1. Saktioto SAKTIOTO*[1], 2. Faridah Hanum SIREGAR[1], 3. Yan SOERBAKTI[1], 4. Ari Sulistyo RINI[1], 5. Syamsudhuha SYAMSUDHUHA[2], 6. Sofia ANITA[3]

Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia (1)
Department of Mathematics, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia (2)
Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia (3)
ORCID: 1. 0000-0001-9200-8998; 2. 0009-0000-6769-1916; 3. 0000-0002-6999-2090;
4. 0000-0002-5435-2568; 5. 0000-0001-6896-4699; 6. 0000-0002-3859-7469
*Corresponding author: saktioto@lecturer.unri.ac.id

doi:10.15199/48.2024.01.27

Excellent integration of a multi-SRR-hexagonal DNG metamaterial into an inverted triangle top microstrip antenna for 5G technology applications at 3.5 GHz

***Abstract**. The application of engineered material methods for the generation of electromagnetic waves continues to be developed, especially in the field of telecommunications. Metamaterial is a suitable reflector material to penetrate telecommunications boundaries in meeting the required antenna specifications and mobility. In this research, the development of telecommunication antenna designs inspired by multi-cell indexed double-negative (DNG) metamaterials was carried out. The microstrip antenna structure consists of an inverted triangular-shaped copper plate superimposed on the top surface of the FR-4 substrate. This antenna design is operated in the frequency range of 0.05 – 9 GHz by integrating a hexagonal split ring resonator (SRR) metamaterial structure with a configuration of 3×3. The proposed metamaterial was successfully identified regarding DNG optical characteristics, which has the highest near-zero resonance index in the frequency range of 1.98 – 2.71 GHz. The original inverted triangle antenna has been designed with a performance of -23.96 dB at 3.75 GHz. The 1.62 GHz bandwidth profile of the same original antenna was also obtained from its combination with a hexagonal pattern SRR metamaterial characterized by a red shift at 3.5 GHz and a reduced reflection coefficient of -35.94 dB. In addition, the gain performance obtained is more optimal at 4.35 dBi at a frequency of 7.26 GHz. However, the improved antenna design with this metamaterial pattern can be applied to the telecommunications technology field of 5G networks.*

Streszczenie.** Zastosowanie metod inżynierii materiałowej do generowania fal elektromagnetycznych jest stale rozwijane, zwłaszcza w dziedzinie telekomunikacji. Metamateriał to odpowiedni materiał odblaskowy używany do penetracji granic telekomunikacyjnych w celu spełnienia wymaganych specyfikacji anteny i mobilności. W ramach tych badań przeprowadzono opracowanie projektów anten telekomunikacyjnych inspirowanych wielokomórkowymi metamateriałami podwójnie ujemnymi (DNG). Struktura anteny mikropaskowej składa się z miedzianej płytki w kształcie odwróconego trójkąta, nałożonej na górną powierzchnię podłoża FR-4. Ta konstrukcja anteny działa w zakresie częstotliwości 0,05 – 9 GHz dzięki zintegrowaniu struktury metamateriału z sześciokątnym rezonatorem pierścieniowym (SRR) w konfiguracji 3×3. Proponowany metamateriał został pomyślnie zidentyfikowany pod kątem właściwości optycznych DNG, który ma najwyższy bliski zeru współczynnik rezonansu w zakresie częstotliwości 1,98 – 2,71 GHz. Oryginalna antena w kształcie odwróconego trójkąta została zaprojektowana z myślą o wydajności -23,96 dB przy 3,75 GHz. Profil szerokości pasma 1,62 GHz tej samej oryginalnej anteny uzyskano również w połączeniu z metamateriałem SRR o wzorze heksagonalnym charakteryzującym się przesunięciem ku czerwieni przy 3,5 GHz i zmniejszonym współczynnikiem odbicia do -35,94 dB. Ponadto uzyskana wydajność wzmocnienia jest bardziej optymalna przy 4,35 dBi przy częstotliwości 7,26 GHz. Jednak ulepszona konstrukcja anteny z tym wzorem metamateriału może być zastosowana w dziedzinie technologii telekomunikacyjnych sieci 5G. **(Doskonała integracja metamateriału DNG multi-SRR-heksagonalnego z odwróconą górną anteną mikropaskową do zastosowań w technologii 5G przy 3,5 GHz)

