part of the printed dipole antennas, they are always flat.

In connection with the above, the aim of this work was to develop the antenna array element in a three-dimensional printed dipole with the stepped shape of its arms. It was assumed that the arms of the dipole should consist of conductors located on different sides of a dielectric substrate and interconnected by the plated-through hole.

II. ARRAY ELEMENT DESIGN AND ITS RADIATION CHARACTERISTICS

Fig. 1 shows the design of the developed array element. It is developed on a metallized dielectric substrate ($\varepsilon = 3$) with a thickness of 0.5 mm. The upper conductors of the dipole arms are connected to a 50-Ohm coaxial cable by the short two-wire line. The lower conductors are shorter than the upper conductors and are connected between by the plated-through hole. The overall dimensions (width × × depth × height (from the top face of the ground)) of the array element are 6 mm × 6 mm × 2 mm. The air layer can be changed on the plastic foam layer. The values of the other antenna parameters are given in Table 1.



(a)

(b)

Fig. 1. The design of the array element: (a) the front view, and (b) the side view.

Modeling of the array element was performed by electromagnetic software HFSS with the finite element method. The study of the characteristics of the array element was carried out as part of an infinite antenna array. The coaxial cable was excited by wave port. The obtained frequency characteristics are shown in Figs. 2–4.

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Table 1: Sizes of Antenna.

Parameters	***Value, mm***
Width of the conductors	0.25
Length of the short conductors	1.45
Length of the long conductors	2.25
Diameter of the plated-through hole	0.2
Diameter of the two-wire line conductors	0.2
Thickness of the substrate	0.5

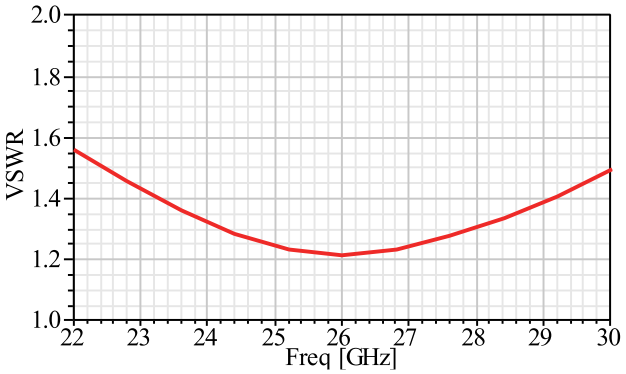


Fig. 2. The VSWR.

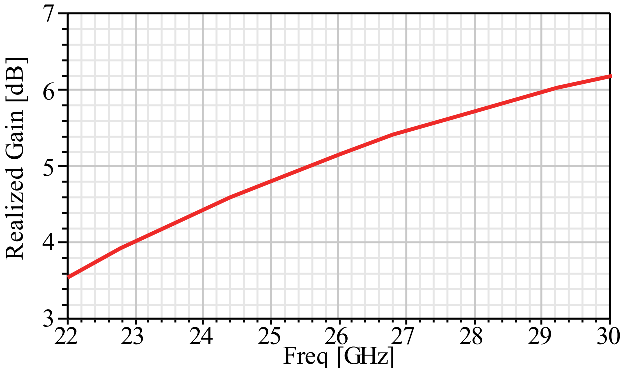


Fig. 3. The realized gain.

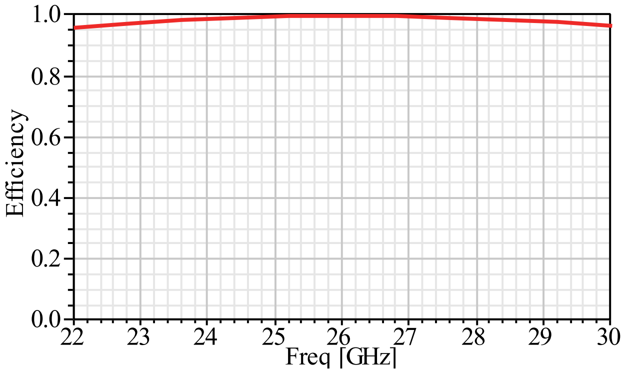


Fig. 4. The efficiency.

