A smart 5G antenna system with butler matrix and PIN diode control for dynamic beamsteering and beamtracking

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Abstract. The design and implementation of an intelligent antenna system for beam steering and tracking is presented in this paper. The proposed system is a 4×4 Butler matrix using PIN diodes for dynamic beam steering of a four-element microstrip antenna array. With the use of the Butler matrix, the antenna array can produce several fixed directional beams pointing in various directions. RF switches are implemented using PIN diodes for real-time beam selection according to the spatial position of the target. This approach provides fast and passive beam tracking without motors or mechanical parts while maintaining high directivity and constant gain. Simulations show the efficiency of this system in cases of wireless communication, smart detection, or object tracking for industry, healthcare, or home automation.

Keywords: Beamsteering, Beamtraking, Butler matrix

1 Introduction

The rapid advancement of wireless networks, particularly in light of 5G growth and sophisticated radar-based applications, has led to a major demand for conventional antenna systems equipped with dynamic beam steering to enhance link capacity, coverage, and robustness. Narrow beamwidth antenna arrays often provide accurate directional control and high signal strength. These arrays often steer the radiation pattern in specific directions to improve communication performance. However, the common antennas of ground stations and radar systems for tracking satellites and object detection are usually large and heavy and thus have limited capabilities of rapidly changing the beam direction [1, 2].

One of the practical solutions for this issue is using beam steerable antennas, also known as beamforming antennas. These systems are made up of several radiating components, which allow us to orient the primary beam in the desired directions. The beam can be steered either mechanically or electronically. However, mechanical steering systems are typically large, expensive, and slow and therefore are not suitable for applications that require fast beam switching.

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Electronic beam steering, on the other hand, allows the beam direction to be steered electronically by changing the value of the phase of the signals transmitted to the individual antenna elements. This results in a fast and more efficient scanning capability [3]. This approach can be implemented by using various technologies including the Butler matrix [4 - 8], Blass matrix [9], Rotman lens [10], RF phase shifters, PIN diode switches [11] and other methods. Each approach has a different set of strengths and limitations concerning cost, performance, frequency range and complexity. The Butler matrix is an effective technique for producing multiple fixed beams from antenna arrays. It employs fixed phase shifters and hybrid couplers to generate orthogonal directional beams with less complex equipment. Beam steering antenna arrays based on the Butler Matrix (BM) architecture have been the subject of numerous investigations. For instance, [12] describes a microstrip antenna array with switched beams and a miniature Butler matrix network, proving that it can be used for beamforming. In [13], a Petri net is utilized to verify a 4x4 Butler matrix's process modelling. While in [14], a thorough analysis of Butler matrix-based beamforming networks, which are considered crucial parts of phased array antennas for upcoming 5G systems, is provided.

However, to meet the requirements of dynamic object tracking in constantly changing environments, fast beam switching methods need to be used. PIN diodes can be used as RF switches to choose a dynamic path and activate or deactivate particular antennas based on where the target object is positioned. Without the use of mechanical components or any other solution, this technique permits passive and rapid beam tracking while maintaining good directivity and stable gain, which is what we are searching for.

In these prior studies, the beamforming mechanisms are outlined with insightful information, but either with a fixed beam generation and no dynamic control or with dynamic control in specific antenna structures without a comprehensive integration of the Butler matrix and PIN diode. In order to address this gap, the main contribution of this paper is the design and implementation of a small 5G antenna system operating at 28 GHz that includes a 4x4 Butler matrix with PIN diodes for real-time dynamic beam steering and tracking. The system delivers reliable and rapid beam switching with no mechanical elements, which gives a small, efficient, and cost-effective solution for the next generation of wireless communication systems.

The structure of the paper is divided into sections as follows: Section 2 describes the Butler matrix design, while section 3 explains the antenna design, section 4 presents the switching circuit using PIN diodes, section 5 discusses the incorporation of the Butler matrix with the antenna array, and section 6 presents the conclusion of the paper.

2 Butler matrix design

For beam steering applications, antenna arrays are fed by the Butler matrix, which is a passive beamforming network. In order to generate several fixed beams in various directions without the need for moving parts, a certain configuration of hybrid couplers, fixed phase shifters, and crossovers is used. The antenna array can electrically steer its beam by choosing the right input, as each input port of the matrix corresponds to a specific radiation direction.