Keywords: hexagonal, metamaterial, microstrip antenna, near-zero index, split ring resonator.
Słowa kluczowe: heksagonalny, metamateriał, antena mikropaskowa, indeks bliski zeru, rezonator z dzielonym pierścieniem.

Introduction

A wireless communication system comprises a transmitter, receiver, and antenna, used to transmit electromagnetic (EM) waves containing information sent and received by users. Its performance and quality, such as stronger interactions and higher directivity, tend to be improved through metamaterial scans [1-3]. Metamaterial is defined as an artificially designed structure with EM properties, and it is also used to produce negative permittivity and permeability values [4]. A characteristic compact antenna is the microstrip type, but its specifications do not align with the relevant requirements. Therefore, its optimization is realized using cell and structural variations as a reflector [5-7]. Some research stated that microstrip antennas are often used as anoption due to their small size, flatshape, and relatively low assembly costs. The modified microstrip type, with arrays of bandwidth, is anticipated to bewidely used in the future, particularly in wireless communication systems [8]. The essence is to produce those with small dimensional metamaterial structures. The properties of these artificially designed structures are not found in nature because it has negative permittivity and permeability, including double-negative (DNG) attributes [9].

The telecommunications sector is currently experiencing rapid development, as seen in the demand for fast and increasing wireless internet access. For example, one of the wireless technologies with fast internet accessis 5G, which can transmit (uplink) and receive data (downlink), including high reliability of relatively 10 Gbps, 20 Gbps, and 1 ms, respectively, is anticipated to be launched in 2023 in Indonesia [10]. In addition, it is intended to be extremely helpful in current and future technological developments due to the consistent provision of stable services, such as live streaming, internet of things, and ultra high definition video. 5G technology has three main spectrums, which are classified based on service coverage, starting from ≤ 1 GHz (very wide), 1 – 6 GHz (wide), and 6 > GHz (small) antenna. This is functional within the range of 1 to 6 GHz, especially at 3.4 to 3.8 GHz, because it supports several 5G devices and has a wide bandwidth [11]. The 2018 SDPPI center for research and development team confirmed that the 3.5 GHz is an excellent antenna specification for a 5G network in the country. This is because, at that frequency, EM waves experience less attenuation [12]. In 2019, the global system for mobile communications associations (GSMA) also stated that the 3.5 GHz frequency has certain advantages, such as a medium coverage area and more capacity [13].

A combined metamaterial antenna arrays with smaller dimensions capable of increasing the parameters of the microstrip type in telecommunication applications were employed. It was also presumed to have better potential than the single arrays reported in previous studies. A microstrip antenna that functions at a frequency within the range of 0.09 – 9 GHz, specifically 3.5 GHz, and return loss as low as -10 dB [14]. The high resonance property of the metamaterial makes its combination with multi-cell arrays in conventional antennas have a positive performance effect. In this research, it is necessary to develop antenna designs for 5G networks with renewable metamaterials which have a high probability of successfully increasing the low profile of microstrip antennas. The design of the antenna is carried out by simulating and several stages of structural optimization. The performance of the original antenna can be compared to that of proposed metamaterial structures such as the hexagonal split ring resonator (SRR). Optical material functions that represent refractive indices such as permittivity and permeability are important choices in determining the integration of metamaterials into antennas.

