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Design and Implementation of a 1 × 4 Bow-Tie Antenna Array Integrated with a Butler Matrix for Switched-Beam ISM-Band Applications

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Wireless communication systems based on beamforming antennas encounter many design issues, including limited directional precision, complexity of implementation, and poor performance in regard to gain at small form factors. This paper presents an integrated 1 × 4 bowtie antenna array (AA) and a 4 × 4 Butler matrix (BM) to achieve effective beam-switching capabilities at the 2.45-GHz ISM frequency band. This integrated design enables four different beams to be generated corresponding to phase shifts of -135°, -45°, +45°, and +135°. The design of the 1 × 4 AA and matched 4 × 4 BM was initially validated using simulation and then further validated by prototyping and measuring the performance of the same configuration. When comparing the results from simulation and measurement, a strong similarity was realised between the two. In addition, the antenna array provided approximately 150 MHz of impedance bandwidth and a voltage standing wave ratio (VSWR) of ≤ 2 and a 23 dB reflection coefficient at the centre frequency of 27. The results of the comparative analysis of the antenna arrays constructed from FR4, PTFE, RT5880, and RO4350B showed the impact of the dielectric properties and thickness on gain performance. The antenna array fabricated with FR4 (1.60 mm) produced a measured gain of 8.71 dBi and a theoretical gain of 9.07 dBi and an elevation and azimuth beam width of 25.5° and 250°, respectively. These experimental results conclusively demonstrate that this integrated system provides stable, low-cost, and effective beam-switching performance that can be utilised in current wireless communications systems.

Keywords: Bow-Tie antenna, Butler matrix, Switched-beam antenna, Antenna array, Beam steering, ISM band

1 Introduction

Today's modern wireless communication would not be nearly as effective or reliable without smart antenna systems, which can both improve link reliability and coverage while reducing interference in highly congested radio-frequency environments. Antenna arrays offer more degrees of freedom than conventional single-element antennas, providing increased gains, spatial selectivity, and directional beam control, all of which are highly desirable in WLAN, IoT and ISM-band applications. Switched beam and beamforming antenna techniques are of particular interest, which are widely used for increasing system capacity and coverage without requiring higher transmission power levels. Butler matrices are one of the most common types of passive beamforming networks used to produce several fixed beams from an antenna array. The Butler matrix utilises hybrid couplers, phase shifters, and crossovers to excite different elements of the array with predetermined phased patterns, allowing users to change paths through the use of different input ports. Initial work on Butler matrices was conducted[1]; their initial theoretical and experimental research laid the foundation for systematic analysis and design improvements[2]. Due to their simple design, compact construction, and stable beamforming performance, Butler matrices have been widely used in multi-beam arrays[3]. Experiments have shown that Butler matrix-fed arrays work well for both small wireless systems and applications that need a lot of directivities. Multi-beam antenna configurations utilising Butler matrix networks have been experimentally evaluated to improve coverage and gain performance in practical communications systems[4].

Additionally, various planar microstrip implementations of the Butler matrix have been presented to provide a reduced size and manufacturability with acceptable performance[5]. As demand for lightweight, compact antenna systems

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continues to increase, there remains active research into integrating beamforming networks with planar radiators[6]. Of the many types of planar antennas, the bow tie antenna is a very practical option because of its small form factor, wide bandwidth, and consistent radiating characteristics. The use of bowtie-based antenna designs is very common in wireless applications due to their broadband impedance response and ease of construction[7]. In addition, the use of bow-tie antenna configurations and their variants have been shown to enhance a radiating antenna's characteristics and improve their gain performance[8]. Several experimental investigations have also looked at modified and self-complementary bow tie antennas for broadband and ultra-broadband applications to improve impedance matching and stabilise radiating patterns[9].

However, because bowtie antennas have been shown to be very sensitive to the design of their feed networks, material properties and manufacturing constraints when implemented in array configurations, performance issues can easily arise during their manufacture. Previous experimental work has shown that substrate-relative permittivity, substrate thickness and substrate loss substantially affect resonance stability, impedance matching, gain and radiation performance in planar arrays[10]. Additionally, the beamforming network (i.e., Butler matrix) can impose limits on both phase balance and insertion loss, thus adversely affecting both the accuracy of beam steering as well as the maximum possible gain obtained from the antenna array[11]. Thus, potential designers of reliable, efficacious switched beam antenna systems must perform a systematic evaluation of the effects of substrate variations in their designs[12].

This research presents a compact bow-tie antenna array (1x4) that was integrated with a 4x4 Butler matrix and designed for operation at 2.45 GHz within the ISM frequency band. The geometry of the bow-tie antenna element is illustrated in Fig. 1. The bowtie

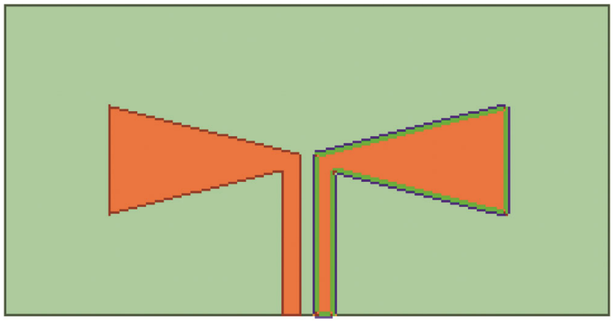

Fig. 1 — Single-element bow-tie antenna

antenna array was modelled and optimised using CST Microwave Studio and then fabricated and experimentally validated. A systematic comparison of various combinations of substrate materials (FR4, PTFE, RT5880, and RO4350B) and four thicknesses (0.25 mm, 0.5 mm, 0.8 mm and 1.6 mm) has b een carried out to determine their effects on gain, beam tilt and beam width. The results indicate that the combined use of the integrated bow-tie antenna array and the Butler matrix feed will produce an efficient and compact solution for switchable high-gain beam wireless systems.

While previous research has been conducted on bow-tie antennas and Butler matrix beamforming networks as stand-alone devices, little information was available regarding integrating bow-tie arrays and Butler matrix feeds with a systematic study of the effect of substrate materials and thicknesses on beam formation and gain. As a result, this paper includes an experimental validation of a bow-tie antenna array (1x4) integrated with a Butler Matrix (4x4) operating at a frequency of 2.45 GHz in the ISM frequency band as well as a comprehensive comparison of various substrate materials (FR4, PTFE, RT5880 and RO4350B) at different thicknesses to determine how they affect gain, beam tilt angle and beam width performance. Such information is useful for designing compact switched-beam antenna systems for WLAN and ISM band wireless applications.

2 Literature Review

Beam steering and multi-beam antennas have become quite popular due to the benefits that they can provide in today's wireless communication systems: improved coverage, suppression of interference, and link reliability. One of the predominant beamforming techniques is the use of passive feed networks, which offer advantages such as ease of use, cost effectiveness and stable radiation characteristics. Research is being conducted on beamforming arrays and multiport antenna systems to develop multiple fixed beams for real-world wireless environments[13]. Some of these studies indicate that switching networks using fixed beams provides reliable beam steering at substantially less computational effort than methods based on adaptive beamforming. Interest in Butler matrix-based beamforming networks is increasing due to their ability to provide many different phase outputs with good isolation and compact planar implementations.

Various design techniques have been researched to optimise design parameters such as phase accuracy, insertion loss and compatibility with fabrication processes. In addition, researchers are studying the fabrication of compact Butler matrix networks for use with microstrip antenna arrays. These studies will optimise design aspects of the networks to produce a consistent phase progression and low return loss over the desired operating frequency range, while also demonstrating the use of Butler matrix feeds to enhance the directivity of the array and improve multi-beam operation[14]. At the same time, planar antennas such as bow-tie radiators are being researched for broadband and compact antenna design applications. Bow-tie antennas are noted for their wide frequency range of impedance bandwidth, conformability to manufacturing processes, and ability to be manufactured as printed circuit boards. Researchers have performed tests on modified versions of bow-tie structures to provide greater radiation characteristics and to facilitate the incorporation of bow-ties into array structures that yield improved performance[15,16]. Some researchers have also tested self-complementary/geometry-optimised designs of bow-tie antennas, producing antennas that maintain a uniform response over a wide frequency range while also enhancing matching[17,18].

