Study of a Mushroom-like EBG Structure Integration in Phased Antenna Array with Improving Radiation Characteristics Purposes

Ivaylo Nachev, Ilia Iliev

Abstract – **The paper provides methodology to determine requirements in the frequency domain in designing a mushroom EBG structure to improve antenna array radiation characteristics. With integrating the structure in front of the antenna radiating surface, a gain increase and a change in beamwidth is observed. The proposed methodology has been tested. Studies with different dielectric substrates in the mushroom–like EBG structure design are provided to prove the proposed concept. Improved radiation parameters of a scanning antenna system (for 2.4 GHz ISM frequency band) consisting of an EBG structure and an antenna array are shown.**

Keywords - **Electromagnetic band gap, EBG structure, Periodic structures, Metamaterials, Antenna array, Improving radiation pattern, Scanning antenna.**

I. Introduction

Integrating periodic structures into antennas design has been a challenge for many researchers around the world over recent years, sharing their results through scientific publications. Periodic structures found in the literature and as metamaterials are divided into defected ground planes (DGP) [1], photonic band gap (PBG) [2], and the most common of them - Electromagnetic band gap (EBG) [3] structures. EBG structures have a many application like: reducing coupling factor between antenna array elements [4], implementation of electronic scanning in a patch antenna [5], fractal antennas optimization [6], improving antenna directivity [7] and etc. Previous research [8,9] has shown the possibility of increasing antenna gain and narrowing the beamwidth by metamaterials integrating. An antenna system model of a patch antenna and a Z-shape EBG structure was made, and satisfactory results were measured [9]. The Z-shaped structure has a topological asymmetry in the x and y planes (relative to the Cartesian coordinate system). Thus integration of a Z-shaped EBG is inappropriate into a phased antenna array - PAA where is necessary for beam deviation on azimuth and elevation plane to be equidistant from the central beam. For example, scanning in azimuth/elevation for two adjacent states of a PAA without a structure with deviations will be –20;20 versus a PAA with an integrated Z-shaped structure with deviations of –23; 17. This makes the improved antenna system unsuitable for radio navigation applications. The symmetrical design of the mushroom-like EBG structure guarantee symmetry between adjacent antenna states in scanning mode.

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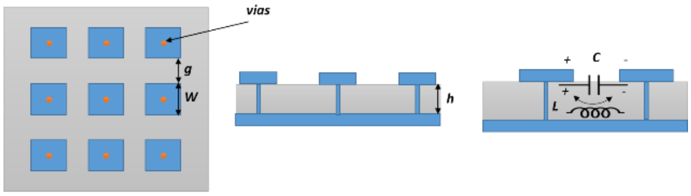
Ivaylo Nachev, PhD student at the Faculty of Telecommunications at the Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: ivaylonachev@yahoo.com

Ilia Iliev, Professor at the Faculty of Telecommunications at the Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: igiliev@tu-sofia.com

This paper presents a design methodology allowing the mushroom-like EBG structure to satisfy specified frequency requirements. Structure satisfying considered frequency parameters is suitable for integrating into an antenna to improve its gain and narrowing of radiation patterns. This periodic structure symmetry makes it suitable for PAA integration and provides symmetry between adjacent antenna beam offset states. Presented results of the antenna system parameters relate to the mushroom-like EBG structure integration in PAA including several designed EBG structures on different dielectric substrates according to the proposed methodology to prove the described concept.

II. The Mushroom-like EBG Structure

Initially, a mushroom-like EBG structure (2D EBG) – Figs. 1(a) and 1(b), was introduced in [10]. Originally, this band gap structure is consisted of a 1) ground plane, 2) dielectric substrate, 3) metallic patches, and 4) connecting vias, and the structure featured passbands and stopbands in frequency bands. The EBG structure operation mechanism can be explained by *LC* filter array as shown in Fig. 1(c). The current flowing through vias causes the inductor *L* effect, whereas the gap between the neighbouring patches results in the capacitor *C* effect. As shown in Fig. 1(c). *W* is the patch width, the gap width is *g*, the substrate thickness is *h*, and the ε_r is the dielectric constant [10].