The analysis of the figures shows that in the required operating frequency band, the value of the VSWR is less than 1.30. At the same time, the realized gain is in the range from 4.53 to 5.59 dB, and the efficiency exceeds 98 %.

III. Comparison with Other Developed Array Element Variants

Compare the frequency characteristics of the VSWR of the developed stepped printed dipole array element with the VSWR of the dipole array elements, which are shown in Fig. 5. In all cases, a metalized dielectric substrate with ε = 3.

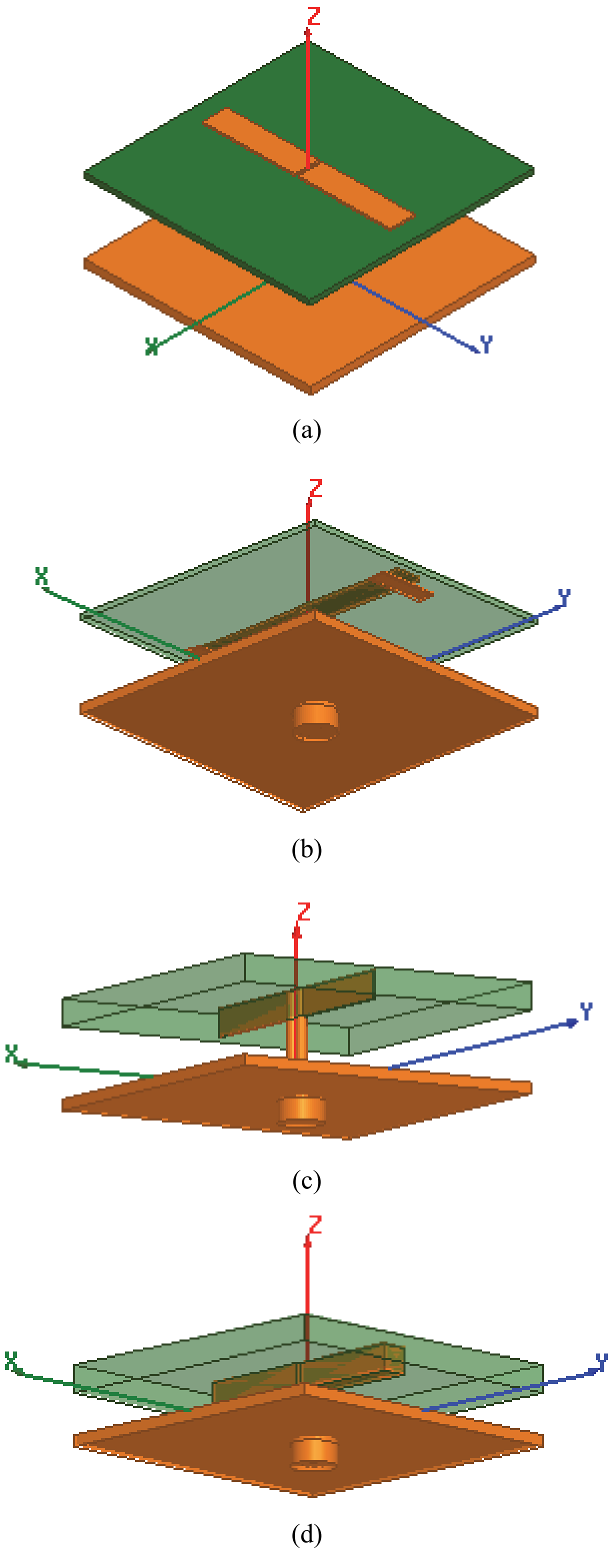


Fig. 5. The variants of the design of the dipole array element: (a) the horizontal flat [17]; (b) the horizontal flat with matching inserts [17]; (c) the vertical flat; and (d) the volumetric (without the step).

