Journal of Engineering Science and Technology
21st EURECA 2024 Special Issue August (2025) 160 - 171

MULTIBEAM ARRAY ANTENNA FOR UNMANNED AERIAL VEHICLE APPLICATION

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Abstract

In the recent years, the use of unmanned aerial vehicles (UAVs) has been increasing rapidly especially in military and civilian applications. The UAVs antenna requires an efficient performance, low profile, lightweight and low cost. Multibeam array antennas play an important role for UAVs application to establish long distance communication by reduce co-channel interference and improve network coverage. This paper presents a single layer multibeam array antenna by employing a 4×4 Butler matrix at 5.8 GHz for unmanned aerial vehicle application. The designed Butler matrix consists of four quadrature hybrids, two crossovers and two phase shifters. Four antenna elements were connected at the output of the Butler matrix. The dimensions of the designed multibeam array antenna were 121 mm x 205 mm x 0.254 mm. The return losses were less than -10 dB at 5.8 GHz. The main beams of the multibeam array antenna were pointed at ±11° and ±35°. The beam coverage of the multibeam array antenna is 70° with an antenna gains between 11.5 dBi to 12.3 dBi.

Keywords: Butler matrix, Multibeam array antenna, Single-layer, Unmanned aerial vehicle.

1. Introduction

Research on unmanned aerial vehicles (UAVs) has received significant interest for military and civilian applications due to the increasing demand for higher data rates and higher data traffic [1, 2]. One of the key components of UAV systems is the antenna that plays an important role to provide continuous signal availability within the network coverage area [3]. Since UAV are powered by batteries, the size of the antenna is crucial. A heavyweight and high profile antenna will increase the UAV's power consumption that limit the payload. Therefore, UAV antenna requires low profile and lightweight besides high antenna gain, high efficiency and good radiation characteristics [4].

Multibeam array antenna plays an important role in developing new UAVs antenna to enhance system capacity, improve network coverage and reduce co-channel interference. There are three types of multibeam antennas that commonly used such as reflector antennas, lens antennas and array antennas. Although the reflector antennas and lens antennas have high gain but are the size of the antennas are high profile and heavyweight [5, 6].

Therefore, these antennas are not suitable to be utilized as UAV antennas. In comparison, array antennas are the most preferred solution in many wireless communications due to low profile, lightweight, low cost and can be mounted easily on the flat surface in which more suitable for UAV application. The array antenna can be fed by beamforming circuits such as the Rotman lens, Blass matrix and Butler matrix. Among these beamforming circuits, the Butler matrix is commonly used because of its simplicity of design and fabrication, low cost and cost-effectiveness [7, 8].

Therefore, the Butler matrix is chosen in this work. However, the literature has reported issues such as high amplitude imbalance and inaccurate phase differences between the output ports of the Butler matrix that cause the radiation characteristics to show incorrect main beam directions. To overcome these issues, the Butler matrix must have highly accurate dimensions to ensure the main beams point at the desired directions.

Previous studies have focused on the improvement of the circuit performance and size reduction of the Butler matrix. Ren et al. [9] proposed continuous tuneable phase progression using 4×4 Butler matrix and tuneable phase shifters to enhance the network coverage. Metamaterial based approaches were used by Vallappil et al. [10] to miniaturise the Butler matrix and improved bandwidth. The main drawbacks of designing a Butler matrix in millimetre waves using microstrip technology are due to its high insertion losses and incorrect output phases at the output ports of the Butler matrix that affect the radiation characteristics [11]. Additionally, the literature has also reported the issue of the inaccurate beam directions in the higher-order Butler matrices as the dimensions of the circuit elements are imprecise [12].

In this paper, a single layer multibeam array antenna employing 4×4 Butler matrix at 5.8 GHz was designed using CST Studio Suite. The dimensions of the multibeam array antenna were optimized to minimize the insertion losses and reduce the output phase errors. The results of the designed multibeam array antenna are presented and discussed in this paper.