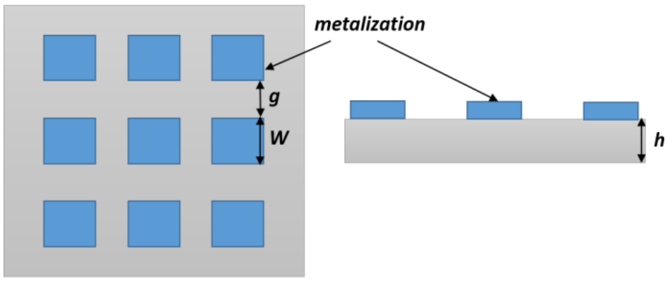
(a) (b) (c)

Fig. 1. Classic mushroom-like EBG dimensions, (a) top view, (b) side view, and (c) lumped *LC* typical analysis.

Classic mushroom-like EBG structure has multiple passes and stops bands in the frequency domain. For the centre frequency for which it is designed this structure has only stop or pass band. The only stop or pass band for central frequency parameters do not satisfy the periodic structure requirements for improving antenna radiation parameters. To increase antenna gain by placing a periodic structure in front of the radiating antenna surface, the structure characteristics of pass band and stop band have to be equal to –3 dB for the centre frequency [8, 9]. For this reason, the classic mushroom-like EBG construction is modified to cover the frequency requirements. For this purpose, the ground plane and vias are removed from the EBG topology. The structure remains only with a square patch and a dielectric substrate – Fig. 2, so the modified structure can efficiently be designed to fulfill the specified requirements: following the dependencies, which are modified by [5, 6] adding the weighting coefficients k and k_0:

$$W = \frac{\lambda}{k}, \qquad \text{where } k \in [3.5 \div 4.5], \qquad (1)$$

$$g = \frac{\lambda}{k_0}, \qquad \text{where } k_0 \in [6 \div 11]. \qquad (2)$$



(a) (b)

Fig. 2. Modify Mushroom-like EBG dimensions: (a) top view and (b) side view.

The dielectric constant of a used substrate should be $1<\varepsilon_r<6$; otherwise, the given dependencies for k and k_0 have to be revised.

Several mushroom-like EBG structures are designed by using the proposed methodology (use of equations (1) and (2)), to achieve the frequency requirements for increasing the antenna gain and narrowing the antenna beam width. The materials used for the structures models are as follows: Structure_1 - FR4, Structure_2 - Rogers RO4003, Structure_3 - Rogers RT/duroid 5870 and Structure_4 - RogersTMM6. All of them correspond to the discussed frequency requirements [8, 9] for improving antenna radiation pattern - RP. The parameters of designed EBG's are presented in Table I, and Figs. 3-6 show the structure's frequency response (obtained by dispersion analysis [11]). The operating frequency of designed structures is chosen as f_0=2400 MHz (part of free ISM frequency bands), and the height of all structures is h=1.5mm.

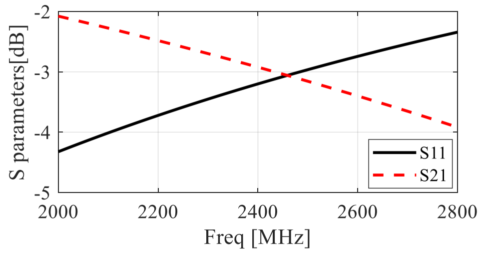


Fig. 3. **Strcuture_1** frequency response.

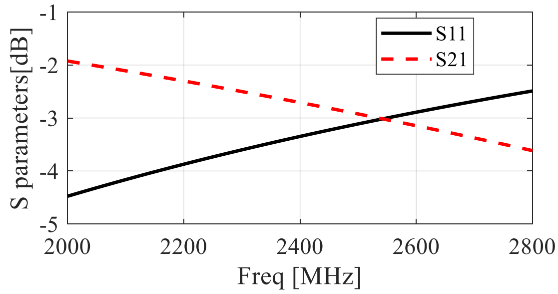


Fig. 4. **Strcuture_2** frequency response.

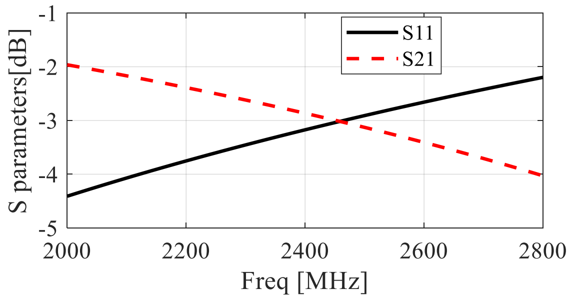


Fig. 5. **Strcuture_3** frequency response.