The dipoles of the horizontal flat shape are made on the thin dielectric substrate with the thickness of 0.13 mm. The option with the vertical flat dipoles is considered only for comparison since the possibility of its implementation in practice is extremely unlikely. Its height is equal to 1.8 mm. The height of the antenna array element with the vertical flat dipoles is equal to 1.1 mm. The height of the otherwise dipole is equal to 2.0 mm. The overall dimensions of the dipole arms are given in Table 2.

TABLE 2: OVERALL DIMENSIONS OF DIPOLE ARM.

Type of the dipole arms	*Value, mm*
Horizontal flat	0.65 mm × 2.45 mm
Horizontal flat with matching inserts	0.65 mm × 2.45 mm 0.8 mm × 2.5 mm
Vertical flat	0.5 mm × 2.5 mm
Volumetric	0.5 mm × 0.5 mm × 2.2 mm

Fig. 6 shows the comparison of the frequency characteristics of the dipole array element with the arms of the next shape: stepped; horizontal flat; horizontal flat with the matching inserts; vertical flat; volumetric.

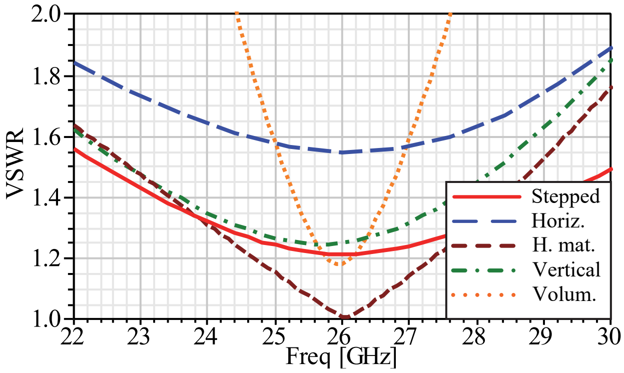


Fig. 6. Comparison of the VSWR.

Fig. 6 shows that the best matching in the required frequency range is observed in the case of the horizontal flat dipole with the matching inserts. A slightly lower value of the minimum value of the VSWR is observed for the volumetric dipole, but it has a maximum value of the VSWR at the edges of the required frequency range. At the frequency of 24.25 GHz, it exceeds 2.00, and at 27.50 GHz, it equals 1.92.

For the vertical flat dipole, the minimum value of the VSWR is slightly higher than in the stepped dipole case. Its maximum value of the VSWR is also greater (equal to 1.38) than that of the stepped dipole (equal to 1.30). The difference is small. However, the stepped dipole has a smoother characteristic. Due to this, in the frequency band of interest, it has the smaller maximum VSWR value (equal to 1.56, and for the vertical flat, it is equal to 1.85). The smoothness of the characteristic can help get a better match with the feed line for a finite antenna array.

The behavior of the graphs for the horizontal flat dipole and the horizontal flat dipole with the matching inserts is similar, but in the second case, the value of the VSWR is less by a value of 0.30 – 0.35.

Separately, it is worth comparing the frequency characteristics of the VSWR of the array elements with the volumetric dipoles and stepped dipoles. We can say that the second variant is a modification of the first variant. It can be seen that the matching of the first variant is much worse. That is, the transition to the stepped shape of the dipole significantly improves the matching with the feed line. In addition, in the studied frequency range from 22 to 30 GHz, the dipole of this shape gives the best matching among all the studied shapes.

IV. COMPARISON OF FINITE ANTENNA ARRAYS CHARACTERISTICS

In order to verify the conclusions made, we will conduct a study of the characteristics of the compared printed dipole antennas as part of the finite antenna array with 4 × 4 elements.

Figs. 7 – 11 shows the comparison of the frequency characteristics of the VSWR of the infinite antenna array element (——) with the VSWR of the central (— —), corner (– – –), and side in the 1st and 4th rows (-·-·) and side in the 2nd and 3rd rows (······) of the finite array element with the various shapes of the dipole.

