Integration of PIN diode switching circuit with Butler Matrix for 2.45 GHz frequency band

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This study has integrated PIN diode switching circuit with the smart antenna of 4×4 Butler Matrix and successfully designed a novel system. A 76 mm×130 mm×1.67 mm switching circuit is fabricated in this study. It is found that the switching circuit can perform better at Industrial, Scientific, and Medical (ISM) frequency of 2.45 GHz with the superior return loss of -33.98 dB. In order to test the switching circuit that operates properly with the Butler Matrix, the radiating pattern of each output of the integrated PIN diode switching circuit as well as Butler Matrix has been simulated. The obtained results show satisfactory performance and good agreement with the simulated results.

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1. Introduction

Recently, semiconductor control circuits (i.e., switches, phase shifters, attenuator, modulator, etc) have been used extensively in radar telecommunication technology, communication system circuit, electronic warfare, optoelectronics, wireless applications, instrumentation, and other systems for controlling the signal flow or to adjust the phase and the amplitude of the signal. At Radio Frequency (RF), microwave, and millimeter-wave frequencies, many of the problems of bandwidth, switching speed, power handling, high dynamic range, low voltage operations, and high operating frequency have already been solved. One of the most suitable Monolithic Microwave Integrated Circuit (MMIC) components is the switching circuit. The PIN (or p-i-n) diodes [1]-[14] and Metal Semiconductor Field Effect Transistor (MESFET) or other transistors are used extensively in Microphones and MMICs, respectively, and also for microwave control circuits, such as switches, phase shifters, attenuators, and limiters. The PIN diode circuits have great flexibility in designing the integrated subsystems, can handle higher power levels MESFET components, can consume negligible power, and offer low-cost compared to other semiconductor control circuits [1].

The objective of this study is to design, fabricate, and analyse an innovative PIN diode switching circuit to integrate with the Butler Matrix [15] that operates at ISM (Industrial, Scientific, and Medical) frequency of 2.45 GHz. The design is fabricated on the FR4 (Flame Resistance) board and has been simulated using Computer Simulation Technology (CST) Microwave Studio. Basically, the input port of the Butler Matrix is divided into four ports with the equal amplitude and the specified relative phase differences, consequently generating four different beams through the connected smart array antenna. However, the Butler Matrix is a passive element, is not occupied with a system that can recognise and select the desired input port. To enhance the functionality of Butler Matrix, the PIN diode switching circuit is used to select the desired input port at Butler Matrix and supply the RF signal to that selective input port of the Butler Matrix. The switching mechanism is controlled by the external DC voltage circuit, which is the voltage regulator circuit. The antenna performance parameters, such as return loss (S_{11}), transmission loss (S_{12}), and radiation patterns are measured in this study. Detailed design and integration of PIN diode switching circuit together with the results and analysis are presented in Sections 2 and 3, respectively. Finally, a conclusion is presented in Section 4 at the end of this paper.

2. Design of PIN diode switching circuit

This section explains the design details of PIN diode switching circuit using CST Design Studio. A single switching circuit is designed as a first step to observe whether the switching circuit can work properly at ISM frequency of 2.45 GHz.

2.1 Design specifications

In general, the switching circuit and design specifications discussed here (is reported in our study [16][17]) in order to steer the Butler Matrix as explained later. Therefore, Philips PIN diodes, BAP 51-02 [18] have been selected in this design. Table 1 shows the detailed design specifications of the switching circuit. On the other hand, Fig. 1 represents the schematic diagram of the switching circuit. As presented in the figure, each switching circuit consists of a PIN diode, two direct current (DC) capacitors, two inductors, and one resistor. The capacitors are used as a DC blocking and the inductors are used as a RF choke, which provide low impedance for DC. The biasing voltage of 6 V has been connected with the 100 Ω resistor to limit the current flow to the switch [16][17].

Table 1. Design specifications.