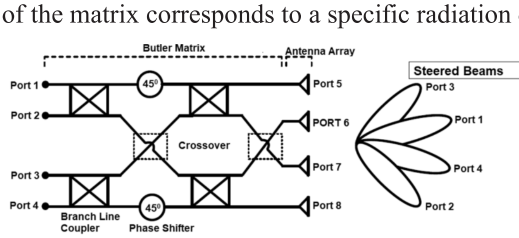


Fig. 1. A 4 × 4 Butler matrix block diagram [2]

A block diagram of a 4 × 4 Butler matrix is displayed in Fig. 1, with each directed beam representing a distinct excited input port. With antenna elements attached to the outputs, this matrix has four input ports and four output ports. The matrix evenly divides the input signal into four equal portions across the outputs by applying a progressive phase shift. The branch line coupler, crossover, and phase shifter are the three main parts of the Butler matrix, as shown in the diagram. The design is implemented on a Rogers RT/Duroid 5880 substrate that has a thickness of 0.5 mm and a dielectric constant of 2.2. The sections that follow provide detailed descriptions of each of these components.

2.1 3 dB hybrid coupler

A 3 dB hybrid coupler, also called a 3 dB directional coupler or quadrature hybrid, is a passive microwave component with four ports that divides an input signal evenly between two output ports with a 90° or 180° phase difference, depending on the coupler type. Similar to a branch-line coupler, a conventional 90° hybrid coupler splits the input signal evenly between two outputs, with one output phase shifted by 90°, while keeping the fourth port perfectly isolated. The ability of hybrid couplers to precisely divide power and control phase makes them essential components of contemporary radar and communication systems and other applications that need the same procedure.

The 3 dB hybrid coupler's S11, S12, S13, and S14 parameters magnitude (in dB) are shown in Fig. 3. (a), and the S31 and S41 parameters phase (in degrees) are shown in Fig. 3. (b).

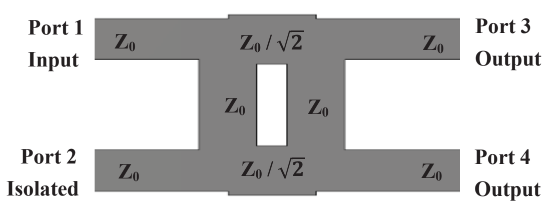
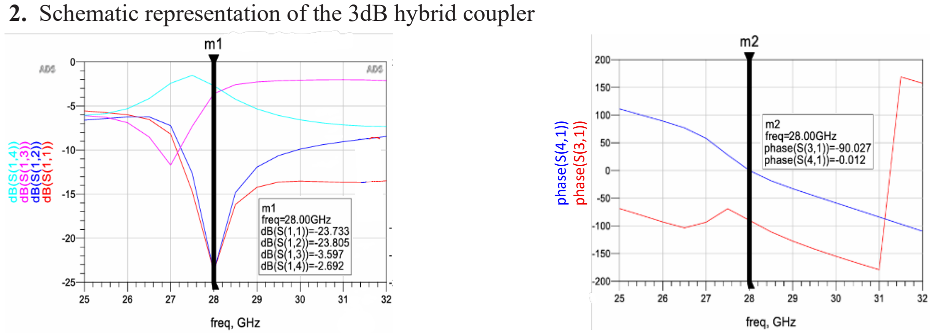


Fig. 2. Schematic representation of the 3dB hybrid coupler



(a) (b)

Fig. 3. (a) S-parameters magnitudes of the 3 dB hybrid coupler. (b) S31 and S41 phases at output ports of the hybrid coupler

The input power at port 3 and 4 is divided by two (-3 dB) at a frequency of 28 GHz. We achieved good return loss at the intended frequency and perfect isolation between ports 1 and 2 in the simulation.

2.2 Crossover

A crossover is a device that allows two signals to cross over one another without interference. In radio frequency and microwave systems, it enables two transmission lines to cross at a 90-degree angle while maintaining them isolated and minimizing interference and losses. The crossover geometry is illustrated in Fig. 4.

Fig. 5 shows simulation results at 28 GHz with good cross-line isolation.