While some of the above studies have occurred for Butler matrix-based beamforming networks or bow-tie antenna systems independently, relatively few studies have been performed evaluating as a unified integrated system bow-tie antenna arrays with Butler matrices while conducting a comparative assessment of the benefits produced by testing multiple materials and thickness levels. Prior studies indicate that substrate characteristics (i.e., relative permittivity, thickness and dielectric loss) have a significant influence on the antenna's impedance match, gain and beamwidth[19].

Additionally, the amount of insertion loss and degradation of phase balance within the feed network will influence the overall accuracy of the multi-beam arrays with regards to beam steering and gain. For these reasons, it is important to perform experiments validating the performance of an integrated switched-beam antenna system that utilises a bow-tie radiating array and a Butler matrix feed network while assessing the effect of varying materials/substitutes and thicknesses on gain and beam steering performance[20].

Therefore, this study is motivated by the above research gaps, will demonstrate experimental validation of a 1x4 bow-tie array with a 4x4 Butler matrix for use in the 2.45 GHz ISM band, and evaluate the gain and beam properties under realistic fabrication conditions using multiple substrates and thicknesses. There continue to be studies performed addressing compact antennas which utilise beamforming arrays and Butler matrix-based feeding networks for wireless communication applications. Reports indicate that researchers have realised improved beam steering as well as increased gain with planar antenna arrays operating within ISM and WLAN bands of frequency[21].

To further substantiate the impact of the proposed antenna system, a comparison of the proposed design with prior reporting of bow-tie and Butler matrix-based beamforming arrays is developed in Table 1. This table will outline not only the frequency and configuration, but also the beam steering capabilities and gain for each antenna array. The results illustrated in the comparison will demonstrate that the proposed design has comparable gain performance to the previous designs, while providing for switched-beam capability through a compact Butler matrix feeding network[22-25].

3 Design and Fabrication

The proposed antenna system provides an interchangeable beam system through a well-organised, formalised design process of three major components: (i) optimisation of a single bow-tie radiator at 2.45 GHz, (ii) development of a 1 × 4 linear array which produces an improvement in gain from the previously optimised radiator and (iii) a complete build-out of the array (4 × 4 Butler

Table 1 — Comparison of the proposed antenna with previously reported bow-tie and beamforming antennas

Reference	Antenna Type	Frequency	Array Size	Beam Steering	Gain
[16]	Bow-tie antenna	2.4 GHz	Single	No	~6.5 dBi
[17]	Modified bow-tie antenna	2.45 GHz	Single	No	~6.8 dBi
[18]	Bow-tie array	2.4 GHz	1×4	Limited	~7.8 dBi
[19]	Butler matrix array	2.45 GHz	1×4	Yes	~8.2 dBi
Ours	Bow-tie array + Butler matrix	2.45 GHz	1×4	Yes	9.07 dBi

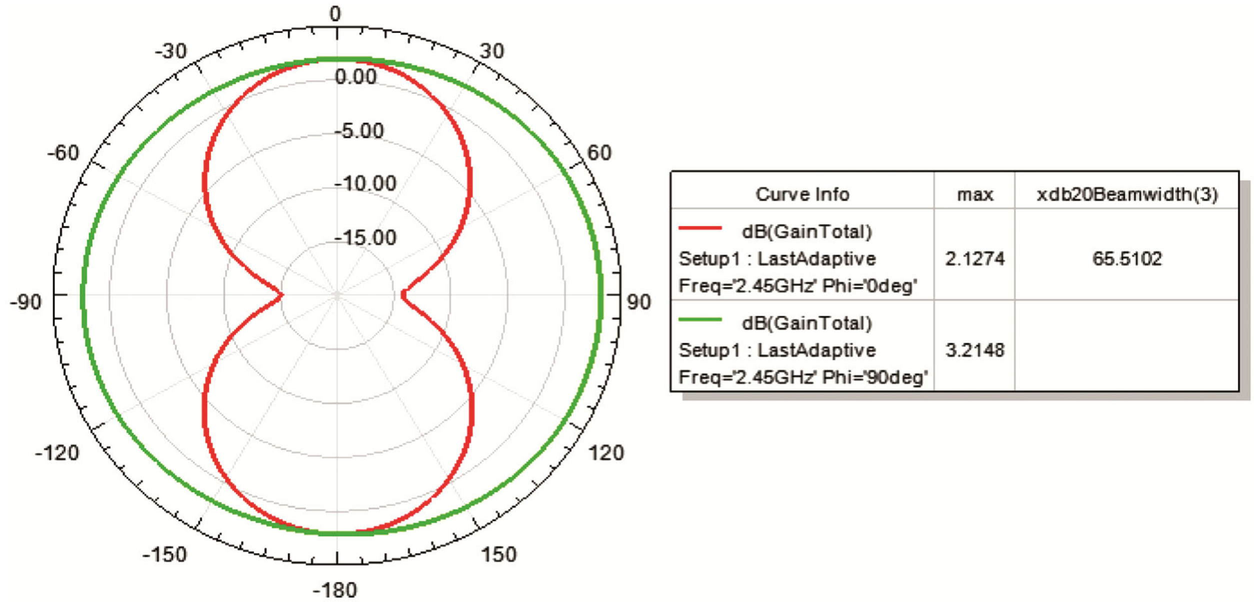

Fig. 2 — 2D radiation pattern of single-element bow-tie antenna

matrix) to create passive steered multi-beams. All components, including the antenna and feed system, have ultimately been designed and optimised using CST Microwave Studio, and the final designs will be fabricated and experimentally tested.

3.1 Single-Element Bow-Tie Antenna Design

The single-element bowtie antenna will be designed to have reliable power transfer and radiation patterns at approximately 2.45 GHz. The bowtie antenna will be used due to its flat nature, small size, and ability to be efficiently manufactured on printed circuit boards. The design will include an appropriate feedline for 50 Ω matching, and the geometrical dimensions will be optimised using full-wave bistatic numerical simulation to achieve the desired resonance within the ISM band. The simulation results showed a stable and reliable radiation pattern for the optimised bow-tie antenna as shown in Fig. 2. This design allows for potential expansion into an array configuration.

3.2 1x4 Bow-Tie Linear Array Configuration

As an enhancement of the gain and directivity of the optimised bow-tie elements, the array is constructed with four linear antenna elements (1×4 array). This arrangement is illustrated in Fig. 3 with each antenna element spaced in a linear direction. In linear array systems, the distance between the successive elements greatly affects the mutual coupling, side lobe levels, and maximum directivity achievable. In this project, the spacing of the adjacent

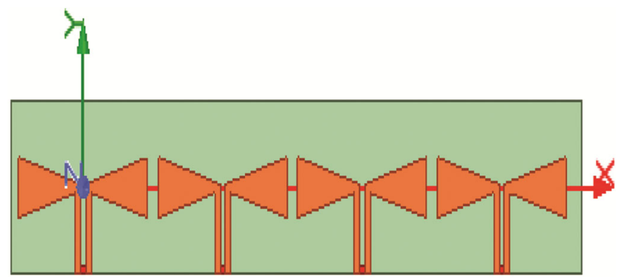

Fig. 3 — Four-element bow-tie arrangement (1×4 linear array configuration)

bow-tie elements was primarily based on wavelength to create the best-performing antenna array while minimising coupling effects. The optimisation of the array geometry was performed in CST to provide improved forward radiation and stable beam characteristics when operated.