Components	Value/Model
PIN diode	BAP 51-02 (Phillips)
Capacitors	6.8 pF
Inductors	22 nH
Resistor	100 Ω

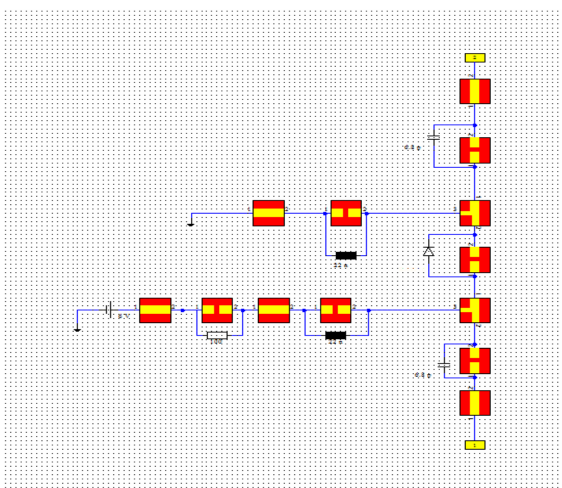


Fig. 1. Schematic diagram of the switching circuit.

2.2 Substrate material

In order to design the PIN diode switching circuit, the substrate chosen in this study is the FR4 Glass Epoxy Laminate. The specifications of the FR4 board are listed in Table 2.

Table 2. Specifications of FR4 board.

Materials	Value
Thickness, h (mm)	1.6
Dielectric constant	4.7
Loss tangent	0.019
Dissipation factor	0.020
Surface resistivity (MΩ)	4×10^{6}
Volume resistivity (MΩ-cm)	2×10^{9}

2.3 T-junction power divider specification

In RF and microwave systems, the power divider is one of the most commonly used components for power division and/or combination ratio as n-port network [16][17][19]. The design is illustrated in Fig. 2. Refer to our study [16][17], a lumped resistor (100 Ω) is connected between the outputs of the two branches that provide the required isolation. The dimension of the chip resistor must be very small of 1×0.5 mm. This involves two branches of the power divider, must be placed close to each other to be connected to the resistor. The 100 Ω resistor will be replaced by the λ /4 lengths of the 100 Ω transmission line. A λ /4 length of 100 Ω transmission line is placed in between λ /4 length of 50 Ω transmission line [16][17].

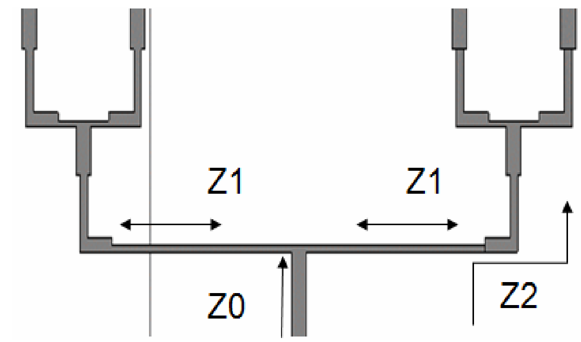


Fig. 2. T-junction power divider.

The electrical performances of the T-junction power divider depend on the width of the transmission line and are represented in Table 3.

Table 3. The electrical performances of the T-junction power divider.

Characteristics	Z_0	Z_1	Z_2
Impedance (Ω)	50	100	70.71
Width (W), mm	2.93	0.65	1.52

2.4 Full design of PIN diode switching circuit incorporated with T-junction power divider

Fig. 3 shows a structure, detailed design of PIN diode switching circuit incorporated with the T-junction power divider. The PIN diode represented as S_1, S_2, S_3, and S_4 in four locations. As the size of the PIN diode is 1.25 mm, the gap between the transmission lines is designed as 1.3 mm. In this method, a DC biasing circuit is used to control the ON/OFF mode of PIN diode switches. For example, if S_1 is switched on, this circuit is basically operated by supplying RF through S_1 and the RF will be received at one of the inputs of Butler Matrix. In contrast, when S_1 is turned OFF, S_1 will block the RF and the connection between RF and input of Butler Matrix will be terminated.