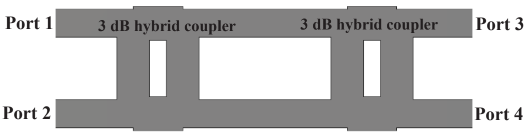


Fig. 4. Geometry of the crossover

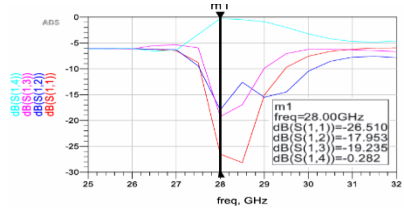


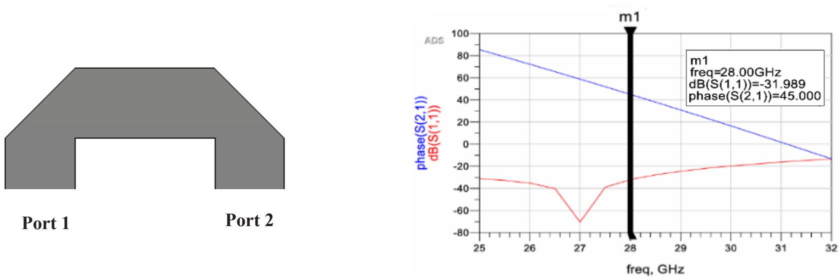
Fig. 5. Simulated crossover S-parameters

2.3 Phase shifter

A 45-degree phase shifter is a passive device that applies a constant phase shift of 45 degrees between its input and output signals. It uses microstrip transmission lines for implementation. For a 45° phase shift, the line length is calculated from equation (1), while the wavelength is calculated from equation (2), where λ_0 is the wavelength in free space and ε_{eff} is the effective dielectric constant of the line. Fig. 6. (a) illustrates the arrangement of the phase shifter and Fig. 6. (b) the phase curve of S21. It should be noted that since the device is implemented by using a uniform microstrip line, the phase shift has a linear relation with frequency, as expected from a transmission line.

$$\mathrm{L} = \frac{\theta \lambda_g}{2\pi} \quad (1)$$

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \quad (2)$$



(a) (b)

Fig. 6. (a) Geometry of the phase shifter. (b) S21 phase curve

2.4 4x4 Buttler matrix

The microstrip design of the Butler matrix that we have made at 28 GHz frequency is shown in Fig. 7. Fig. 8. (a) shows the simulated results obtained from the ADS when the input signal is applied at port 1 of the Butler matrix.

The magnitude values found at 28 GHz are roughly -6 dB, which is regarded as quite acceptable, therefore the results are very encouraging. Fig. 8. (b) shows how the phase between the output ports stays fairly constant at 28 GHz.

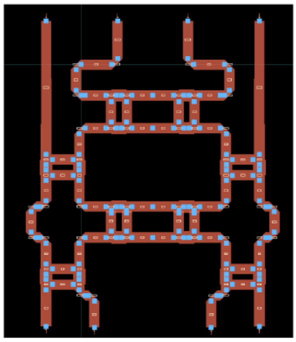
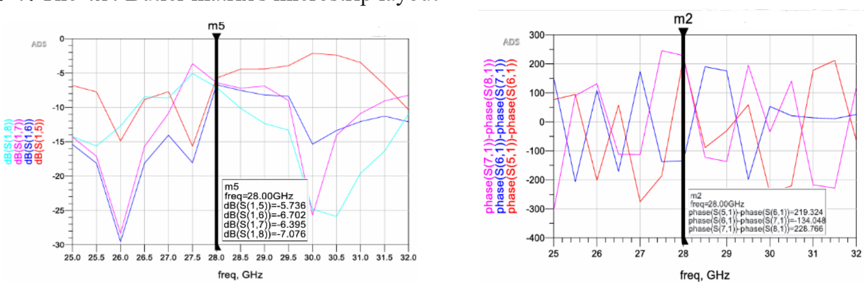


Fig. 7. The 4x4 Butler matrix's microstrip layout



(a) (b)

Fig. 8. (a) S-S-parameters of the suggested Butler matrix. (b) Phase parameters of the suggested Butler matrix

3 Antenna design

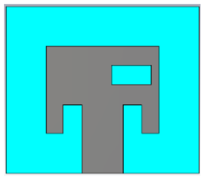
A rectangular patch microstrip antenna with a length Lp and a width Wp, operating at 28 GHz is designed on a Rogers RT/Duroid 5880 substrate. A microstrip feed line with a characteristic impedance of Z_0=50 Ω is used to excite the antenna.

3.1 Antenna design in CST

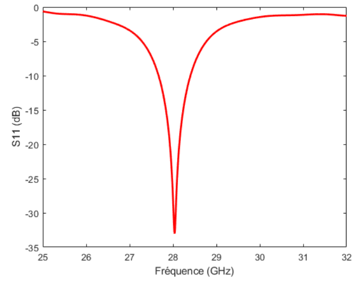
Fig. 9. (a) illustrates the antenna design as simulated by the CST Microwave Studio. The S11 curve demonstrates good impedance matching at the target frequency, which means efficient power transfer. The antenna has a simulated gain of 6.19 dBi, which shows the ability of the antenna to increase the radiated signal. It has also an efficiency of 71.65% and directivity of 7.635 dBi.