Selection of inter-element spacing for the proposed 1 × 4 bow-tie array was based on wavelength and practical beam-forming requirements. Based on the designed array geometry, the centre-to-centre spacing between adjacent elements is $d = 73.44$ mm. The free-space wavelength at the operating frequency of 2.45 GHz is $\lambda_0 = 122.45$, thus:

$$\frac{d}{\lambda_0} = \frac{73.44}{122.45} \approx 0.60 \qquad \dots (1)$$

The selected spacing is approximately $0.60\lambda_0$. The value was chosen as a compromise between improving gain, reducing mutual coupling, controlling sidelobes, and maintaining beam overlap. While very close spacing increases mutual coupling and may affect impedance and the radiation pattern, large inter-element spacing yields higher side lobes or grating lobes while steering beams. Therefore, the chosen spacing of $0.60\lambda_0$ offers enough distance to provide acceptable separation between the bow-tie elements while preserving stable switched-beam radiation for use within the ISM-band operating range.

3.3 Array Factor Analysis of the Linear Antenna Array

The beam-switching behaviour of the proposed 1 × 4 bow-tie antenna array can be analytically explained using the array factor of a uniform linear array. For the theoretical formulation, the four bow-tie radiating elements are assumed to be identical, equally spaced, and excited with approximately equal amplitudes through the Butler matrix feed network. The elements are arranged along the linear array axis with an inter-element spacing d. The far-field observation angle θ is measured with respect to the broadside direction of the array. In the ideal array factor formulation, the individual element radiation pattern, mutual coupling, substrate loss, and fabrication tolerances are not included. Therefore, the total radiation pattern may be interpreted as the product of the single-element radiation pattern and the array factor.

For a uniform linear array with Nelements, the general array factor is expressed as;

$$AF(\theta) = \sum_{n=0}^{N-1} a_n e^{j\,n\,\psi} \qquad \dots (2)$$

Here, $\psi = k_0 d\sin\,\theta + \beta$ and $a_n$is the excitation amplitude of the n^{th}element, $k_0 = 2\pi/\lambda_0$is the free-space wave number, λ_0 is the free-space wavelength at the operating frequency, d is the spacing between two adjacent array elements, and β is the progressive phase shift between adjacent elements.

For the proposed 1 × 4 bow-tie antenna array, $N = 4$. Since the Butler matrix is designed to divide the input power nearly equally among the four output ports, the excitation amplitudes can be considered uniform;

$$a_0 = a_1 = a_2 = a_3 = 1 \qquad \dots (3)$$

Therefore, the array factor of the proposed four-element linear array becomes;

$$AF(\theta) = 1 + e^{j\psi} + e^{j2\psi} + e^{j3\psi} \qquad \dots (4)$$

The closed-form expression is;

$$AF(\theta) = e^{j\frac{3\psi}{2}} \frac{\sin(2\psi)}{\sin\left(\frac{\psi}{2}\right)} \qquad \dots (5)$$

Thus, the normalized magnitude of the array factor is;

$$\left|AF_{n(\theta)}\right| = \frac{1}{4}\left|\frac{\sin(2\psi)}{\sin\left(\frac{\psi}{2}\right)}\right| \qquad \dots (6)$$

The main beam direction occurs when the phase terms from adjacent elements combine constructively. Therefore;

$$\psi = k_0 d\ sin\theta_0 + \beta = 0 \qquad \dots (7)$$

Hence, the beam angle can be predicted as;

$$\theta_0 = \sin^{-1}\left(-\frac{\beta\,\lambda_0}{2\pi d}\right) \qquad \dots (8)$$

At the operating frequency of 2.45 GHz, the free-space wavelength is;

$$\lambda_0 = \frac{c}{f} = \frac{3\times10^8}{2.45\times10^9} = 122.45\ mm \qquad \dots (9)$$

From the designed 1 × 4 array geometry, the adjacent bow-tie element spacing is;

$$d = 73.44\ mm \qquad \dots (10)$$

Therefore,

$$d \approx 0.60\lambda_0 \qquad \dots (11)$$

Substituting $d = 0.60\lambda_0$into Eq. (7), the simplified beam-angle prediction becomes;

$$\theta_0 = \sin^{-1}\left(-\frac{\beta}{1.20\pi}\right) \qquad \dots (12)$$

where βmust be expressed in radians. Equivalently, if $\beta$is expressed in degrees;

$$\theta_0 = \sin^{-1}\left(-\frac{\beta}{216^\circ}\right) \qquad \dots (13)$$

The ideal excitation vector for the four-element array can be written as;

$$\left[1, e^{j\beta}, e^{j2\beta}, e^{j3\beta}\right] \qquad \dots (14)$$

This means that each selected input port of the Butler matrix excites the four antenna elements with equal amplitude but with a different progressive phase shift. These different phase progressions cause constructive interference in different angular directions, resulting in switched-beam operation.

The ideal beam directions predicted using the array factor for $d = 0.60\lambda_0$are shown in Table 2.

The ideal beam direction, as provided by array response, assumes that all elements are excited with equal amplitudes and that all of the element types are identical. However, many of the beam directions that are observed when measuring the real-world fabricated antennas deviate from those ideal values

Table 2 — Ideal beam-angle prediction for the proposed 1 × 4 array using $d = 0.60\lambda_0$

Progressive phase shift, β	β in radians	Ideal beam angle, θ_0
$-135°$	$-3\pi/4$	$+38.7°$
$-45°$	$-\pi/4$	$+12.0°$
$+45°$	$+\pi/4$	$-12.0°$
$+135°$	$+3\pi/4$	$-38.7°$

due to each bowed tie element's directional radiating pattern, mutual coupling between neighbouring elements, considerations for the finite dimensions of the ground and dielectric media, losses in the connectors or other components due to dielectric phenomena, tolerances in the fabrication of the elements, and the different amounts of phase or amplitude imbalance present in the Butler matrix. The formulation provides proof of the principle by which the proposed antenna can implement beam steering; by varying the progressive phase shift β via the Butler matrix, the primary direction of the radiating beam is shifted to different directions in space.

The proposed Butler matrix fed array has a beam-steering mechanism that is defined by the array factor formulation. The physical distance between adjacent antenna elements creates a spatial phase difference characterised by the expression $k_0 d\sin\theta$. The perpendicular beam positions relative to this value define the electrical phase difference caused by the input ports of the Butler Matrix, which generates either a '+' or '-' electrical phase shift for each port and determines how the additional phase shifts from space combine with the previously calculated phase shift values, ultimately leading to either cancellation or addition. Therefore, modifying the Butler Matrix operating from various input ports shifts the angle at which constructive interference occurs, resulting in switched-beam radiation.

3.4 4×4 Butler Matrix Feed Network Design

The proposed design for the beamforming network would allow for the creation of 1x4 bow-tie antenna arrays by using the 4x4 Butler matrix beam former as a passive beamforming network. This will enable the bow-ties to be excited with equal-amplitude signals, with different phase shifts, depending on the selected input port. As such, the beam former would produce a certain phase distribution, which could then be connected to the output ports of the Butler matrix beam former to create a switchable beam antenna system without the use of active phase shifters.

As seen in Fig. 4, the layout of the 4×4 Butler matrix for beamforming includes 3-dB hybrid couplers and

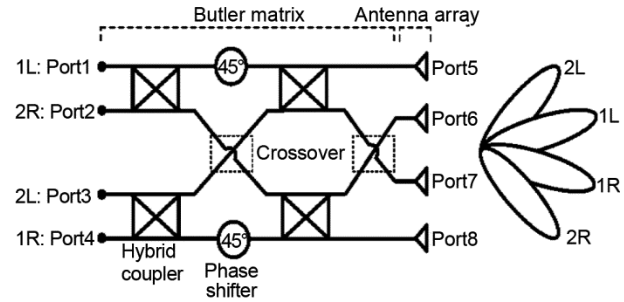

Fig. 4 — Layout of the 4 × 4 Butler matrix beamforming network

fixed phase shifter sections. The 3-dB hybrid couplers split the incoming signal in half and allow for two output signals (one 90° out of phase with the other). The fixed phase shifter sections produce a certain amount of phase shift necessary to create the desired phase distribution at the output ports. The crossover sections of the transmission lines allow for the signals to cross within the same compact planar area without providing any isolation between the lines.