2. Methods

In this work, a multibeam array antenna fed by 4×4 Butler matrix was designed using CST Studio Suite. The substrate used in this work is NPC-F220A from Nippon Pillar Packing Co. Ltd. The substrate has thickness of 0.256 mm, copper thickness of 18 μm, dielectric constant of 2.2 and dissipation factor of 0.0007.

2.1. Design of the Butler matrix

The Butler matrix is chosen in this work as a beamforming circuit to control the main beam directions of the multibeam array antenna. The 4×4 Butler matrix consists of four hybrid couplers, two crossovers, and two phase shifters. It has four inputs (Pi) and four outputs (Oi). Four antenna elements are connected to the output ports of the 4×4 Butler matrix. The structure of the 4×4 Butler matrix with four antenna elements is shown in Fig. 1. The phase differences between the output ports can be calculated using Eq. (1). Table 1 lists the phase differences between the antenna elements and the design of the 4×4 Butler matrix is shown in Fig. 2.

$$\phi = \pm \frac{(2p-1)\times 180^\circ}{N} \quad (1)$$

where N = 4 and p = 1, 2 and ϕ is the phase difference between output ports.

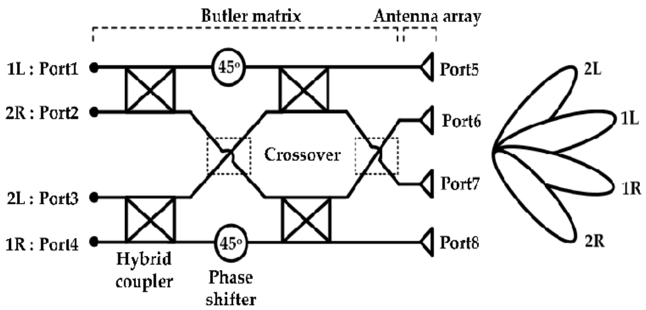

Fig. 1. The structure of the 4×4 Butler matrix with four antenna elements [13].

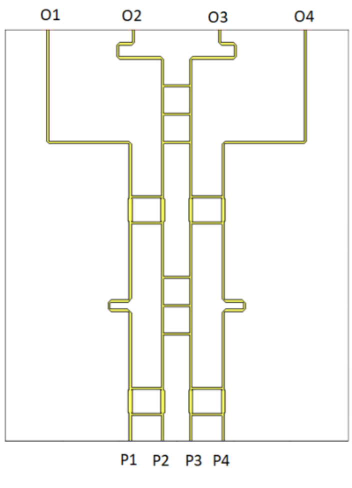

Fig. 2. Designed structure of the 4×4 Butler matrix.

Table 1. Phase differences between output port for each input ports.

Input port	Phase difference, ϕ (°)
1	-45
2	135
3	-135
4	45

2.2. Designed of the antenna element

The rectangular microstrip antenna was designed using CST Studio Suite. The geometry of the designed antenna is shown in Fig. 3. The antenna was fed at the centre of the antenna edge using a 50 Ω microstrip transmission line with a quarter-wavelength transformer. The dimensions of the antenna were optimized, and the optimised parameters are shown in Table 2.

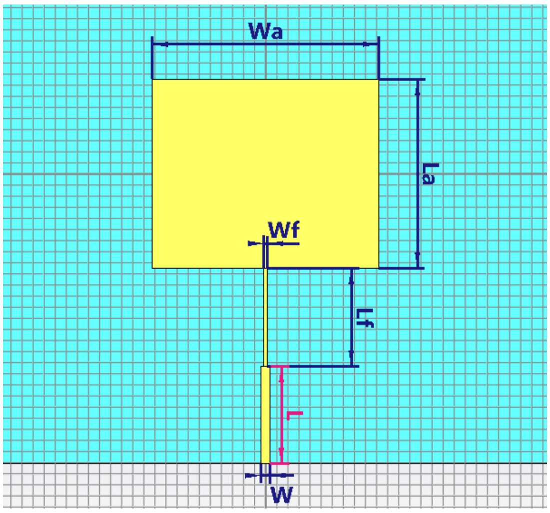

Fig. 3. Geometry of the antenna element with quarter-wavelength transformer.

Table 2. Optimised parameters of the antenna element.