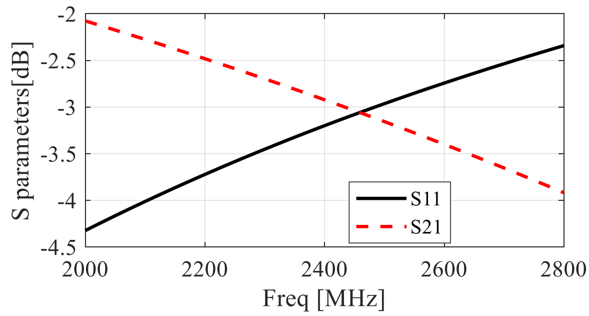


Fig. 6. **Strcuture_5** frequency response.

TABLE I
THE DESIGN MODIFIED MUSHROOM-LIKE EBG STRUCTURES DIMENSIONS

Mushroom-like EBG structure	ε_r	***W*** [mm]	***g*** [mm]	***Number of patches***
Structure_1	4.4	31.25	15.62	16
Structure_2	3.55	31.25	13.88	20
Structure_3	2.33	31.25	11.36	20
Structure_4	6	31.25	20.83	20

III. Integration of Mushroom-Like EBG Structures In PAA and Obtained Results

Mushroom-like EBG structures designed in the previous section are implemented in a phased antenna array with fo=2.4 GHz, $S11\approx-16$ dB (in different antenna states), 2x2 type antenna architecture, and a left-handed circular polarization with five antenna beam (radiation pattern) states, one central and two states for deviation - azimuth (state 3 and 5) and elevation (state 2 and 4) planes. Fig. 7 shows the EBG structure relation to PAA. The antenna was designed using Matlab [12÷14]. The distance between the elements of the antenna grid is 0.5λ [15,16]. Fig. 8 shows a parametric optimization to determine optimal distances between the designed EBGs and PAA in order to attain the highest antenna gain achievable for a certain structure. The results from Fig. 8 show that the best results are observed at a distance of 75 mm. Since all designed periodic structures have the same frequency parameters, the optimal distance between the EBG and antenna is the same for all of them. Figs. 9 to 14 present radiation patterns for all antennas beam states without and with integrated designed EBG structures. Figs. 9 and 10 show the central state of E plane (phi = 0º) and H plane (phi = 90º).

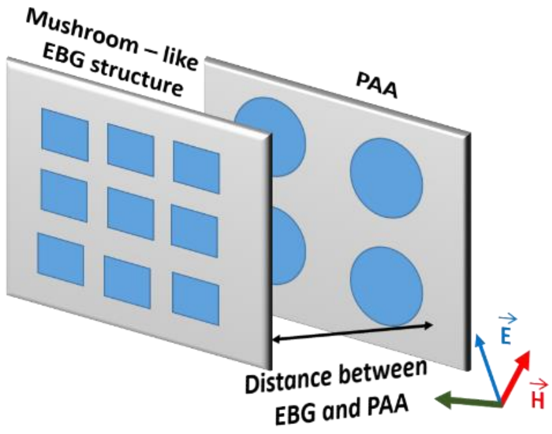


Fig. 7. EBG structure location relative to the antenna radiating surface.

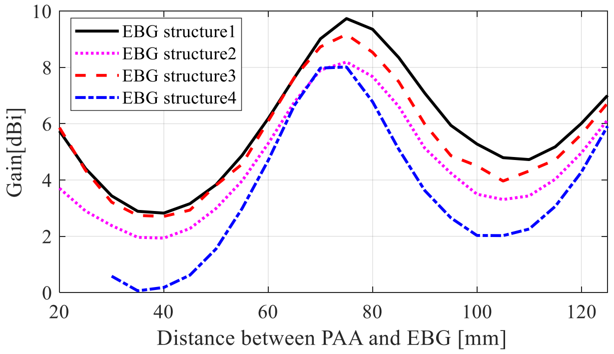


Fig. 8. Antenna gain vs. distance between PAA and EBG.