When there is a single active input port, and all remaining ports are terminated with 50 Ω loads, power from the active port will be ideally split evenly among the four output ports. Therefore, the ideal transmission loss from the active input port to each of the output ports would be approximately.

$$20\log\_10(1/\sqrt{4}) = -6.02\ dB \quad \ldots (15)$$

The significance of this uniform power splitting is that the re-emitters (bow-tie elements) will all be powered evenly (i.e., have similar currents). The direction of the beam will primarily be determined by the progressive phase shift between adjacent output ports. The ideal excitation to the four elements of the antenna will be given by the following vector:

$$V = \left[1, e^{j\beta}, e^{j2\beta}, e^{j3\beta}\right] \quad \ldots (16)$$

where β represents the phase difference between two adjacent elements of the antenna. The direction of the beam for an array with an approximate spacing of $d \approx 0.60\lambda_0$ can be found using the Eq. (13).

Table 3 shows the theoretical output-phase relationship for each input of a 4×4 Butler matrix-fed antenna array.

Table 3 has shown the phase adjustments of how a Butler matrix creates four fixed beams. The first part of the table states that since the main beam will point positively when using a negative progressive phase shift, it will therefore point negatively with a positive progressive phase shift. The predicted beam directions are idealised and based on the array-factor model, while the measured beam directions of an actual Butler Matrix antenna array will differ from theoretical predictions due to many physical factors affecting performance: mutual coupling, the directivity of the bow-tie elements, limited substrate size, dielectric losses, connector effects, fabrication tolerances, and amplitude/phase imbalances within the Butler Matrix.

In addition, the 3 dB hybrid couplers, fixed phase shifters, and crossover sections on the schematic in Fig. 4 are designed to provide equal amplitudes of signals while generating controlled progressive phase shifts. This shows that the Butler matrix acts like a passive beamforming network from a design aspect and produces the proper phase arrangement needed for switched beam operation of a proposed 1 x 4 bow-tie antenna array.

3.5 Butler Matrix S-Parameter Analysis

The expected performance behaviour of the Butler matrix feed network is summarised in Table 4.

S-parameter analysis was used to determine the performance of the Butler matrix's feed network, particularly the power distribution and impedance matching. The S-parameters of the designed 4×4 Butler matrix at an operating frequency of 2.45 GHz were simulated. The results indicate that the return loss from the input ports is greater than -10 dB at the operating frequency, which indicates that the feed network has excellent impedance matching. When port 1 is excited, the output ports have nearly the same power distribution, with transmission coefficients of about -6 dB.

This result indicates that the Butler matrix can divide the input signal into several output signals, which is desirable because the array elements must be excited with an input signal of nearly equal amplitude. The fact that the Butler matrix will distribute the power equally among the array elements will ensure that all the elements are excited with equal power, while the phase shifts produced by the matrix will steer the radiation beam towards various spatial points, depending on which port receives the input signal. The analysis demonstrates that this design of the Butler matrix is suitable for the applications of switched-beam antenna arrays that use the 2.45 GHz ISM band.

3.6 Phase Distribution of the Butler Matrix

The phase distribution obtained from the 4×4 Butler matrix output ports is presented in Table 5.

The beam steering characteristics of the antenna array are greatly impacted not only by the amplitude balance but also by the phase characteristics of the Butler matrix. To verify that the Butler matrix produces progressive phase shifts as expected, the phase response of the transmission coefficients from each output port was analysed. The corresponding phase measurements indicate the network produces phases of approximately -135°, -45°, +45° and +135° across the output ports.

These progressive phase shifts play a critical role in generating multiple fixed beams in various spatial directions. By exciting the antenna array elements via the Butler matrix with these specific progressive phase differences, constructive interference occurs in particular angular locations, while destructive interference occurs in other locations, thereby enabling beam steering. Thus, the simulated performance of the phase shift characteristics of the designed Butler matrix substantiates that the device is capable of producing the required phase progression, which is necessary for the operation of a switched-beam antenna array.

3.7 Integrated Array with Butler Matrix

The complete integrated antenna system consists of the individually optimised bow-tie element, full-dimension array geometry in 1 x 4 array form, and Butler matrix network. The integrated bow-tie array design using a Butler matrix is depicted in Fig. 5, where the output ports of the Butler matrix elements with the appropriate phase difference relationships. The

Table 3 — Theoretical phase progression and predicted beam direction of the Butler matrix-fed 1 × 4 array

Excited input port	Progressive phase shift β	Ideal output phase excitation across antenna elements	Predicted beam direction θ_0
Port 1	$-45°$	$0°, -45°, -90°, -135°$	$+12.0°$
Port 2	$+135°$	$0°, +135°, +270°, +405°$	$-38.7°$
Port 3	$-135°$	$0°, -135°, -270°, -405°$	$+38.7°$
Port 4	$+45°$	$0°, +45°, +90°, +135°$	$-12.0°$

Table 4 — Typical Butler matrix behaviour

Parameter	Expected Value
Return loss	< -10 dB
Output amplitude	≈ -6 dB each
Phase difference	−135°, −45°, +45°, +135°

Table 5 — Phase distribution of the 4×4 Butler matrix output ports

Output Port	Phase
Port 1	−135°
Port 2	−45°
Port 3	+45°
Port 4	+135°

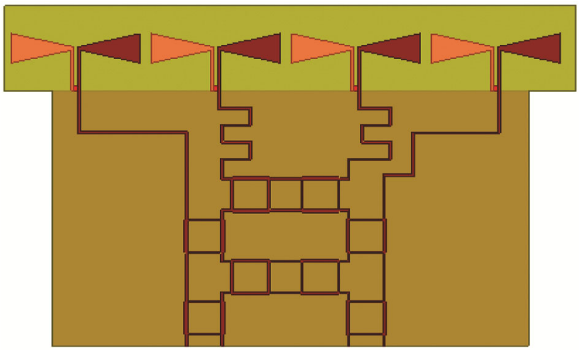

Fig. 5 — Integrated 1 × 4 bow-tie antenna arrays with Butler matrix feeding network

alternating input excitation at the Butler matrix will change the phase distribution between the four elements within the array and result in a new main beam direction. Therefore, the integration of this antenna system provides an efficient, compact solution for passive beam steering for ISM frequency systems.

3.8 Substrate Materials and Thickness Study

In order to evaluate the effects of substrate characteristics on the performance of antennas, a number of different substrates (FR4, PTFE, RT5880 & RO4350B) as well as their thicknesses (0.25 mm, 0.5 mm, 0.8 mm & 1.6 mm) were tested to find out if the dielectric properties of the substrates affect the gain and beam width of the antennas. The relative dielectric constant, along with the loss tangent, is both a very important electrical parameter, as they directly affect how antennas will radiate energy, as well as how wide or narrow the pattern of the radiation will be. Each substrate at each of the four different thicknesses was compared to all the others based on both simulation and experimental results.

4 Results and Discussion

The characterisation of the proposed 1 × 4 bow tie antenna array with an integrated 4 × 4 Butler matrix (operating at 2.45 GHz) is presented in this section with both simulation and experimental results. The characteristics measured are impedance characteristics (S11 & VSWR), radiation patterns, beam switching ability to each of the 4 ports, and the effects of substrate material type & thickness on both directivity and beam characteristics.