Parameter	Values (mm)
Width of antenna, Wa	23.0530
Length of antenna, La	16.8575
Width of quarter-wave transformer, Wf	0.3822
Length of quarter-wave transformer, Lf	9.0284
Length of transmission line, L	9.2307

2.3. Design of the multibeam array antenna

The structure of a multibeam array antenna fed by the 4×4 Butler matrix is shown in Fig. 4. The antenna spacing of the multibeam array antenna was 0.58λ to reduce the effect of mutual inductance between antenna elements and to avoid the appearance of the grating lobes. In this design, the extended lines were designed at the input ports of the multibeam array antenna to allow the implementation of the coaxial connectors.

The Butler matrix produced four beams at four different angles. The main lobe direction of the multibeam array antenna can be calculated using Eq. (2) [13]. Table 3 lists beam angles for each input port.

$$\sin(\theta) = \pm\frac{\lambda}{d}\frac{\phi}{360°} \tag{2}$$

where λ is the wavelength, d is the antenna spacing, ϕ is the phase difference between antenna and θ is angle of main lobe.

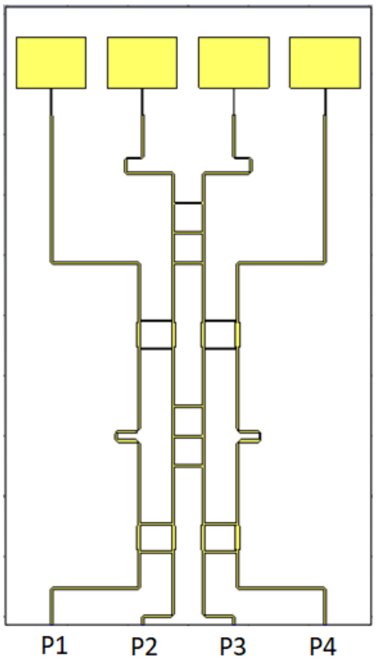

Fig. 4. Structure of the multibeam array antenna.

Table 3. The main beam directions of the multibeam array antenna for each input ports.

Input port	Main beam direction, θ (°)
1	12
2	-40
3	40
4	-12

3. Results and Discussion

The results of the designed 4×4 Butler matrix, antenna element and multibeam array antenna are presented and discussed in detail in the following subsections.

3.1. Results of the Butler matrix

Figure 5 presents the return losses of the 4×4 Butler matrix at the input and output ports from 5.3 GHz **to** 6.3 GHz. The return losses are less than -16 dB at 5.8 GHz. Figure 6 shows the isolations between the input port of the 4×4 Butler matrix and the isolation is less than -14 dB at 5.8 GHz. Figures 7 to 10 show the insertion loss when input ports are excited, respectively. From the figure, the average insertion loss is -7.1 dB at 5.8 GHz, therefore the average insertion loss of the Butler matrix is -1.1 dB.

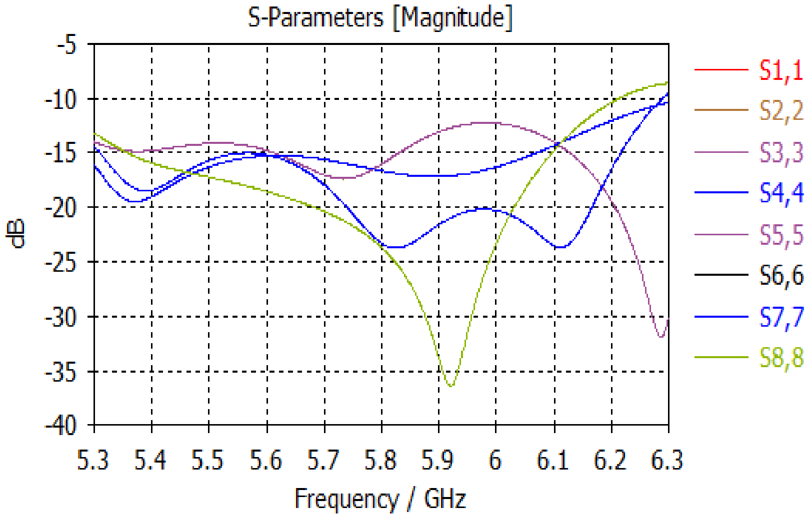

Fig. 5. Return losses for the input and output ports of the 4×4 Butler Matrix.