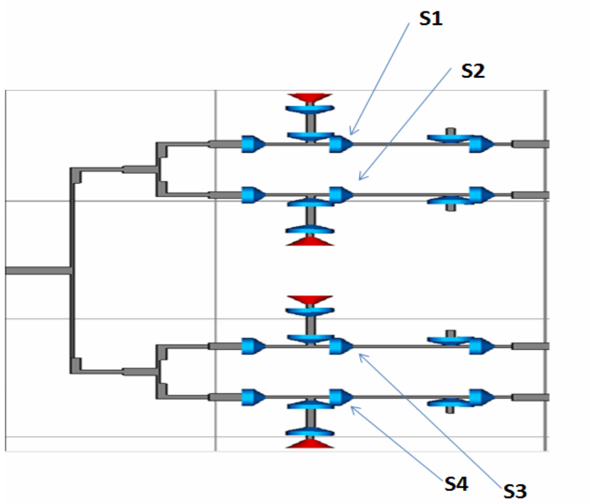


Fig. 3. PIN diode switching circuit incorporated with T-junction power divider.

2.5 Fabrication process

The fabrication process consists of cutting the FR4 board according to the dimension in the simulation, creating the photo resist pattern, etching, and lastly, soldering. In order to achieve the optimum results, safety precaution must be taken, especially in a fabrication room. This is because during fabrication, chemical and sharp apparatuses are used. In addition, PIN diode switching circuit design and fabrication involves considering of the properties of chemical resistance, the strain relief, and permeability. Fig. 4 illustrates the design of actual PIN diode switching circuit after soldering process.

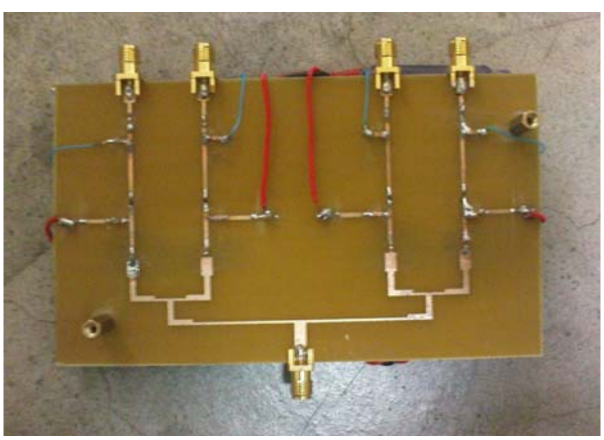


Fig. 4. Photo of actual PIN diode switching circuit.

3. Experimental results

This section has explained the detailed simulation results using CST Microwave Studio and the measurement results of PIN diode switching circuit are obtained using network analyser (Agilent E5071C ENA Series). The PIN diode switching circuit measurement parameters include return loss (S_{11}), transmission loss (S_{12}), radiation pattern, main lobe magnitude, and main lobe direction.

3.1 Return loss (S_{11}) and transmission loss (S_{12})

The PIN diode switching circuit in Fig. 1 is integrated with the array antenna and the Butler Matrix to switch the beam as presented in Fig. 5, which is the main contribution of this study. The final design of the integrated PIN diode switching circuit with the Butler Matrix is included in Fig. 6. Figs. 7 and 8 illustrate the S-parameter of PIN diode switching circuit, where S_{11} shows the value of -33.9824 dB and S_{12} shows the value of -0.2543 dB at ON state while S_{11} shows the value of -6.9340 dB and S_{12} shows the value of -1.5576 dB at OFF state, respectively.

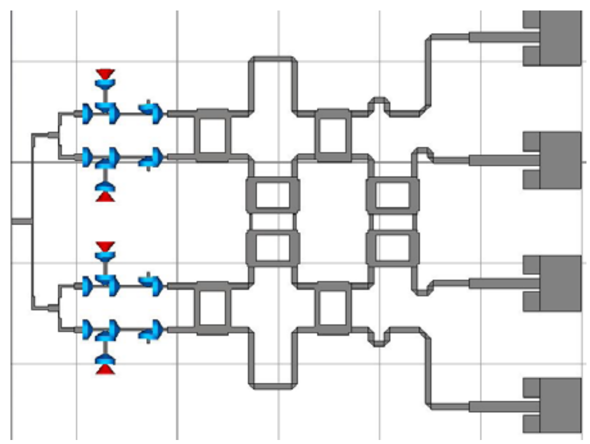


Fig. 5. Layout of integrated PIN diode switching circuit with Butler Matrix.