Metamaterial configuration

The metamaterial is designed as a hexagonal pattern SRR structure with a 3×3 array arrangement as shown in Fig. 1a. The designed metamaterial structure consists of two resonator rings made of pure copper (ε_r = 1) placed on the top surface of the FR-4 dielectric substrate (ε_r = 4.3). The dimensions of the 3×3 array metamaterial structure are designed with a size of 26 × 26 mm^2 or set smaller than the wavelength at the operating frequency of 0.05 – 9 GHz. One SRR cell with a symmetrical hexagonal pattern as shown in Fig. 1b and Fig. 1c has different thicknesses, widths, and ring radii as shown in Table 1.

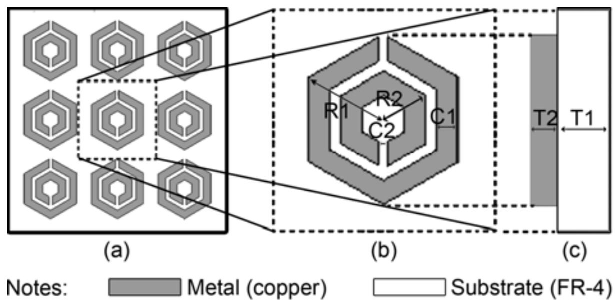

Fig.1. Metamaterial structure design: (a) 3X3 array configuration; (b) hexagonal pattern SRR geometry; and (c) thickness

Table 1. The geometry of the hexagonal pattern SRR structure

Parameter	Value (mm)	Parameter	Value (mm)
R1	2.5	C2	0.5
R2	2	T1	1.6
C1	0.75	T2	0.035

The characteristics of the metamaterial are determined based on the spectral parameter data obtained from the simulation of EM wave radiation on the metamaterial samples. Reflection (S11) and transmission (S12) spectrum data were processed to obtain the permittivity, permeability, and refractive index properties of the metamaterial using the modified Nicolson-Ross-Weir equation as follows [15]:

$$\varepsilon_r = \frac{2}{jk_0 t_m} \times \frac{1-(S12+S11)}{1+(S12+S11)} \tag{1}$$

$$\mu_r = \frac{2}{jk_0 t_m} \times \frac{1-(S12-S11)}{1+(S12-S11)} \tag{2}$$

$$n = \sqrt{\varepsilon_r \mu_r} \tag{3}$$

where: k_0 – wave number, t_m – propagation length, ε_r – relative pemittivity, μ_r – relative permeability, and n – refractive index.

Indexed double-negative

The SRR structure metamaterial with a hexagonal pattern with a 3×3 array configuration has been successfully identified as a material with a DNG index as shown in Fig. 2. The permittivity properties of the metamaterial were obtained at a frequency of 1.48 GHz with a very high resonance depth (see Fig. 2a). Meanwhile, the permeability properties of the metamaterial have a very low resonance depth at a frequency of 1.99 GHz (see Fig. 2b). This shows that the properties of the metamaterial have the ability to induce an electric field that is higher than the magnetic field from the propagation of the EM wave beam toward the sample. In Fig. 2c, the refractive index peak resonance represents the permittivity property compared to the permeability at the bottom resonance. Therefore, permeability has a more dominant influence in obtaining a negative refractive index compared to permittivity. Despite all that, this metamaterial exhibits an outstanding near-zero index in the frequency range of 1.98 – 2.71 GHz with a resonance depth of -8.36. The permittivity, permeability, and refractive index values of the metamaterial have been summarized and can be seen in Table 2.