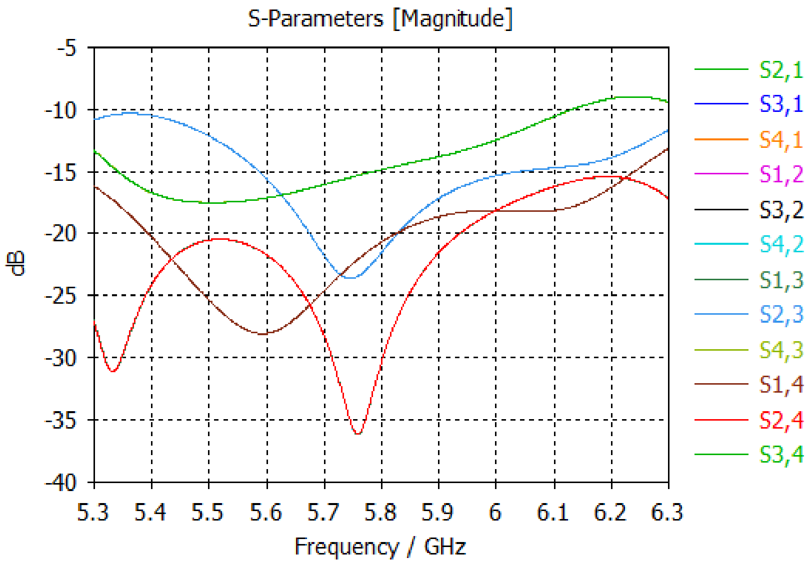

Fig. 6. Isolation between input ports of the 4×4 Butler matrix.

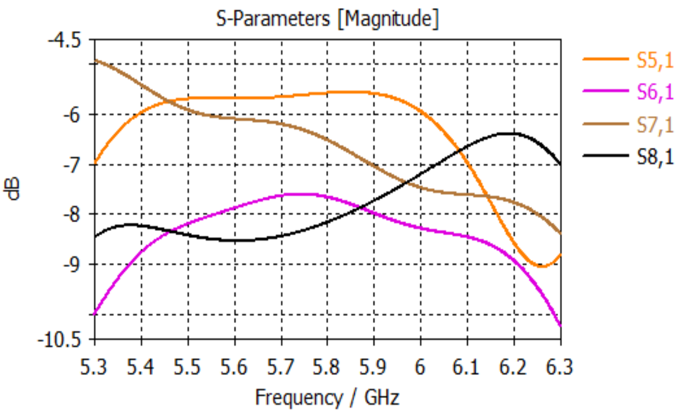

Fig. 7. Insertion loss of the Butler matrix for port 1.

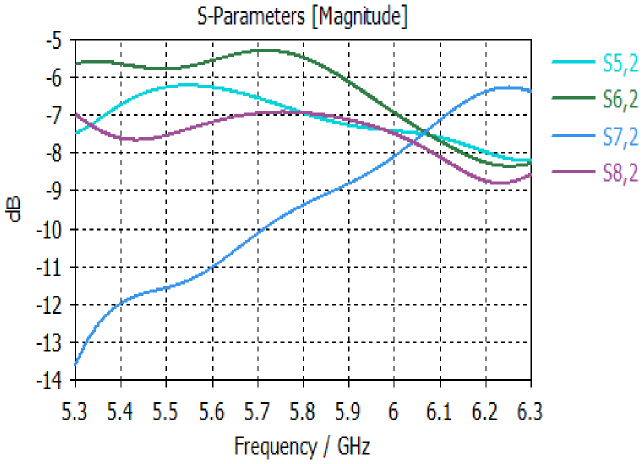

Fig. 8. Insertion loss of the Butler matrix for port 2.