For clarity, Fig. 12 shows the numbering of the finite array elements. The color correspondence of the curves for the VSWR of the various elements in Figs. 7–11 and the places of these elements in the finite antenna array are also given.

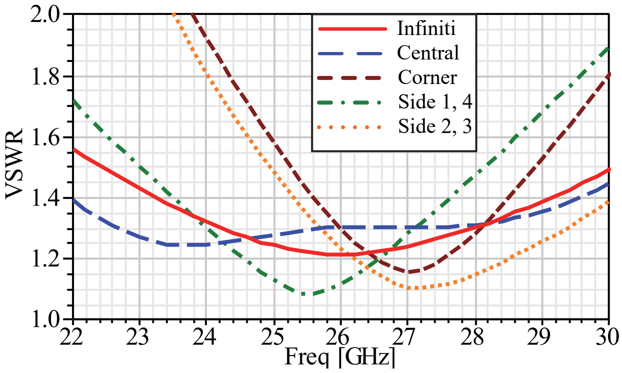


Fig. 7. The comparison of the VSWR (the stepped).

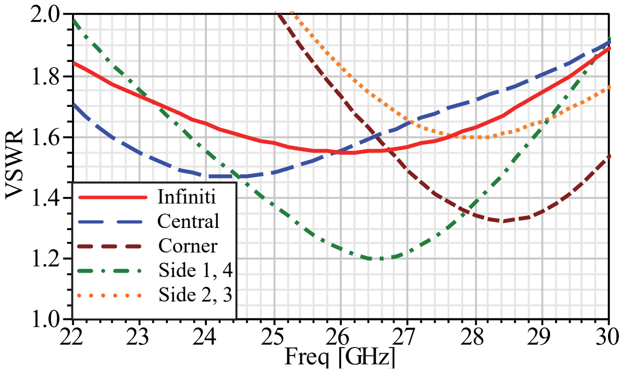


Fig. 8. The comparison of the VSWR (the horizontal flat).

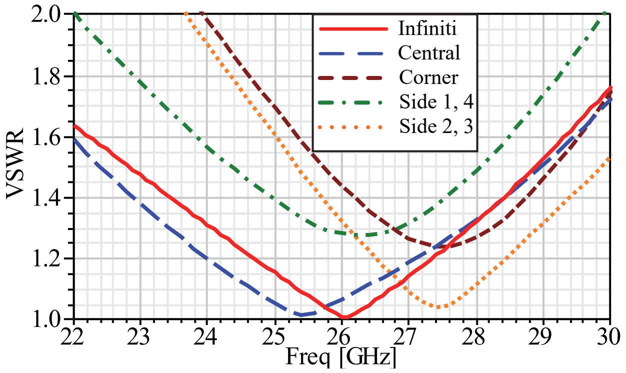


Fig. 9. The comparison of the VSWR (the horizontal flat with the matching insert).

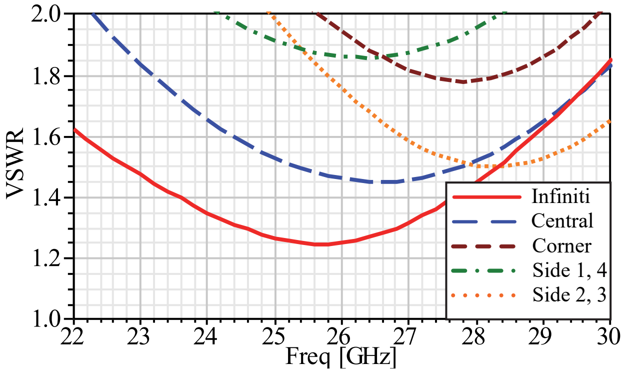


Fig. 10. The comparison of the VSWR (the vertical flat).