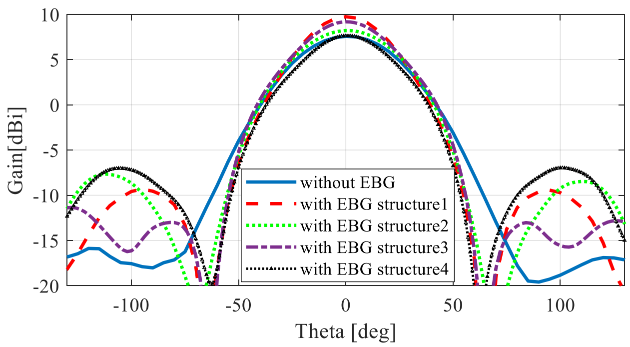


Fig. 9. RP state 1 – phi=0 degree.

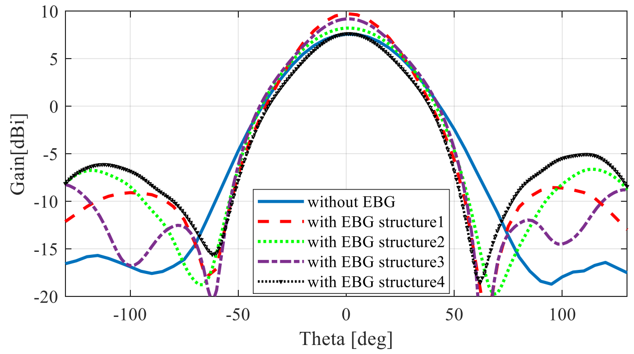


Fig. 10. RP state 1 – phi=90 degree.

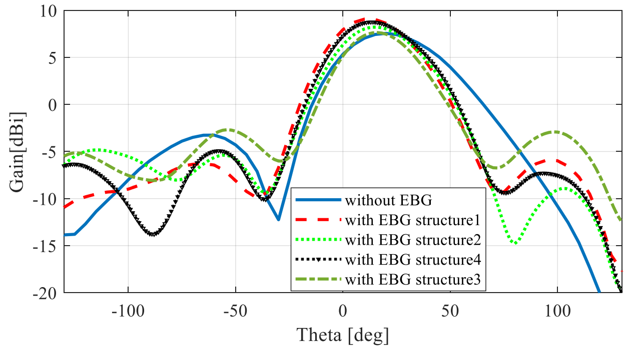


Fig. 11. RP state 2.

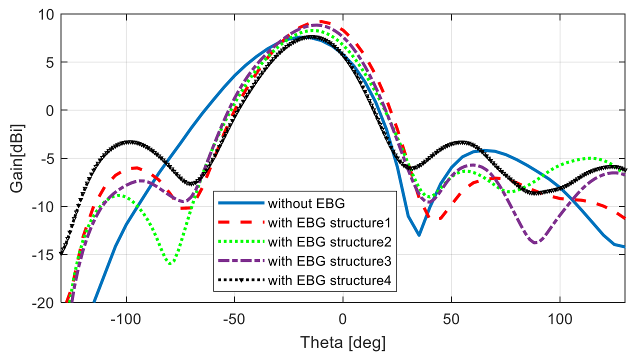


Fig. 12. RP state 4.

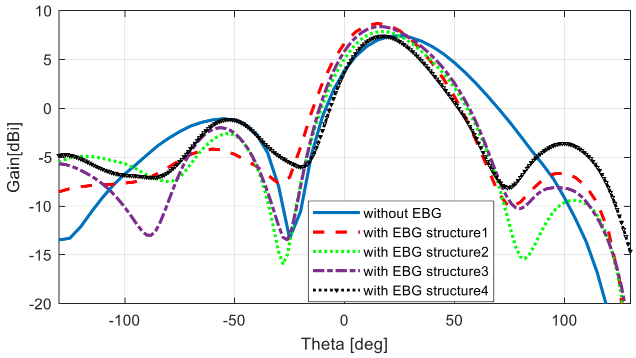


Fig. 13. RP state 3.

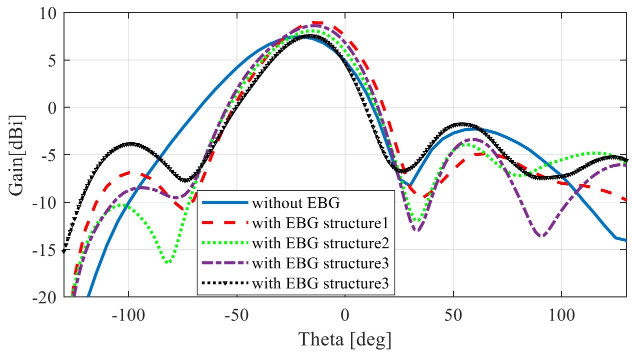


Fig. 14. RP state 5.