3.2 Antenna array

Based on the previously constructed antenna, an antenna array consisting of four identical radiating elements is produced. The array elements are uniformly spaced along one axis for optimal beamforming and radiation characteristics. The idea behind this configuration is to increase the overall gain and directivity of the system.



(a)



(b)

Fig. 9. (a) Antenna design. (b) Simulated S-parameter of the proposed design

The antenna array is operating effectively at the target frequency of 28 GHz, according to simulation results. The array is well-matched to the desired frequency, with maximum power transfer and minimum reflection. The array has a significant gain of 13.78 dBi and high directivity of 14.17 dBi, which are suitable for applications requiring concentrated energy transfer and increased signal strength in specific directions.

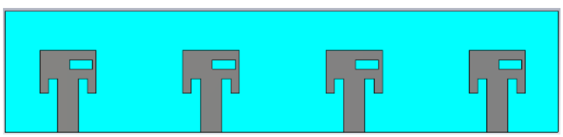
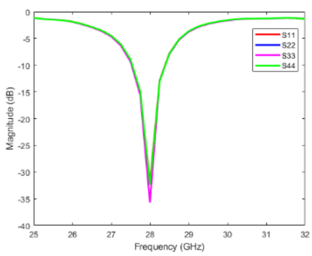
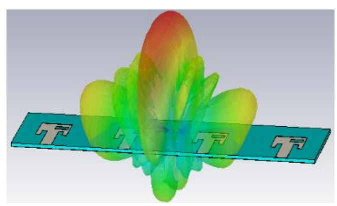


Fig. 10. Antenna array



(a)



(b)

Fig. 11. (a) Simulated antenna array S-parameters. (b) Antenna array radiation pattern.

4 Switching circuit with the T-junction power divider

4.1 Switching circuit

The switching circuit is consisting of:

- **4 PIN Diodes:** used for signal path switching.
- **Biasing Circuit:** supplies the necessary voltages to regulate the PIN diodes in ON/OFF states.

These components, collectively, change the direction of the antenna beams via the routing of the RF signals to different ports of the Butler matrix. The PIN diodes used in the switching circuit operate as follows:

- **Diodes ON:** The RF signal can pass through, as the path is open.
- **Diodes OFF:** The signal is blocked since the path is closed.

This technique allows the antenna to change its beam direction by selectively activating different paths within the Butler matrix. One of the main features of the proposed design is the dynamic real-time control of the beam direction according to the network requirements.

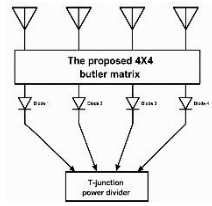
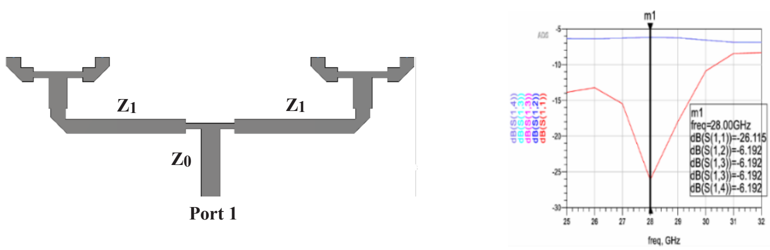


Fig. 12. The proposed system

4.2 T-junction power divider

The power divider is one of the most commonly used components for dividing and/or combining power in an n-port network in radio frequency and microwave systems. To obtain the desired isolation, a 100 Ω resistor is included in the design and placed between the two branch outputs. In order to do this, the two branches of the power divider need to be located close to each other so they can connect to the resistor. Alternatively, the resistor can be replaced by a transmission line of length λ/4, which can serve the same purpose. This configuration consists of a 100 Ω transmission line between two 50 Ω transmission lines of length λ/4.