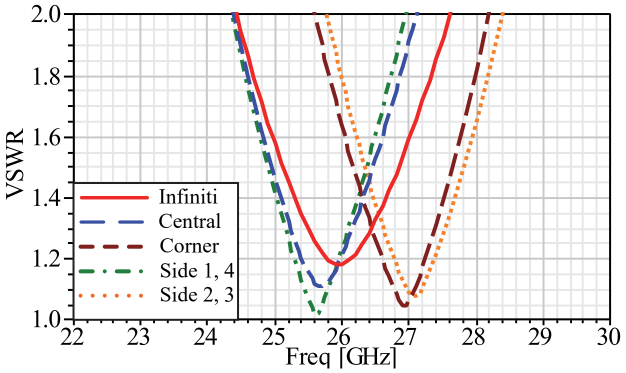
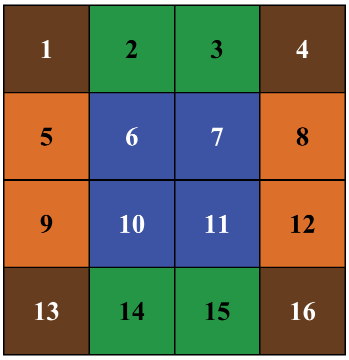


Fig. 11. The comparison of the VSWR (the volumetric).



1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Fig. 12. The numbering of the finite array elements.

The analysis of the figures shows that in all cases, the frequency characteristics of the VSWR of the corner and side elements in the 2nd and 3rd rows of the finite antenna array are shifted to the region of the higher frequencies. In the required frequency range, they have the maximum value of the VSWR. If we do not consider the VSWR of these elements, then the best matching is observed with the stepped shape of dipole s (since, in this case, the value of the VSWR of the remaining elements does not exceed 1.38). For the horizontal flat dipole with the matching insert, its value does not exceed 1.52. In other cases (except for the case with the volumetric dipoles), it does not exceed 1.99.

Figs. 13 – 14 show the comparison of the frequency characteristics of the transmission coefficients S(1,2) and S(1,5) between adjacent antennas. The correspondence of the types of curves and the shape of the dipole elements of the antenna array are as follows: stepped; horizontal flat; horizontal flat with the matching inserts; vertical flat; volumetric.

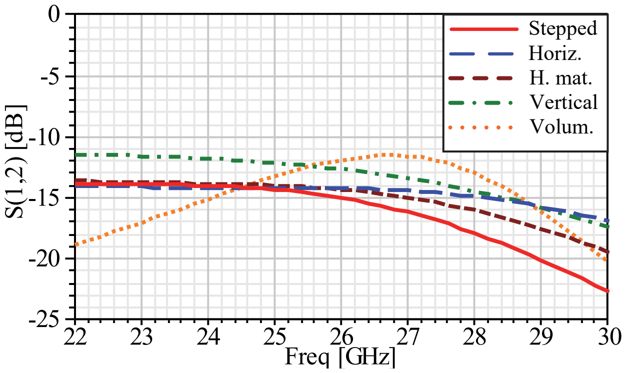


Fig. 13. The comparison of the S(1,2).

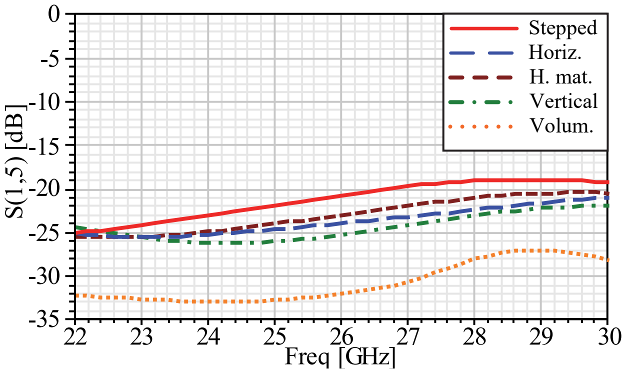


Fig. 14. The comparison of the S(1,5).