Fig. 8 shows that the PAA gain with different EBGs is not the same with different structure implemented (due to the different dielectric constant of the material on which the corresponding periodic structure is made). It is also seen that the best results are achieved at approximately the same distance between the EBG and the antenna – 1.6λ. Figs. 9 to 14 show the PAA RP for the different antenna states. It can be seen that for all structures, a contraction of the directional action beam is also observed in addition to the gain improvement. It is also observed that when integrating the structure into the antenna, the states in the scanning mode have a slight offset angle to the maximum of the central state and the beam deflection without an integrated structure in the PAA. The results of changing the PAA RP by integrating the EBG structure are presented in Table II.

The designed mushroom-like EBG structure, apart from improving the antenna radiation properties, it may reduce the antenna gain. For example, in communication antennas, gain of an adjacent receiving antenna can be lowered to suppress interference with the observed antenna RP avoiding the appearance of intermodulation disturbances.

TABLE II
COMPARISON OF THE PHASED ANTENNA ARRAY RPS BY INTEGRATING DIFFERENT EBGS STRUCTURES IN ITS CONSTRUCTIONS

Mush-room-like EBGs	***RP state***	***Gain without /with EBG*** [dBi]	***RP beamwidth without/with EBG*** [deg]	***RP deviation from central state without/with EBG*** [deg]
EBG structure 1	State 1	7.4/9.7	55.6º/40.24º	-
	State 2	7.4/9.1	54.1º/40.7º	19.7º/10.4º
	State 3	7.4/8.9	53.5º/40.4º	24.2º/15.1º
	State 4	7.4/9.1	53.9º/41.0º	-19.7º/-10.9º
	State 5	7.4/8.9	53.5º/40º	-23.9º/-15.2º
EBG structure 2	State 1	7.4/8.3	55.6º/48.7	-
	State 2	7.4/8.2	54.9º/41.5º	19.7º/14.2º
	State 3	7.4/8.3	53.5º/42.6º	24.2º/14.7º
	State 4	7.4/8.3	53.9º/41.8º	-19.7º/-13.9º
	State 5	7.4/8.2	53.5º/41.8º	-23.9º/-14.1º
EBG structure 3	State 1	7.4/9.2	55.6º/43.4º	-
	State 2	7.4/8.9	54.9º/41.4º	19.7º/13.2º
	State 3	7.4/7.9	53.5º/42.1º	24.2º/15.1º
	State 4	7.4/8.8	53.9º/41.5º	-19.7º/-12.6º
	State 5	7.4/7.9	53.5º/41.9º	-24.5º/-14.8º
EBG structure 4	State 1	7.4/7.8	55.6º/41.1º	-
	State 2	7.4/7.5	54.9º/36.8º	19.7º/17.9º
	State 3	7.4/7.6	53.5º/38.25º	24.2º/18.5º
	State 4	7.4/7.6	53.9º/37.1º	-19.7º/-16.8º
	State 5	7.4/7.6	53.5º/37.9º	24.5º/19.1º

IV. Conclusion

The paper presented the methodology for calculating mushroom-like EBG structures of the considered type to achieve precisely defined frequency parameters. An antenna system consists of a mushroom-like EBG structure implemented in a phased antenna array with four scanning beam states. A periodic structure of the considered type can be used in already existing antennas where an increase in gain and narrowing of pattern beam width is required, and the corresponding communication does not require a wide coverage area. Also, the structure can be used to reduce the gain of an antenna from an adjacent communication channel to avoid unwanted interference. It is important to note that the considered structure can be used not only to improve the radiation characteristic of an antenna array but also to change the angle of the antenna beam tilt from the central state to the scanning mode. The described process has been tested with several dielectric materials, and its effectiveness can be seen from the results presented.

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References

[1] B.P. Stošić, M. Nedelchev, N.S. Dončov and A. Kolev, "Wave Digital Model of Edge Coupled Filter Based on Halfwave Coupled Resonator with Dumbbell-Shaped DGS", *2019 14th International Conference on Advanced Technologies, Systems and Services in Telecommunications (TELSIKS)*, 2019, pp. 29-32, doi: 10.1109/TELSIKS46999.2019.9002355.