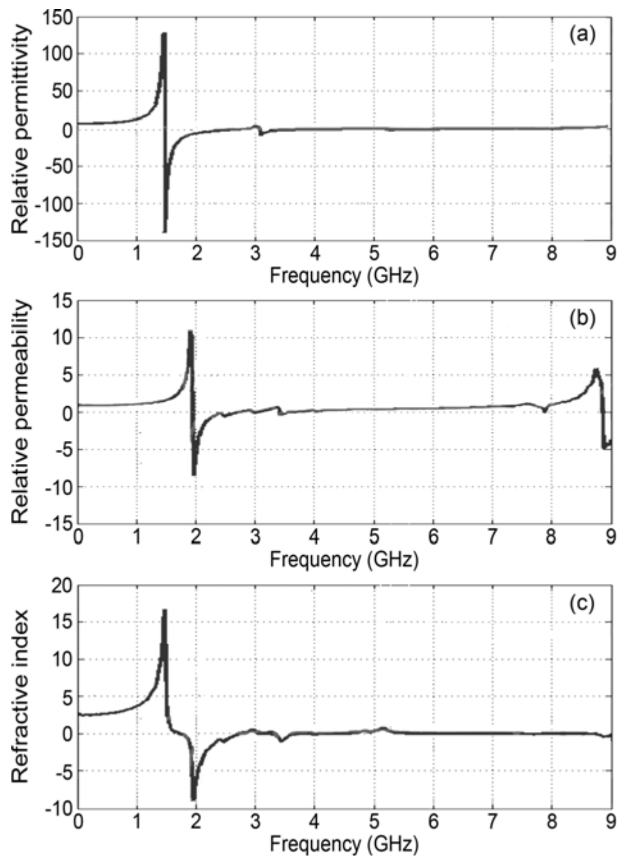

Fig.2. Negative resonance optical properties of the metamaterial: (a) permittivity, (b) permeability, and (c) refractive index

Table 2. Maximum negative resonance in the DNG metamaterial

Properties	Frequency (GHz)	Value
Relative permittivity	1.48	-137.03
Relative permeability	1.99	-8.37
Refractive index	1.98	-8.36

Integrated antenna

The design of the antenna is carried out by integrating the hexagonal pattern SRR structure metamaterial with a 3×3 array configuration just above the inverted triangle-shaped antenna as shown in Fig. 3a. The choice of a complementary triangular shape is based on optimizing antenna performance by cutting metal patches (copper) to minimize power reflections. In addition, the addition of a ladder-shaped grounding element is applied to the back of the substrate (FR-4) surface as shown in Fig. 3b. The dimensions of this microstrip antenna are designed to be 44 × 26 mm^2 with a certain thickness (see Fig. 3c) and have several antenna structure parameters as shown in Table 3.

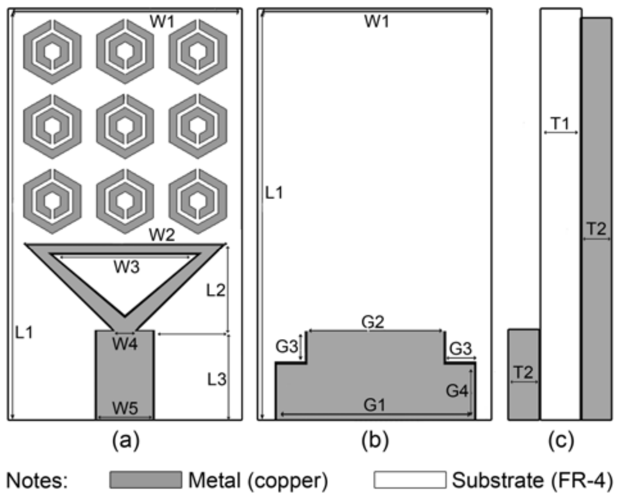

Fig.3. Design of microstrip antenna integrated hexagonal pattern SRR metamaterial structure with 3×3 array configuration for display: (a) front (radiation element); (b) back (ground element); and (c) the cross-section (thickness of the antenna structure)

Table 3. Complete parameters of the integrated antenna structure

Parameter	Value (mm)	Parameter	Value (mm)
L1	44	W5	6
L2	9	G1	22
L3	9	G2	19
W1	26	G3	3
W2	22	G4	6
W3	16	T1	1.6
W4	2	T2	0.035

Optimization and characterization of this microstrip antenna can be calculated using the following equation [15]:

$$W = \frac{c}{2f_0\sqrt{\frac{(\varepsilon+1)}{2}}} \tag{4}$$

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right) \tag{5}$$

$$\varepsilon_{eff} = \frac{\varepsilon+1}{2} + \frac{\varepsilon-1}{2}\left(\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right) \tag{6}$$

where: W – width of the patch, c – speed of light (3 × 10^8 m/s), f_0 – resonance frequency, ε – dielectric constant (substrate), L – length of the patch, ε_{eff} – effective dielectric constant, and h – substrate thickness.