In accordance with Fig. 12, the S(1,2) denotes the transmission coefficient between adjacent antennas in the E-plane (according to the figure, these are adjacent elements of the rows). The S(1,5) denotes the transmission coefficient between adjacent antennas in the H-plane (according to the figure, these are adjacent column elements). The values of S(1,2), S(2,3), S(3,4), S(5,6), etc. are approximately the same. Similarly, the values of S(1,5), S(2,6), S(3,7), etc. are approximately the same. Therefore, only S(1,2) and S(1,5) are shown on the graphs for convenience.

The analysis of the graphs in Fig. 13 shows that the lowest value of the transmission coefficient S(1,2) is observed with the stepped dipole (it is less than -14.1 dB in the required frequency range). The situation is a little worse in the case of the array of horizontal flat dipoles with the matching inserts.

Fig. 14 shows that the minimum value of the transmission coefficient S(1,5) is observed for the volumetric dipoles (less than -29.3 dB). The maximum value is for the stepped shape of the dipole (less than -19.4 dB).

Since the S(1,5) is less than the S(1,2), it is more correct to make the comparison based on the values of the S(1,2). According to this criterion, the stepped shape of the dipoles is preferable. Thus, it is preferable both in terms of the VSWR value and in terms of the transmission coefficient.

Figs. 15 – 16 show the comparison of the frequency characteristics of the realized gain and efficiency of the finite antenna arrays. The correspondence of the curve types and the shape of the dipole elements is the same as for the S(1,2) and S(1,5).

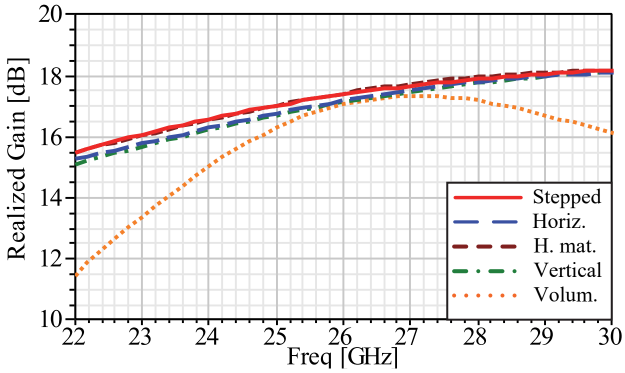


Fig. 15. The comparison of the realized gain.

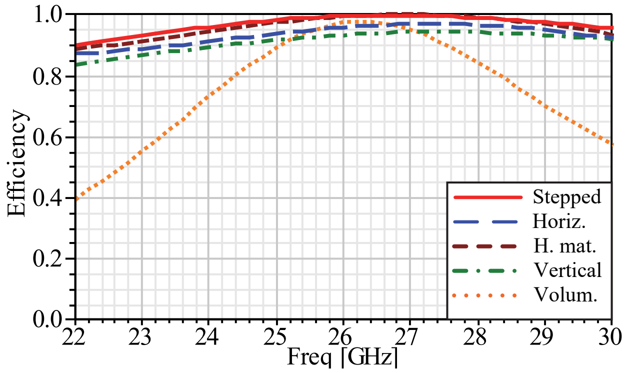


Fig. 16. The comparison of the efficiency.

From the last two figures, it can be seen that the arrays of dipole antennas of stepped and horizontal flat shapes have the highest values of realized gain (approximately from 16.6 to 17.8 dB) and efficiency (at least 94%). These characteristics are directly related to the VSWR values, which are the smallest for these antennas.

Figs. 17 – 18 show the normalized radiation patterns of the antenna arrays. The correspondence of the types of curves and the shape of the dipole elements of the antenna array is as follows: stepped (——); horizontal flat (— —); horizontal flat with the matching inserts (- - -); vertical flat (-·-); and volumetric (······).