4.1 Impedance Matching Performance of the 1 × 4 Bow-Tie Array

In order to determine whether the impedance of this four-element bow-tie array does indeed achieve

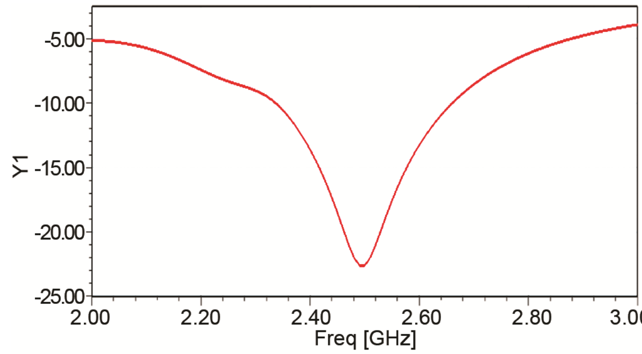

Fig. 6 — Reflection coefficient (S11) of the four-element bow-tie antenna array

resonance within the frequencies specified for operation at 2.45 GHz (the target frequency within the ISM band), a simulation was conducted to evaluate the S11 characteristics of the proposed four-element bow-tie array, which is illustrated in Fig. 6. From the results of this evaluation, it is obvious that the four-element array design has developed resonances at approximately 2.45 GHz (which corresponds to acceptable levels of impedance matching for use as wireless communication devices in the ISM frequency band) and demonstrates comparable levels of impedance matching when comparing results from the four-element design against those obtained from the single-element design. Based on these measurements, the components of mutual coupling between the adjacent antenna elements and the influence of the feeding network altered the resonances and improved the return losses obtained from the use of the proposed four-element bow-tie array design; however, despite these two (2) electrical phenomena occurring in the proposed four-element array configuration, the four-element bow-tie array is still able to maintain an acceptable level of stability with regard to resonance and impedance performance throughout the entire ISM frequency band.

The S11 Graph indicates that the Bow-Tie Array with Four Elements will resonate near its designed 2.45 GHz frequency in the ISM band. The reflection coefficient is below -10 dB (an acceptable level of reflection) throughout the operation band, indicating that power is efficiently being transferred from the feed network to the radiating elements. The small difference in resonance when compared to the single-element bow-tie array case is due to the mutual coupling between adjacent elements and a change to the current distribution created by the bow-tie array configuration.

4.2 Radiation Characteristics of the 1 × 4 Bow-Tie Array

The achievement of meeting the anticipated impedance characteristics leads to an examination of the radiated energy characteristics of the combined elements (array) to determine if there is any increase in gain or directivity gain due to constructing the radiator with multiple elements rather than using a single element. The two-dimensional radiation patterns of the simulated bow-tie array (4 total elements) are shown in Fig. 7. The array configuration provides increased directivity compared to that of the single element radiator, confirming the effectiveness of using multiple elements in combination, rather than one element alone, to achieve increased gain.

The 1 × 4 array produces an improved directional radiation pattern in comparison to a single bowtie element, according to the radiation pattern in Fig. 7. The main lobe of this array is more tightly clustered because of the constructive combination of the fields from the four elements in the appropriate direction. As shown in the radiation pattern, the spacing between the selected elements provides adequate symmetry in the beam without causing excessive growth of the sidelobes.

4.3 Radiation Performance with Butler Matrix Feed Network (Beam Switching)

A 4 x 4 Butler matrix is used to switch the energy into a 1 x 4 bow-tie array (changing the calibration of antennas), enabling beam switching by providing different phase angles to the elements of the bow-tie array, causing the signal to be available in different directions at the antenna's output. These results are illustrated in Fig. 8. The radiation patterns of the total system (bow-tie array with Butler matrix feed) show how the direction of the main lobe of radiation (beam) will change for radiation from the bow-tie array by different input ports of the Butler matrix. This result confirms that the antenna system can switch the beam direction by simply changing the input to the Butler matrix. Thus, the Butler matrix-fed array will provide multi-beam coverage without needing active phase shifters; therefore, it is a compact, cost-efficient means of producing a beamforming system.

The beam-switching property of the Butler matrix-fed array was demonstrated in Fig. 8. The change of the main beam location with respect to which input port is excited, thereby validating that the Butler matrix is able to provide the necessary progressive phase distribution to the antenna elements. The beam direction that was observed correlates well with the array factor prediction; however, there is some minor asymmetry as well as variation in the side lobes, primarily due to mutual coupling effects as well as the finite size of the substrate and practical phase balance error in the feed network.

4.4 Port-wise S11 Characteristics (FR4, 1.6 mm Case Study)

To qualitatively validate the real-life port reaction, the response of the reflection coefficient from all four