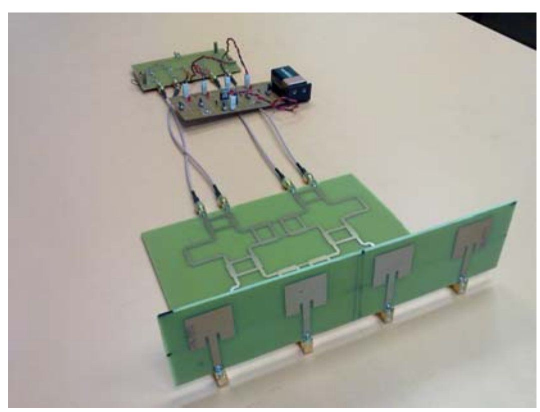


Fig. 6. Photo of integrated PIN diode switching circuit with Butler Matrix.

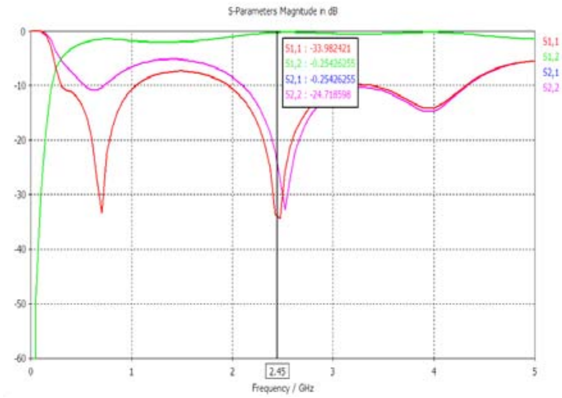


Fig. 7. Calculated return loss (S_{11}) and transmission loss (S_{12}) for switch ON mode.

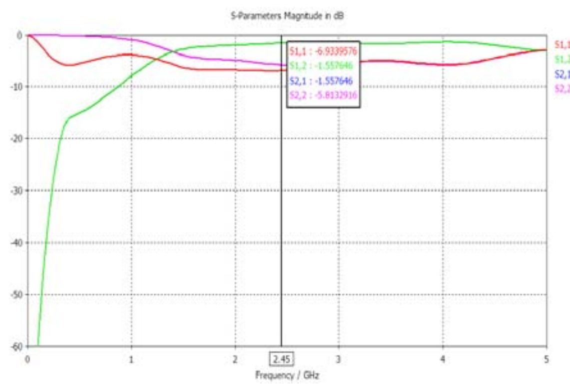


Fig. 8. Calculated return loss (S_{11}) and transmission loss (S_{12}) for switch OFF mode.

3.2 Radiation pattern of integrated PIN diode switching circuit with Butler Matrix

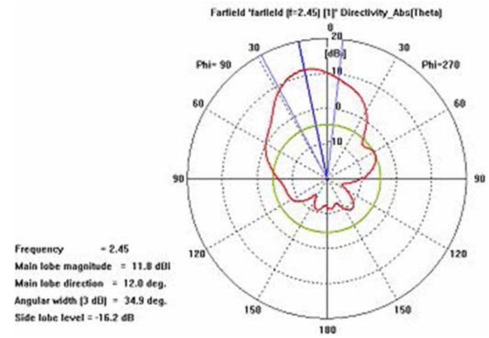
The radiation patterns of all four integrated PIN diode switching circuits with the Butler Matrix are presented in the following.

3.2.1 When S_1 is ON mode

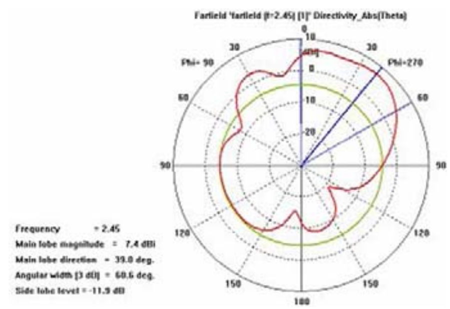
Fig. 9 (a) shows the simulation results of radiation pattern when S_1 is activated. It can be observed that, the main lobe direction is +12° with magnitude of 11.8 dBi. The simulation results also show that the angular width and the side lobe level of radiation pattern are 34.9° and -16.2 dB, respectively.