The analysis of the figure shows the next. The normalized radiation pattern coincides with the graphical accuracy within the main lobe. The only difference is observed in the side lobe levels. Of them are given in Table 3.

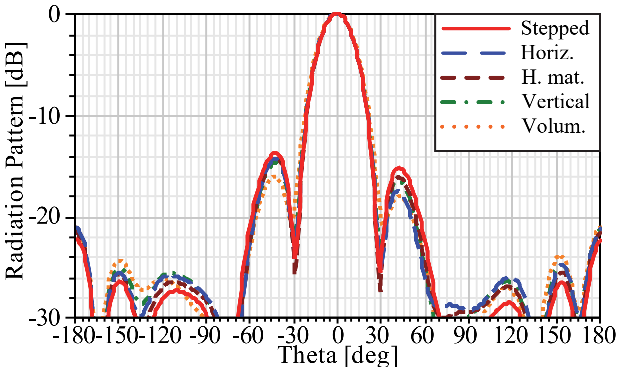


Fig. 17. The normalized radiation patterns in the E-plane.

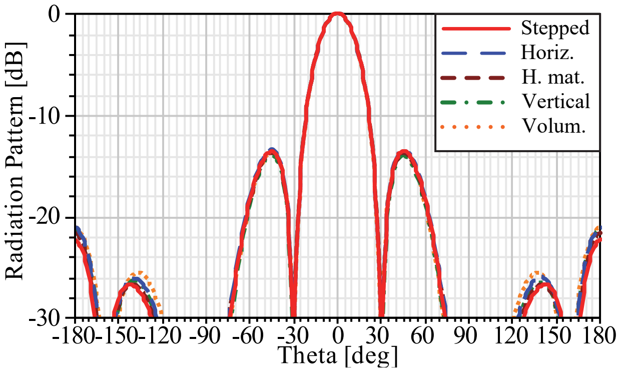


Fig. 18. The normalized radiation patterns in the H-plane.

TABLE 3: SIDE LOBE LEVELS.

Type of the dipole arms	***Value in E-/H-plane, dB***
Stepped	-13.72/-13.56
Horizontal flat	-14.33/-13.42
Horizontal flat with matching insert	-14.22/-13.70
Vertical flat	-14.65/-13.93
Volumetric	-16.05/-13.68

V. CONCLUSION

The results of the study show that the stepped printed dipole element of the antenna array can be used in the development of antennas and antenna arrays for the 5G mm-Wave range with frequencies from 24.25 to 27.50 GHz. It can be assumed that it can find application in the development of ultra-wideband antenna arrays.

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REFERENCES

[1] H. Chu, Y.-X. Guo, and Z. Wang, "60-GHz LTCC Wideband Vertical Off-Center Dipole Antenna and Arrays," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 1, pp. 153–161, Jan. 2013, doi: 10.1109/TAP.2012.2220094.

[2] Z.-C. Hao and B.-W. Li, "Developing Wideband Planar Millimeter-Wave Array Antenna Using Compact Magneto-Electric Dipoles," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2102–2105, 2017, doi: 10.1109/LAWP.2017.2697903.

[3] Z.-C. Hao, Q. Yuan, B.-W. Li, and G. Q. Luo, "Wideband W-Band Substrate-Integrated Waveguide Magnetoelectric (ME) Dipole Array Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 6, pp. 3195–3200, Jun. 2018, doi: 10.1109/TAP.2018.2820503.

[4] J. Cao, H. Wang, S. Mou, P. Soothar, and J. Zhou, "An Air Cavity-Fed Circularly Polarized Magneto-Electric Dipole Antenna Array With Gap Waveguide Technology for mm-Wave Applications," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 9, pp. 6211–6216, Sep. 2019, doi: 10.1109/TAP.2019.2925186.

[5] L. Zhang et al., "Wideband High-Efficiency Circularly Polarized SIW-Fed S-Dipole Array for Millimeter-Wave Applications," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 3, pp. 2422–2427, Mar. 2020, doi: 10.1109/TAP.2019.2940468.