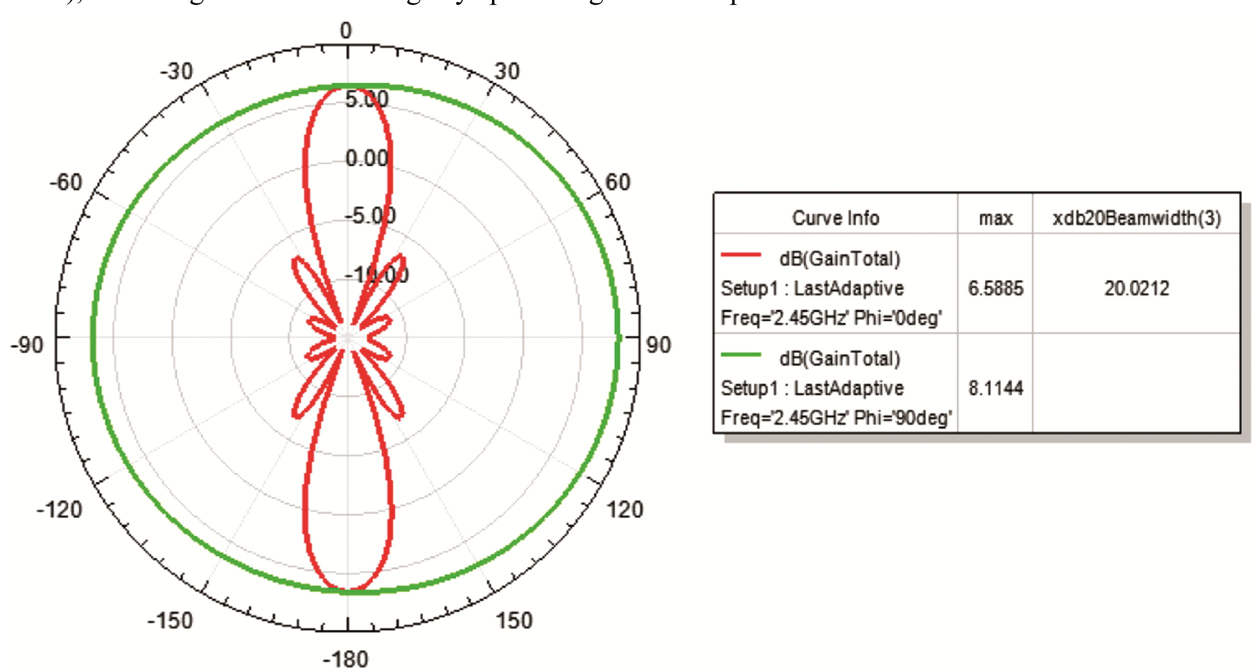

Fig. 7 — 2D Radiation pattern of the four-element bow-tie antenna array

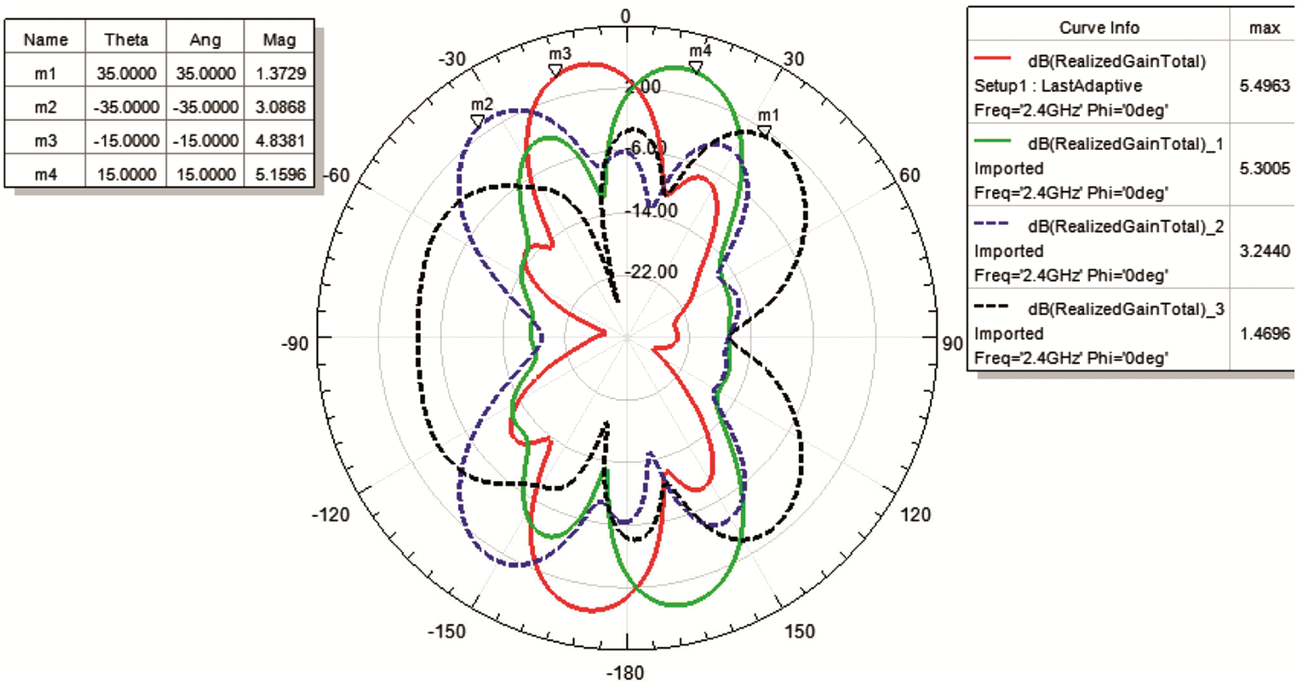

Fig. 8 — 2D radiation pattern of 1 × 4 bow-tie array with Butler matrix feed (beam switching)

input ports has been evaluated. The reflection coefficient response from each of the four ports (S11) is shown in Fig. 9 to have been matched with a longitudinal FR4 (1.6 mm thick) substrate. As indicated by the S11 curves, there are resonant peaks present in all ports at an appropriate match impedance using the frequency of operation of the ISM band, demonstrating that the Butler network supports excitation characteristics for all four ports and will therefore provide a reliable switched beam operation at stabilised steady-state conditions.

As illustrated in Fig. 9, the S11 port-wise impedance curves indicate that all four ports provide adequate impedance matching around 2.45 GHz. This provides evidence that the Butler matrix and the antenna array have been well matched for multi-port excitation. Differences between the four curves were anticipated, since each port will see a slightly different signal path via hybrid couplers, phase shifters, and crossover sections.

4.5 VSWR Analysis for All Ports (FR4, 1.6 mm Case Study)

The evaluation of matching performance through S11 in addition to VSWR is a useful indicator of how well an antenna can be matched up with the transmitter and receiver, as well as the bandwidth available. The VSWR response for ports 1-4 was measured on an FR4 substrate having a thickness of 1.6 mm; the results can be seen in Fig. 10.

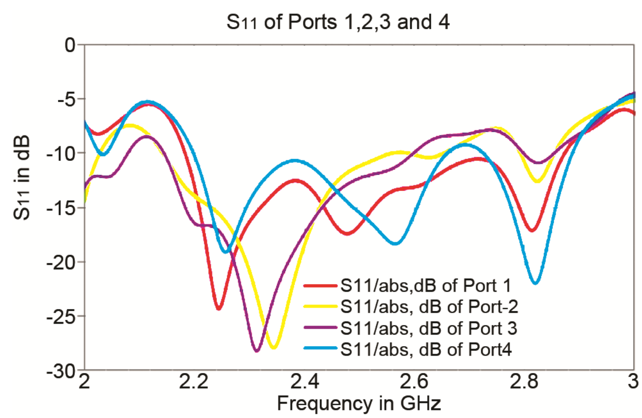

Fig. 9 — Reflection coefficient (S11) of Port 1, Port 2, Port 3, and Port 4 (FR4, 1.6 mm)

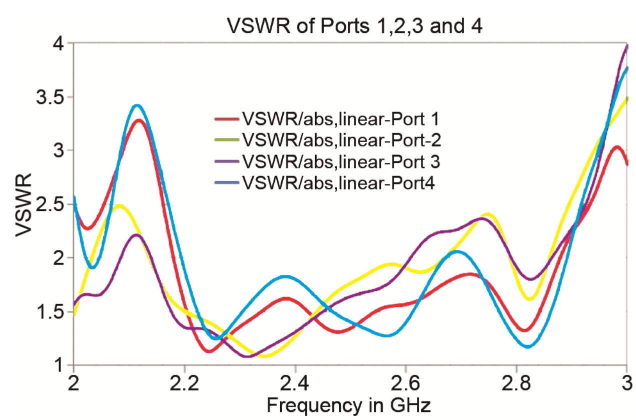

Fig. 10 — VSWR of Port 1, Port 2, Port 3, and Port 4 (FR4, 1.6 mm)

The VSWR values were acceptable around the desired operating frequency, indicating stable operation is possible for ISM band communication systems.

The VSWR response from each of the four ports listed in Fig. 10 shows acceptable operating conditions around 2.45 GHz. This also confirms the S11 results, giving evidence that the proposed structure is capable of operating with minimal mismatch loss. The differences between the ports in VSWR are primarily attributed to differences in the physical layout asymmetry, the effect of connectors used in the circuit, or varying amounts of electrical path lengths through the Butler matrix connecting the four ports.

4.6 Comparative Performance Across Substrates and Thickness Variations

The paper demonstrates how different types of substrates and substrate thicknesses can affect the performance characteristics of the proposed system. It also demonstrates how the thicknesses, in turn, can influence the overall gain of the antenna system. The substrates were tested as follows: FR4, PTFE, RT5880, and RO4350B. The thicknesses of each of these substrates were as follows: 0.25 mm, 0.5 mm, 0.8 mm, and 1.6 mm. The maximum gain values obtained for different substrate materials and thicknesses are summarised in Table 6.

From our comparative measurements, it is evident that the type of substrate material combination and substrate thickness have a significant impact on the gain and beam characteristics of the various planar antennas. The use of low dielectric loss substrates combined with an optimised substrate thickness improved radiation efficiency, allowing for the maximum possible gain to be achieved by the antenna systems being tested. The first example of this finding is the FR4 substrate at 1.6 mm thickness, which had a measured gain of ~8.71 dBi due to better radiation efficiency from the bow-tie-shaped antenna with optimised current distribution within the arms of the bow-tie antennas. The second example is RT5880 substrates with low loss tangents, which resulted in more gain as less electrical energy was dissipated within the substrate and suffered losses from the substrate. Based on these study results, it is evident that choosing the proper substrate has a major effect on the antenna array's radiation performance and beam characteristics.