Excellent performance

The antenna model integrated with metamaterial managed to provide better performance compared to conventional antennas as shown in Fig. 4. The original model without metamaterial has a return loss of -23.96 dB at 3.75 GHz. Meanwhile, antennas with the addition of metamaterials have the ability to absorb power more effectively by reaching -35.94 dB at 3.5 GHz. In addition, the two models have the same bandwidth of 1.62 GHz.

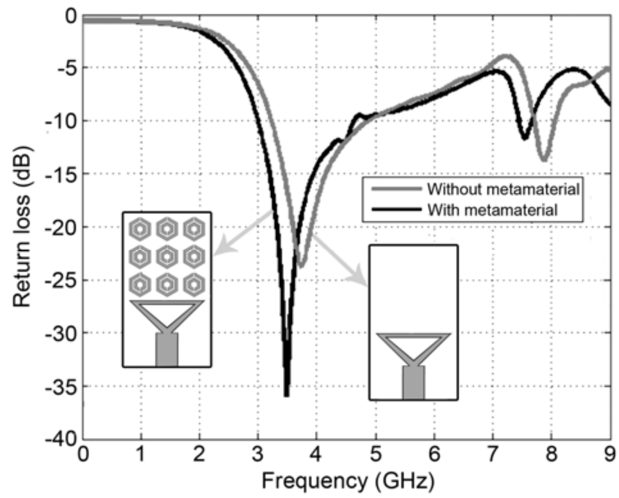

Fig.4. Antenna return loss profile after adding metamaterial

The presentation of return loss at the voltage standing wave ratio (VSWR) is set at -10 dB down or at a ratio of 1 ≤ n ≤ 2. In Fig. 5a, the original antenna has a VSWR ratio at higher frequencies (3.24 – 4.86 GHz) compared to the addition of metamaterial (2.97 – 4.59 GHz). In addition, the antenna gain has increased up to 4.35 dBi after the addition of the metamaterial as shown in Fig. 5b. A complete profile of antenna performance can be seen in Table 4.

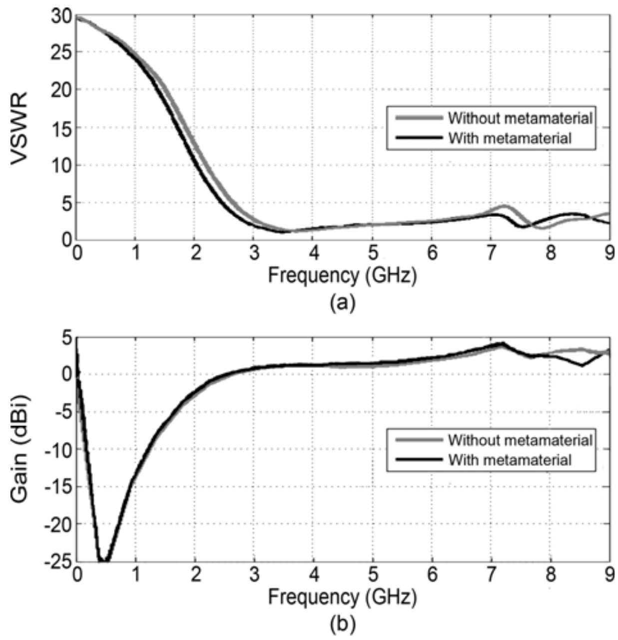

Fig.5. Antenna performance based on: (a) VSWR and (b) gain

Table 4. Antenna performance without and with metamaterials

Properties	Antenna design	
	Without metamaterial	With metamaterial
Frequency (GHz)	3.75	3.5
Return loss (dB)	-23.96	-35.94
Bandwidth (GHz)	1.62	1.62
Gain (dBi)	-24.98 – 4.31	-24.92 – 4.35