[2] Y. Qian, V. Radisic and T. Itoh, "Simulation and Experiment of Photonic Band-gap Structures for Microstrip Circuits", *1997 Asia-Pacific Microwave Conference*, pp. 585-588, vol. 2, doi: 10.1109/APMC.1997.654609.

[3] A. Aminian, F. Yang and Y. Rahmat-Samii, "In-phase Reflection and EM Wave Suppression Characteristics of Electromagnetic Band Gap Ground Planes", *IEEE Antennas and Propagation Society International Symposium*. Digest. Held in conjunction with: USNC/CNC/URSI North American Radio Sci. Meeting (Cat. No.03CH37450), 2003, pp. 430-433, vol. 4, doi: 10.1109/APS.2003.1220288.

[4] M. Salehi, A. Motevasselian, A. Tavakoli and T. Heidari, "Mutual Coupling Reduction of Microstrip Antennas using Defected Ground Structure", *2006 10th IEEE Singapore International Conference on Communication Systems*, 2006, pp. 1-5, doi: 10.1109/ICCS.2006.301375.

[5] B. A.F. Esmail, S. Koziel, L. Golunski, H. B.A. Majid and R.K. Barik, "Overview of Metamaterials-Integrated Antennas for Beam Manipulation Applications: The Two Decades of Progress", *IEEE Access*, vol. 10, pp. 67096-67116, 2022, doi: 10.1109/ACCESS.2022.3185260.

[6] A. Slavov and P. Petkov, "Fractal Antenna Over EBG Structure for UHF RFID Applications", *2017 13th International Conference on Advanced Technologies, Systems and Services in Telecommunications (TELSIKS)*, 2017, pp. 101-104, doi: 10.1109/TELSKS.2017.8246238.

[7] H. Errifi, A. Baghdad, A. Badri and A. Sahel, "Directivity Enhancement of Aperture Coupled Microstrip Patch Antenna Using Two Layers Dielectric Superstrate", *2014 Mediterranean Microwave Symposium (MMS2014)*, 2014, pp. 1-4, doi: 10.1109/MMS.2014.7088994.

[8] I. Nachev and I. Iliev, "Improving an Antenna Radiation Pattern Using Photonic Band Gap Structure", *2021 56th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, 2021, pp. 137-140, doi: 10.1109/ICEST52640.2021.9483462.

[9] I. Nachev and I.G. Iliev, "Study of Band Gap Structure for Improving Antenna Radiation Pattern", *2021 29th National Conference with International Participation (TELECOM)*, 2021, pp. 1-4, doi: 10.1109/TELECOM53156.2021.9659719.

[10] D. Sievenpiper, L. Zhang, R. F.J. Broas, N.G. Alexopolous, and E. Yablonovitch, "High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band", *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 11, pp. 2059-2074, November 1999, doi: 10.1109/22.798001.

[11] I. Nachev and I. Iliev, "Linearly Polarized Phased Antenna Array with an Application for the Automatic Landing of Unmanned Flying Vehicle", *2022 57th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, 2022, pp. 1-4, doi: 10.1109/ICEST55168.2022.9828473.

[12] V. Grout, M.O. Akinsolu, B. Liu, P.I. Lazaridis, K.K. Mistry and Z.D. Zaharis, "Software Solutions for Antenna Design Exploration: A Comparison of Packages, Tools, Techniques, and Algorithms for Various Design Challenges", *IEEE Antennas and Propagation Magazine*, vol. 61, no. 3, pp. 48-59, June 2019, doi: 10.1109/MAP.2019.2907887.

[13] A. Slimani, S. D. Bennani and A. El Alami, "Effect of Inter-elements Distance and Phase Shift Excitation on Radiation Performance of Linear, Planar and Circular Arrays Antennas □," *2017 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS)*, 2017, pp. 1-7, doi: 10.1109/WITS.2017.7934629.

[14] M.H. Yazd and R. Faraji-Dana, "Novel Smart Antenna Array for IEEE 802.11a Wireless LAN Applications", *2005 IEEE Antennas and Propagation Society International Symposium*, 2005, vol. 3A, pp. 295-298, doi: 10.1109/APS.2005.1552239.

[15] M. Skolnik, *Radiolocation Guide*, Moscow, Soviet radio, 1976.

[16] Y.-K. Jung and B. Lee, "Dual-Band Circularly Polarized Microstrip RFID Reader Antenna Using Metamaterial Branch-Line Coupler", *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 786-791, February 2012, doi: 10.1109/TAP.2011.2167943.