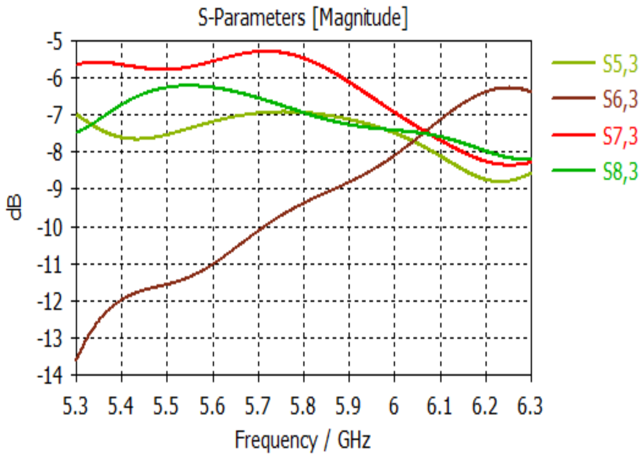

Fig. 9. Insertion loss of the Butler matrix for port 3.

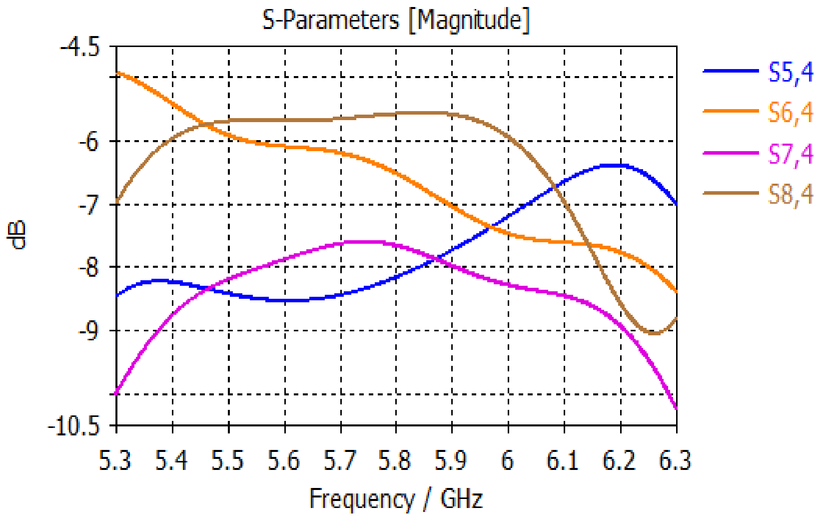

Fig. 10. Insertion loss of the Butler matrix for port 4.

3.2. Results of the antenna element

Figure 11 shows the return loss of the antenna element. The return loss of the antenna element is less than -10 dB at 5.8 GHz. The bandwidth of the antenna element is 47 MHz from 5.776 GHz to 5.823 GHz. The radiation patterns of the antenna element at plane of phi = 0° and phi = 90° are presented in Figs. 12 and 13, respectively. The results show an antenna gain of 8.27 dBi with good symmetry.

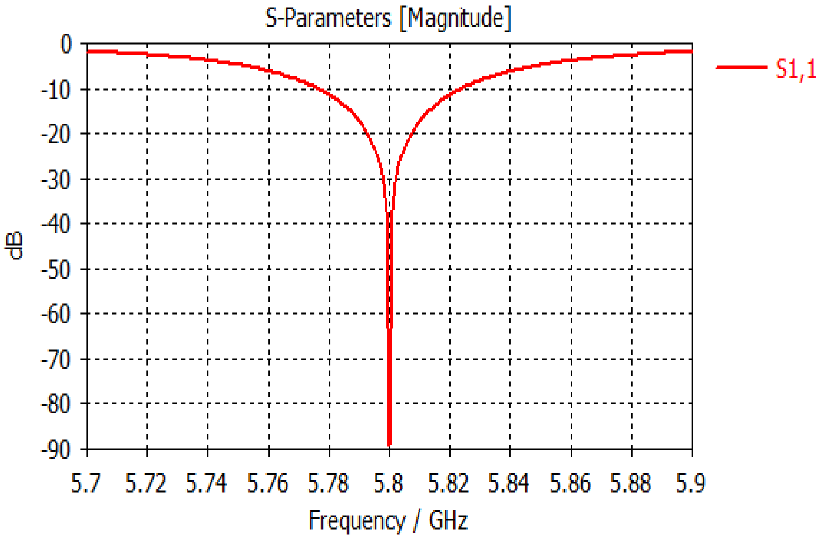

Fig. 11. Return loss of the antenna element.