(a) (b)

Fig. 13. (a) Geometry of the T-junction. (b) S-parameters magnitudes of the T-junction

5 Butler matrix integrated with the antenna array and PIN diodes

The antenna array, Butler matrix, and PIN diodes are incorporated in the global system and presented in Fig. 14. The given schematic shows how these elements function together for the beam control. In this design, PIN diodes act as switches, which dynamically select the signal route depending on the desired direction of the beam. At the same time, the Butler matrix provides the distribution of the signal between all the antennas in order to achieve the desired direction of the beam through providing the necessary phase shifts. The activation of one specific PIN diode and the deactivation of other PIN diodes allow the steering of the beam into the desired direction. In the ON state, an RLC circuit in series with low resistance and inductance of about 0.5 nH is used. The OFF state uses the parallel RLC circuit, where the resistance is high (about 10 kΩ) and the capacitance is 0.15 pF.

The simulated reflection coefficients of the suggested beam steering antenna are shown in Fig. 15. The operational frequency band shows that the antenna's impedance is well matched, and all S-parameters have values less than -10 dB. By activating the PIN diodes, the beam's direction can be adjusted. Activating diode number 1 directs the main beam at an angle of 13°, whereas diode number 2 shifts the beam to 17°. The symmetry of the design of the Butler matrix results in similar beam patterns for port numbers 3 and 4, respectively.

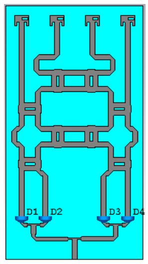


Fig. 14. Butler matrix integrated with antenna array and PIN diodes

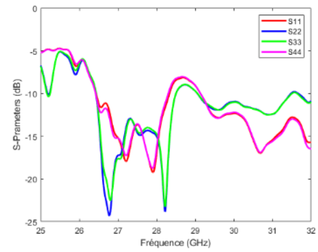
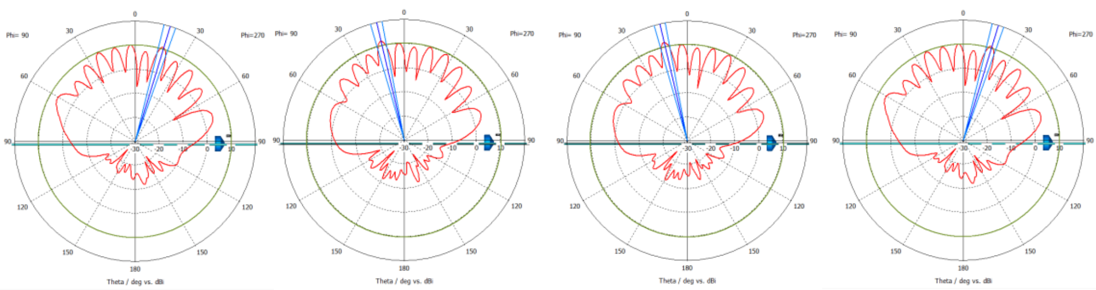


Fig. 15. S-parameters magnitudes of the global system



(a) (b) (c) (d)

Fig. 16. Radiation pattern of the entire system: (a) Diode 1 is on. (b) Diode 2 is on. (c) Diode 3 is on. (d) Diode 4 is on

Table 1. Comparison of the suggested work with related existing works.

Ref	Antenna Size (mm^3)	Substrate Used	Resonant Frequency (GHz)	Array Type	Antenna Elements	Bandwidth (%)	Beam Steering Angle (°)	Max Beam Gain (dBi)	Efficiency (%)
[8]	140.47 x 89.82 x 0.508	Rogers 5870	5.8	4x4 Butler Matrix	4	15	-51 to +52	8	_
[2]	160.5 x 80 x 0.381	Rogers 5880	10	4x4 Butler Matrix	4	30	±10, ±38	>10.5	>85
[15]	440 x 340 x 110	FR4	3.5	5x5 Butler Matrix	5	11.43	-35 to +35	11.4	83.8
[12]	_	Rogers 5880	2.4	4x4 Butler Matrix	4	14.5	+14, -44	7	_
This work	41.2 x 76 x 0.5	Rogers 5880	28	4x4 Butler Matrix	4	7.32	+13, +17	11	99

6 Conclusion

In this study, we proposed an antenna system design for a 5G base station antenna with beam steering and tracking capability at 28 GHz. The whole system is using PIN diodes and a Butler matrix to dynamically select the path. The entire system has a compact size, with a dimension of 41.2 × 76 × 0.5 mm³. The circuit was composed of four patch antennas, two crossovers, four 3 dB hybrid couplers, four phase shifters, four PIN diodes, and a T-junction power divider. The main benefits of the above design include large bandwidth, high gain, high efficiency, and the ability to steer the beam in two directions.