Table 6 — Maximum gain achieved for different substrate materials and thickness values

Substrate Material	Thickness (mm)	Maximum Gain (dBi)	Corresponding Port
FR4	1.6	8.71	Port 1
PTFE	1.6	9.05	Port 4
RT5880	1.6	9.07	Port 4
RO4350B	0.8	9.09	Port 4

The differences in gain and beamwidth that can be seen in various antennas depend largely on how dielectric the materials used in constructing the host structures are; specifically, a higher dielectric constant will hold more of the electromagnetic energy up inside the host structure (and will, therefore, decrease the effective radiated power emitted by the host antenna), while a lower loss substrate (with a lower loss tangent) will reduce the amount of dielectric power dissipated so that there is more of it available for radiation. The thickness of the substrate (host material) will also cause changes in the fringing fields around the bow-tie arms of the antenna; if an optimal substrate is used with respect to its thickness, then the ability of the antenna to radiate is maximised. If the substrate is too thick, then the amount of surface waves and pattern distortion will increase. Therefore, the combined effects of relative permittivity, loss tangent, substrate thickness, impedance matching, and radiation efficiency account for the differences in gain exhibited by FR4, PTFE, RT5880, and RO4350B.

4.7 Tested Radiation Pattern Validation

In order to experimentally verify the radiation characteristics of the manufactured prototype, radiation patterns were measured at frequencies within the ISM band. The radiation pattern of the modified bow-tie antenna at the 2.45 GHz ISM band for the Port 1 excited configuration is shown in Fig. 11. The measured radiation pattern shows a noticeable main lobe, which is consistent with the expected directional nature of the array-fed configuration, confirming acceptable radiation performance.

Additionally, the radiation patterns of all of the excitation ports at 2.45 GHz are shown in Fig. 12 to verify multi-port beam behaviour measurements. Different input ports create different beam patterns that confirm switched-beam operation of 1×4 (bowtie) arrays fed by a Butler matrix experimentally.

The evaluation of antenna performance with respect to beam-switching confirmed that the fabricated antenna has the capability of being used as a switchable directional antenna system. The measured results from the fabricated antenna showed

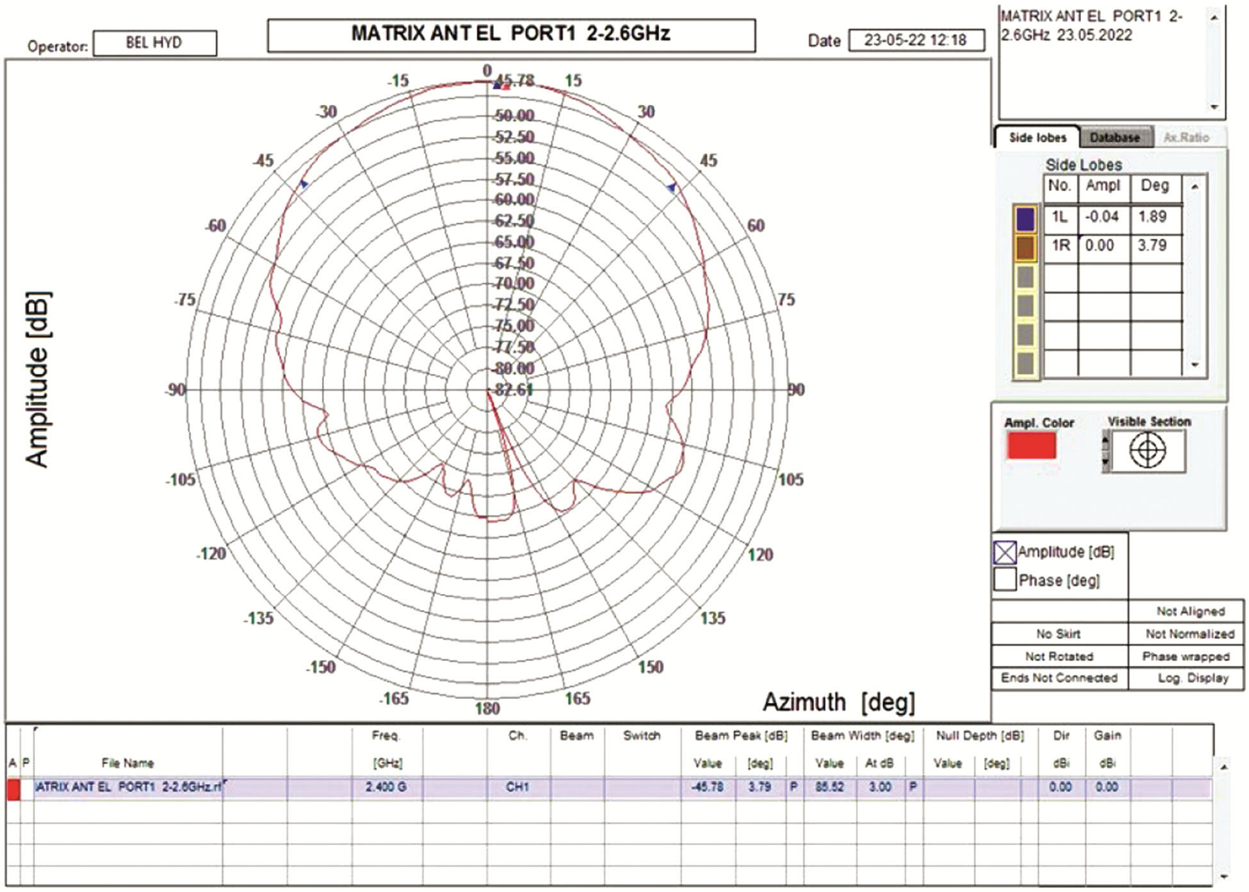

Fig. 11 — Tested radiation patterns of a modified Bow-Tie antenna at 2.4 GHz (Port 1)

separate and distinct main-lobe orientations at each of the four input ports, which, owing to the Butler matrix, produced different phase excitations to the array. Areas where the measurements deviate from the predicted performance are expected owing to issues such as loss or impedance mismatches at the coaxial feed connection points, tolerances in the antenna's substrate, and/or differences in amplitude and phase from one port to another. Although there are small deviations in the beam orientation, sidelobe levels, and symmetry from the expected predicted values calculated using the simulated model, the measurements taken from the fabricated antenna validate the proposed simulated 1 × 4 Bow-Tie Antenna Array Beam-Steering Capability.

To assess how the choice of substrate type and thickness affects the antenna gain, the highest value of gain measured from all substrate arrangements is recorded in Table 6.

From Table 6, it can be seen that as the thickness of the substrate is increased, the amount of gain produced by the antenna will also increase. This increase in gain is due to increased radiation efficiency and lower dielectric loss. Of the materials considered, RT5880 and RO4350B had slightly higher gains than the other substrates, FR4 and PTFE, due to their lower dielectric loss tangents. The highest gain measured at approximately 9.07 dBi was measured using an RT5880 substrate at 1.6 mm thick, demonstrating that low-loss substrates have the potential to greatly improve antenna performance.

To evaluate the beam steering capability of the Butler matrix-fed antenna array, the radiation direction for each excitation port was analysed, and results are summarised in Table 7.

The analysis indicates that the various excitation ports produce different beam directions through the progressive phase shift introduced by the Butler matrix. For example, the beam produced from port 1 will be directed about +14°; port 2 is directed towards −36°; and port 3 is directed towards +38°, with port 4 producing a beam close to −11°. Therefore, the result confirms that the antenna array has a switched-beam capability.