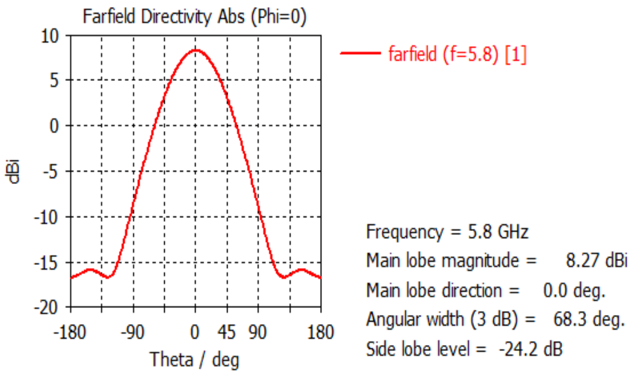

Fig. 12. Radiation pattern of single antenna element at Phi = 0°.

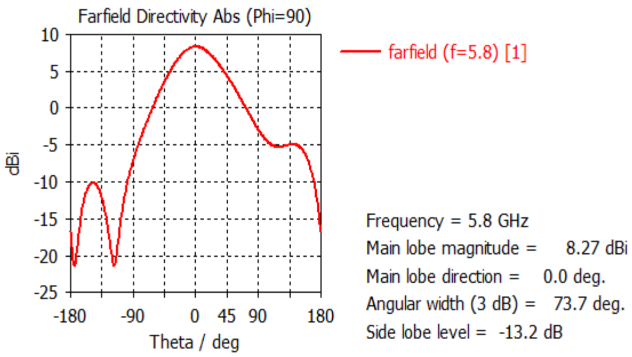

Fig. 13. Radiation pattern of single antenna element at Phi = 90°.

3.3. Results of the multibeam array antenna

Figures. 14 to 17 show the radiation patterns of the multibeam antenna for the input port at 5.8 GHz, respectively. The main beams are directed at ± 11° and ± 35°. As compared to the calculated results shown in Table 3, the main lobe direction has a phase error of ± 5°. These phase errors could be caused by conductor losses in the Butler matrix. The beam coverage of the designed multibeam array antenna is 70° and the antenna gains for the input ports of the multibeam array antenna are between 11.5 dBi to 12.3 dBi at 5.8 GHz.

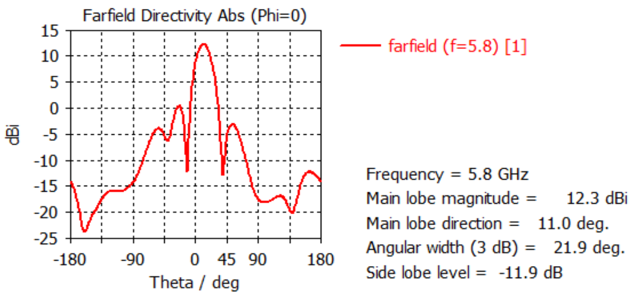

Fig. 14. Radiation pattern of the multibeam array antenna at 5.8 GHz when port 1 was excited.

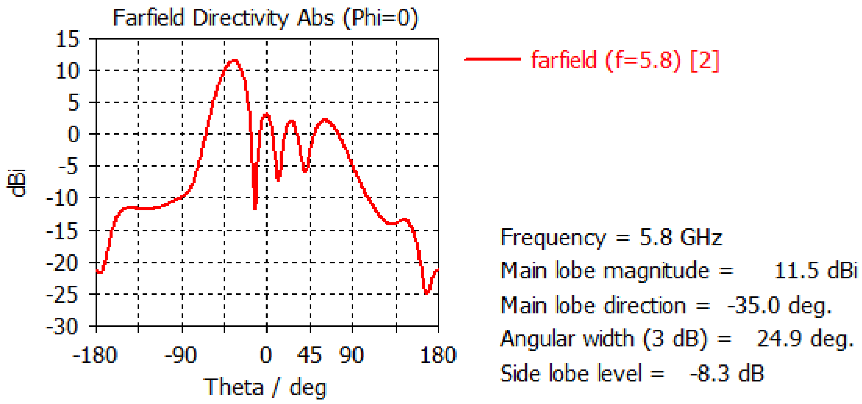

Fig. 15. Radiation pattern of the multibeam array antenna at 5.8 GHz when port 2 was excited.