[6] H.-N. Hu, F.-P. Lai, and Y.-S. Chen, "Dual-Band Dual-Polarized Scalable Antenna Subarray for Compact Millimeter-Wave 5G Base Stations," *IEEE Access*, vol. 8, pp. 129180–129192, 2020, doi: 10.1109/ACCESS.2020.3009431.

[7] J. Xu, W. Hong, Z. H. Jiang, and H. Zhang, "Millimeter-Wave Broadband Substrate Integrated Magneto-Electric Dipole Arrays With Corporate Low-Profile Microstrip Feeding Structures," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 10, pp. 7056–7067, Oct. 2020, doi: 10.1109/TAP.2020.3011168.

[8] X. Dai and K. M. Luk, "A Wideband Dual-Polarized Antenna for Millimeter-Wave Applications," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 4, pp. 2380–2385, Apr. 2021, doi: 10.1109/TAP.2020.3043886.

[9] V. A. Carey et al., "Millimeter Wave Photonic Tightly Coupled Array," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 8, pp. 4488–4503, Aug. 2021, doi: 10.1109/TAP.2021.3052340.

[10] A. Nesic, Z. Micic, S. Jovanovic, and I. Radnovic, "Millimeter wave printed antenna array with high side lobe suppression," in *Proc. 2006 IEEE Antennas and Propagation Society International Symposium*, Albuquerque, NM, USA, Jul. 09–14, 2006, pp. 3051–3054, doi: 10.1109/APS.2006.1711252.

[11] A. Nesic, Z. Micic, S. Jovanovic, I. Radnovic, and D. Nesic, "Millimeter-wave printed antenna arrays for covering various sector widths," *IEEE Antennas and Propagation Magazine*, vol. 49, no. 1, pp. 113–118, Feb. 2007, doi: 10.1109/MAP.2007.370991.

[12] R. A. Alhalabi and G. M. Rebeiz, "High-Efficiency Angled-Dipole Antennas for Millimeter-Wave Phased Array Applications," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 10, pp. 3136–3142, Oct. 2008, doi: 10.1109/TAP.2008.929506.

[13] J.-Y. Shim, J.-G. Go, and J.-Y. Chung, "A 1-D Tightly Coupled Dipole Array for Broadband mmWave Communication," *IEEE Access*, vol. 7, pp. 8258–8265, 2019, doi: 10.1109/ACCESS.2018.2889333.

[14] J. Zeng and K. -M. Luk, "Wideband Millimeter-Wave End-Fire Magnetoelectric Dipole Antenna With Microstrip-Line Feed," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 4, pp. 2658–2665, Apr. 2020, doi: 10.1109/TAP.2019.2957089.

[15] I.-J. Hwang, J.-I. Oh, H.-W. Jo, K.-S. Kim, J.-W. Yu, and D.-J. Lee, "28 GHz and 38 GHz Dual-Band Vertically Stacked Dipole Antennas on Flexible Liquid Crystal Polymer Substrates for Millimeter-Wave 5G Cellular Handsets," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 5, pp. 3223–3236, May 2022, doi: 10.1109/TAP.2021.3137234.

[16] K. Fan, X. Fan, Q. Tan, F. Zhu, Y. Yu, and G. Q. Luo, "SICL-Fed Balanced Antipodal Dipole Antenna With Wideband Operation and Cross-Polarization Improvement at Millimeter-Wave Band," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 3, pp. 447–451, Mar. 2023, doi: 10.1109/LAWP.2022.3201350.

[17] A. V. Gevorkyan, "Printed Dipole Antenna Array Element for 5G mm-Wave Applications," in *Proc. 2023 Radiation and Scattering of Electromagnetic Waves (RSEMW)*, Divnomorskoe, Russia, Jun. 26–30, 2023, pp. 412–415, doi: 10.1109/RSEMW58451.2023.10201939.