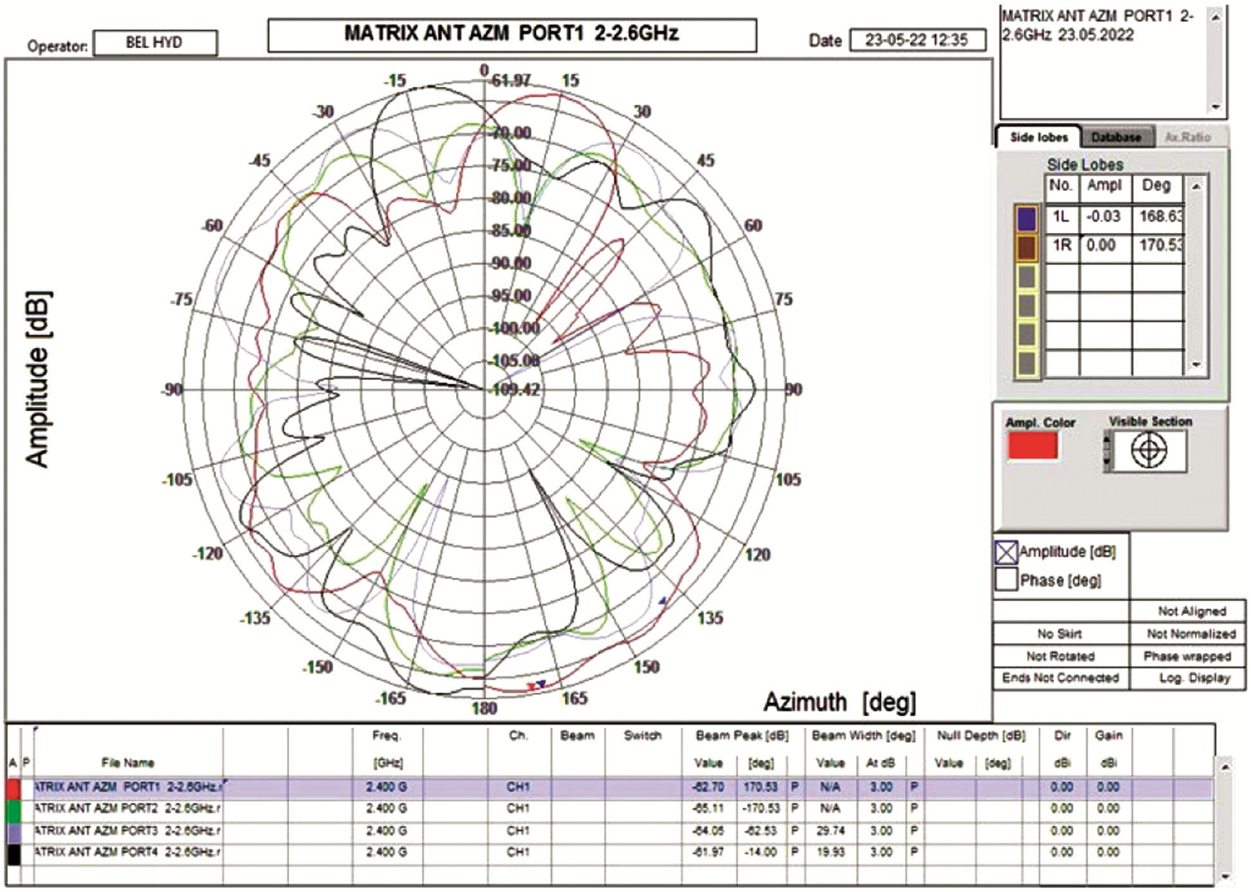

Fig. 12 — Tested radiation patterns of all ports at 2.45 GHz

Table 7 — Beam steering directions obtained from the Butler matrix-fed antenna array

Port	Phase Shift	Beam Direction (°)
Port 1	−135°	+14°
Port 2	−45°	−36°
Port 3	+45°	+38°
Port 4	+135°	−11°

Table 8 — Radiation characteristics of the proposed antenna array for the FR4 substrate (1.6 mm thickness)

Port	Gain (dBi)	Angular Tilt (°)	Elevation BW (°)	Azimuth BW (°)
Port 1	8.71	14	25.5	250
Port 2	7.92	−35	23.1	110
Port 3	5.86	38	29.4	169
Port 4	8.47	−11	21.7	199.6

The radiation characteristics of the proposed antenna array fabricated on an FR4 substrate with 1.6 mm thickness are summarised in Table 8.

A summary of the antenna array characterised by radiation performance and dimensions of the design was performed using an actual FR4 substrate with a 1.6 mm thick platen. The radiating mode of array elements also influences the number of beam-widths obtained by each array excitation port. In terms of elevation beam widths measured, they ranged from approximately 21° to 29°. For azimuth beam widths measured, they varied from around 110° to 250°. Results from this study reveal the directional nature of the proposed antenna design.

4.8 Quantitative Error Analysis

The agreement between theoretical values and measured values was quantified using percentage deviation for both gain and beam direction. For Gain and Beam Direction, % Error was determined by applying the formula provided below;

$$Percentage\ error = \frac{|Theoretical\ value - Measured\ value|}{|Theoretical\ value|} \times 100 \quad \ldots (17)$$

Using this methodology for evaluating FR4 substrate material with 1.6mm thickness, a theoretical gain of 9.07 dBi and a measured gain of 8.71 dBi was used to calculate a deviation of 3.97 %. The resulting

Table 9 — Quantitative comparison between predicted and measured beam directions

Port	Predicted beam direction	Measured beam direction	Absolute error	Percentage error
Port 1	+12.0°	+14°	2.0°	16.67 %
Port 2	−38.7°	−35°	3.7°	9.56 %
Port 3	+38.7°	+38°	0.7°	1.81 %
Port 4	−12.0°	−11°	1.0°	8.33 %

gain percentage deviation shows that the theoretical performance nearly matches the experimental performance very well.

The quantitative comparison between predicted and measured beam directions is presented in Table 9.

The beam direction error is well within the standard deviation of a fabricated microstrip antenna array due to fabrication tolerance, connector loss, dielectric loss, finite substrate size, mutual coupling between adjacent bow-tie elements and an amplitude/phase imbalance in the Butler matrix feed network, which are the main contributors to the resultant beam direction error. The comparison shows that the measured beam switch response is compliant with the proposed Butler matrix-fed 1 x 4 bow-tie antenna array's predicted beam switch response as per its beam steering characteristics.

5 Discussion

There are several important points to note about the outcomes of this research. First, a 1x4 bowtie antenna array was able to direct the radiation from the individual elements more effectively than a single element radiator because of the way that multiple elements combine constructively to produce a stronger radiated beam from each constructor. Second, the four-port Butler matrix was able to switch the direction of the radiated beam in relation to the array by providing for the introduction of progressively phase-excited currents in the radiating elements in the array and directing the radiated energy outward in different directions. Finally, the electronics established impedance matching (S11) and voltage standing wave ratio (VSWR) across all of the ports of the antenna arrays, thus indicating that integrated antennas are practically feasible. Third, based on the comparative analysis performed on each of the various substrates, it is apparent that both substrate dielectric constant and substrate thickness have significant effects on the gain and beamwidth of a planar antenna array. These findings will be of enormous benefit in enabling the design of compact, multi-beam antenna systems for wireless communication applications.

6 Conclusion

The research presented here involves designing, fabricating, and validating through experimentation an integrated 1 × 4 bowtie antenna array with a 4 × 4 Butler matrix at 2.45 GHz in the ISM band. The achieved results indicate that there is satisfactory impedance matching for the proposed antenna system, with a minimum reflection coefficient across all of the excitation ports of approximately 23 dB near the operating frequency. The use of a Butler matrix allows for switched-beam operation through progressive phase excitation of the elements, thus steering the radiation beams in multiple spatial directions based on which port is selected. The maximum gain achieved by the antenna array for different substrate configurations was measured as approximately 9.07 dBi; however, the FR4 substrate with a thickness of 1.6 mm produced a gain of 8.71 dBi with an angular tilt of 14°. The experimental radiation pattern measurements further support the beam-switching ability of the Butler matrix-fed antenna array and correlate well with the simulated results; therefore, the comparison of various substrate materials and thicknesses demonstrates that the dielectric properties and thickness of the substrate have a significant effect on the gain, beamwidth, and the total radiation characteristics of the antenna. In conclusion, the bowtie antenna array with Butler matrix feeding offers an ideal low-cost compact switched-beam solution for use in ISM-band wireless communication systems, including WLAN, IoT devices, and smart antenna platforms.

Areas for future research may include the use of reflector or lens-based structures to increase gain of the antennas, expansion of the design into higher-frequency wireless systems, and integration of the beam-switching network into compact multi-element smart antenna architectures for next-generation wireless communication applications.

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