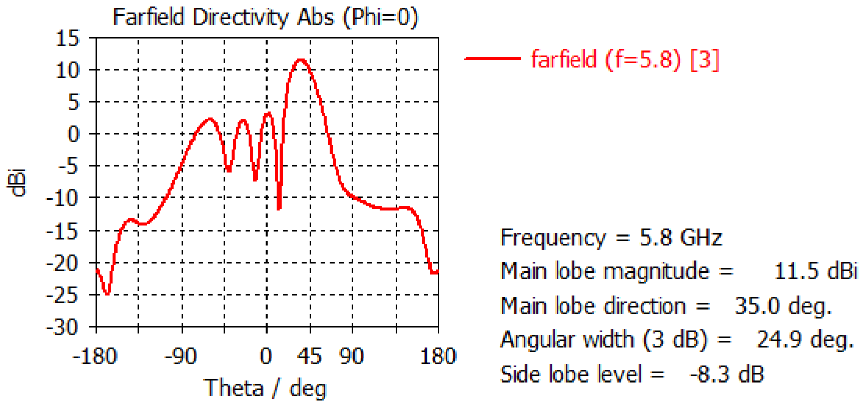

Fig. 16. Radiation pattern of the multibeam array antenna at 5.8 GHz when port 3 was excited.

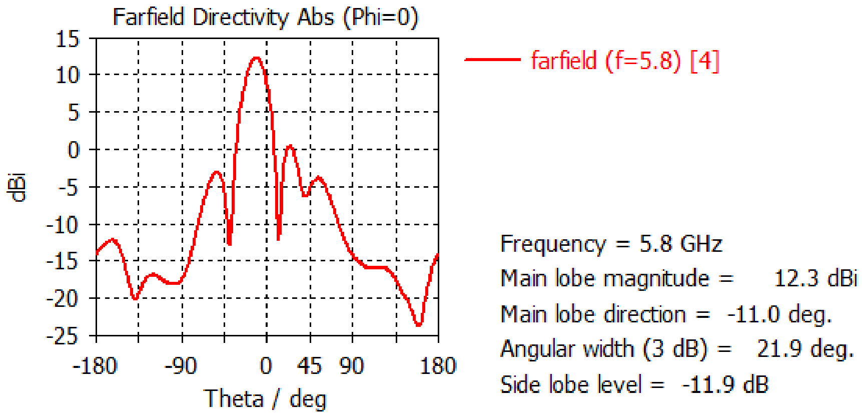

Fig. 17. Radiation pattern of the multibeam array antenna at 5.8 GHz when port 4 was excited.

4. Conclusions

In this paper, a single layer multibeam array antenna fed by a 4×4 Butler matrix at operating frequency of 5.8 GHz is presented. The size of the designed multibeam array antenna is 121 mm × 205 mm × 0.292 mm which is low profile and lightweight and it makes the designed antenna easy to be mounted on different types of UAVs. The multibeam array antenna is designed using a low dielectric constant and a low dissipation factor substrate material named NPC-F220A. At 5.8 GHz, the return losses are less than –10 dB and the insertion loss is –1.1 dB. The main lobe directions are ±11° and ±35°. The beam coverages of the multibeam array antenna are 70° and the antenna gains are between 11.5 dB and 12.3 dB Therefore, the designed multibeam array antenna in this work is adequate for UAV application.

Acknowledgement

This research was supported by Taylor's University, Malaysia through Taylor's Internal Research Grant Scheme - Impact Lab Grant (TIRGS-ILG/2/2024/SOE/002).

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