The proposed method is a simpler and more concise approach to beam steering at millimeter-wave frequencies compared to other works in the literature. The Butler matrix and PIN diodes provide fast beam switching without mechanical components. This is crucial for real-time beam tracking in dynamic environments, like 5G networks.

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References

1. O. Kodheli, E. Lagunas, N. Maturo, et al., Satellite Communications in the New Space Era: A Survey and Future Challenges. IEEE Commun. Surv. Tutor. 23, 70–109 (2020). https://doi.org/10.1109/COMST.2020.3028247
2. M.H. Reddy, D. Siddle, D. Sheela, Design and implementation of a beam-steering antenna array using butler matrix feed network for X-band applications. AEU - Int. J. Electron. Commun. 147, 154147 (2022). https://doi.org/10.1016/j.aeue.2022.154147
3. I. Uchendu, J.R. Kelly, Survey of beam steering techniques available for millimeter wave applications. Prog. Electromagn. Res. B 68, 35–54 (2016). https://doi.org/10.2528/PIERB16030703
4. S.A. Babale, O. Elijah, S.K.A. Rahim, S.I. Orakwue, Two-dimensional beam-steering phased array utilizing 2×2 Butler matrix. in Proc. IEEE 3rd Int. Conf. Electro-Technology for National Development (NIGERCON) 245-248 (2017). https://doi.org/https://doi.org/10.1109/NIGERCON.2017.8281896
5. S. Kuwana, H. Hayashi, R. Ueda, Simple design of four-element planar butler matrix using two section branch-line hybrids. IEEJ Trans. Electr. Electron. Eng. 12, S187–S188 (2017). https://doi.org/10.1002/tee.22435
6. L. Ma, Y. Wu, W. Wang, Design of Wideband Butler Matrix with Equal/Unequal Phase Differences for Flexible Beam-Controllability. IEEE Trans. Circuits Syst. II, Exp. Briefs 68, 3537–3541 (2021). https://doi.org/10.1109/TCSII.2021.3078751
7. H. Liu, X. Liu, F. Effenberger, N. Chand, X. Qi, G. Li, Optical Implementation of Butler Matrix for Hardware-Efficient Multiuser Beamforming. IEEE Photon. J. 10, 1–8 (2018). https://doi.org/10.1109/JPHOT.2018.2805875
8. H. Ren, P. Li, Y. Gu, B. Arigong, Phase Shifter-Relaxed and Control-Relaxed Continuous Steering Multiple Beamforming 4×4 Butler Matrix Phased Array. IEEE Trans. Circuits Syst. I, Reg. Papers 67, 5031–5039 (2020). https://doi.org/10.1109/TCSI.2020.3009215
9. S. Mosca, F. Bilotti, A. Toscano, L. Vegni, A Novel Design Method for Blass Matrix Beam-Forming Networks. IEEE Trans. Antennas Propag. 50, 225–232 (2002). https://doi.org/10.1109/8.997999

10. S.K. Karki, M. Varonen, M. Kaunisto, et al., Beam-Reconfigurable Antenna Based on Vector Modulator and Rotman Lens on LTCC. IEEE Access 9, 52872–52882 (2021). https://doi.org/10.1109/ACCESS.2021.3070037
11. L. Gong, R. Ramer, K. Yuk, Beam steering spiral antenna reconfigured by PIN diodes. Int. J. Microw. Wireless Technol. 6, 619–627 (2014). https://doi.org/10.1017/S1759078714000130
12. W. Nie, Y. Fan, S. Luo, Y. Guo, A switched-beam microstrip antenna array with miniaturized butler matrix network. Microw. Opt. Technol. Lett. 57, 841–845 (2015). https://doi.org/10.1002/mop.28972
13. V. Prakash, S. Dahiya, S. Kumawat, P. Singh, Design of 4×4 Butler Matrix and Its Process Modeling Using Petri Nets for Phase Array Systems. Prog. Electromagn. Res. C 103, 137–153 (2020).
14. A.K. Vallappil, M.K.A. Rahim, B.A. Khawaja, N.A. Murad, M.G. Mustapha, Butler Matrix Based Beamforming Networks for Phased Array Antenna Systems: A Comprehensive Review and Future Directions For 5G Applications. IEEE Access 9, 3970–3987 (2020). https://doi.org/10.1109/ACCESS.2020.3047696
15. W.H. Peng, Y.S. Chen, Beam-Switching Antennas Using a Butler Matrix with a Five-Element Configuration. Electronics 14(5), 959 (2025). https://doi.org/10.3390/electronics14050959