The radiation pattern at a resonant frequency of 3.5 GHz for the metamaterial integrated antenna gives a maximum gain distribution in the direction of the back of the structure of 2.79 dBi as shown in Fig. 6a. Whereas the front of the antenna structure or rather the metamaterial has a fairly good gain spread of 1.65 dBi. In addition, Fig. 6b shows the polarization angle of the antenna radiation in the direction of the z-axis plane. The maximum radiation aft of the antenna at 172.5° indicates a greater range of polarization angles in quadrants II and III. While the maximum radiation of the front of the antenna occurs at an angle of 16.8° in the area of quadrant IV. However, the implication of the metamaterial structure on the antenna structure can affect the distribution of the radiation pattern to become more directional and convergent which is accompanied by a decrease in gain.

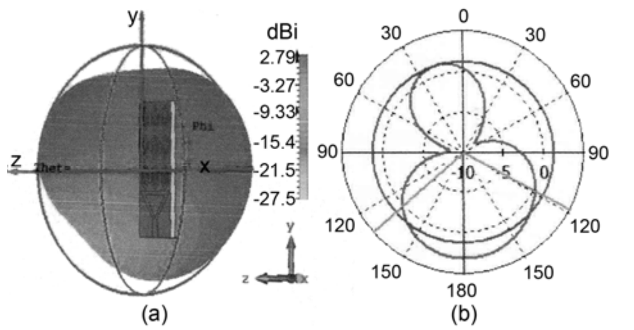

Fig.6. The metamaterial integrated antenna radiation pattern with the appearance of: (a) three-dimensional in the x-y-z direction and (b) two-dimensional in the z-plane direction

Conclusion

Integration of the hexagonal pattern SRR metamaterial with 3×3 configuration on the microstrip antenna structure has been successfully designed and simulated. The characteristics of the DNG metamaterial in the form of a negative refractive index at 1.98 – 2.71 GHz forces a shift in the antenna resonant frequency to 3.5 GHz which is feasible for 5G technology applications. The power absorption by the antenna based on the reflection coefficient of -35.94 dB becomes more optimal after the addition of the metamaterial structure. While the antenna gain increases up to 4.35 dBi along with the increase in operating frequency. In addition, the antenna radiation pattern shows a more directional and polarized gain distribution just in front of the metamaterial structure at 16.8° quadrant IV in the z-direction.

Acknowledgments

The author would like to thank the Ministry of Education and Culture of the Republic of Indonesia for the support of the 2023 research grant. Furthermore, the author would like to thank the Research and Community Service Institute (LPPM) of the University of Riau Pekanbaru Indonesia for providing research facilities.

***Authors**: Prof. Dr. Saktioto, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia, E-mail: saktioto@lecturer.unri.ac.id; Faridah Hanum Siregar, B.Sc, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia, E-mail: faridah.hanum2031@student.unri.ac.id; Yan Soerbakti, M.Sc, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia, E-mail: yansoerbakti2@gmail.com; Dr. Ari Sulistyo Rini, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia, E-mail: ari.sulistyo@lecturer.unri.ac.id; Dr. Syamsudhuha, Department of Mathematics, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia, E-mail: syamsudhuha@lecturer.unri.ac.id; Dr. Sofia Anita, Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Riau, Pekanbaru 28293, Indonesia, E-mail: sofia.anita@lecturer.unri.ac.id.*

REFERENCES

[1] Bilotti F., Alu A., Vegni L., Design of Miniaturized Metamaterial Patch Antennas with μ-Negative Loading, *IEEE Trans. Antennas Propag.*, 56 (2008), No. 6, 1640-1647

[2] Guelber E.F., Cardoso A.S.V., Capovilla C.E., Araujo H.X., A Modified Ultra Wide Band Antenna with Metamaterial Patterns for Telecommunications Systems, *Przeglad Elektrotechniczny*, 92 (2016), No. 1, 166-169

[3] Santalunai N., Santalunai S., Rattananamlom A., Chaipanya P., Meesawad P., Thongsopa C., Pumpoung T., Investigation on Characteristics of Metamaterials by Using Metallic Rod Structure for Antenna Engineering, *Przeglad Elektrotechniczny*, 98 (2022), No. 5, 103-109

[4] Kurnia M.F., Syahputra R.F., Saktioto, Expansion of Filter Design from GHz to THz with Metamaterial Hexagonal Split Ring Resonator, *J. Phys. Conf. Ser.*, 1090 (2018), No. 1, 1-6

[5] Keriee H.H., Rahim M.K.A., Nayyef N.A., Ayop O., Al-Gburi A.J.A., Compact Wideband Metamaterial Quadrature Coupler for 5G Beamforming Applications, *Przeglad Elektrotechniczny*, 99 (2023), No. 3, 172-175

[6] Jalil M.A., Abdolkarim A., Saktioto T., Ong C.T., Yupapin P.P., Generation of THz Frequency Using PANDA Ring Resonator for THz Imaging, *Int. J. Nanomed.*, 7 (2012), 773-779

[7] Saktioto T., Irawan D., Yupapin P.P., Phatharacorn P., A Single Eye 3D Image Perception Device Using Vertical Double Ring Resonator Construction, *Microw. Opt. Technol. Lett.*, 57 (2015), No. 8, 1802-1805

[8] Al-saedi A.J.H., Perez J.C., A Review: Compact Size and Isolation of MIMO Antenna, *Przeglad Elektrotechniczny*, 98 (2022), No. 7, 11-17

[9] Saktioto T., Syahputra R.F., Punthawanunt S., Ali J., Yupapin P., GHz Frequency Filtering Source Using Hexagonal Metamaterial Splitting Ring Resonators, *Microw. Opt. Technol. Lett.*, 59 (2017), No. 6, 1337-1340

[10] Qi Y., Hunukumbure M., Nekovee M., Lorca J., Sgardoni V., Quantifying Data Rate and Bandwidth Requirements for Immersive 5G Experience, *IEEE Int. Conf. Commun. Workshops*, 2016 (2016), 455-461

[11] Ahmad W.S.H.M.W., Radzi N.A.M., Samidi F.S., Ismail A., Abdullah F., Jamaludin M.Z., Zakaria M., 5G Technology: Towards Dynamic Spectrum Sharing Using Cognitive Radio Networks, *IEEE Access*, 8 (2020), 14460-14488

[12] Awangga F.S.A., Adaniah W.R.A., Ariyanti S., Kusumawati D., Kiki P.E., Aziz A., Studi Lanjutan 5G Indonesia 2018–Spektrum Outlook dan Use Case untuk Layanan 5G Indonesia, *Research Team of Puslitbang SDPPI*, (2018)

[13] GSMA, 5G Guide: GSMA Public Policy Position, *Global System for Mobile Communications Association*, (2019), 1-15

[14] Wenshan C., Shalaev V., Optical Metamaterials: Fundamentals and Applications, *Springer*, 3 (2010), 1-9

[15] Saktioto, Soerbakti Y., Syahputra R.F., Gamal M.D.H., Irawan D., Putra E.H., Darwis R.S., Okfalisa, Improvement of Low-Profile Microstrip Antenna Performance by Hexagonal-Shaped SRR Structure with DNG Metamaterial Characteristic as UWB Application, *Alex. Eng. J.*, 61 (2022), No. 6, 4241-4252