3.2.2 When S_2 is ON mode

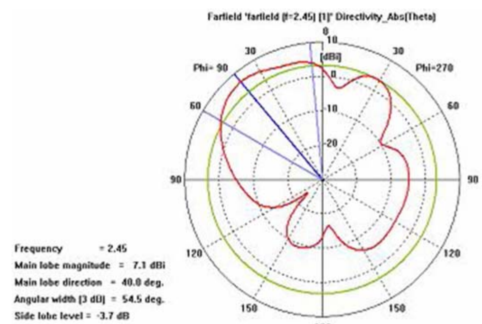
Fig. 9 (b) shows the simulation results of radiation pattern when S_2 is activated. It can be observed, the main lobe direction is -39° with magnitude of 7.4 dBi. The simulation results also show that the angular width and the side lobe level of radiation pattern are 60.6° and -11.9 dB, respectively.



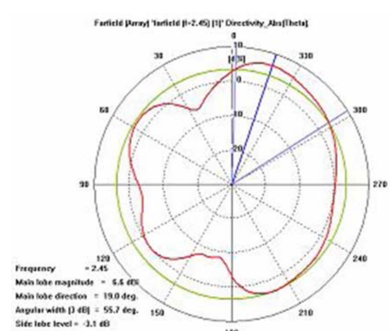
(a)



(b)



(c)



(d)

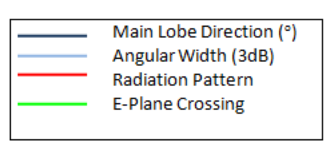


Fig. 9. Radiation pattern of integrated PIN diode switching circuit with Butler Matrix (a) when S_1 ON Mode, (b) when S_2 ON Mode, (c) when S_3 ON Mode, and (d) when S_4 ON Mode.

3.2.3 When S_3 is ON mode

Fig. 9 (c) shows the simulation results of radiation pattern when S_3 is activated. As can be observed, the main lobe direction is +40° with magnitude of 7.1 dBi. In addition, the simulation results show that the angular width and the side lobe level of radiation pattern are 54.5° and -3.7 dB, respectively.

3.2.4 When S_4 is ON mode

Fig. 9 (d) shows the simulation results of radiation pattern when S_4 is activated. It is seen that, the main lobe direction is -19° with magnitude of 6.6 dBi. On the other hand, the simulation results also show that the angular width and the side lobe level of radiation pattern are 55.7° and -3.1 dB, respectively.

The results obtained from Sections 3.2.1, 3.2.2, 3.2.3, and 3.2.4 are summarised in Table 4. To verify the proposed system, all obtained results of radiation patterns are compared with the theory of Butler Matrix's radiation patterns as reported in our study [20]. It is found that the obtained results of integrated PIN diode switching circuit with the Butler Matrix are approximately the same with the theory of Butler Matrix's radiation patterns. The slight difference (very small discrepancy) is observed in the obtained results, which is due to the mismatch error occurred between the PIN diode switching circuit and the Butler Matrix.

Table 4. Summary of radiation patterns for different switching states.

Parameters	Main Lobe Magnitude (dB)	Main Lobe Direction (°)	Angular Width (3 dB) (°)	Side Lobe Level (dB)
S_1	11.8	+12.0	34.9	-16.2
S_2	7.4	-39.0	60.6	-11.9
S_3	7.1	+40.0	54.5	-3.7
S_4	6.6	-19.0	55.7	-3.1

3.3 Measurement results

The data collected from the measurements of return loss and transmission loss are plotted in the following sub-sections.

3.3.1 Return loss (S_{11}) at ON state

As can be observed from Fig. 10, the PIN diode switching circuit's optimum operation with the maximum voltage or power transfer occurs at the frequency of 2.45 GHz. The obtained return loss (S_{11}) for this design is -33.9824 dB, which is acceptable as this value is lower than -10 dB. The value of S_{11} should be limited at -10 dB or 10% of the transmitted power, to ensure that the operating frequency (2.45 GHz) only reflected at least 10% of the transmitted power. It can be also seen that, the measured return loss is approximately the same with the simulation, which is -10.0688 dB; however, the resonance frequency is shifted to 3 GHz. The shifting of frequency might be occurred due to the permittivity of the board, which varies from 4.0 to 4.8.

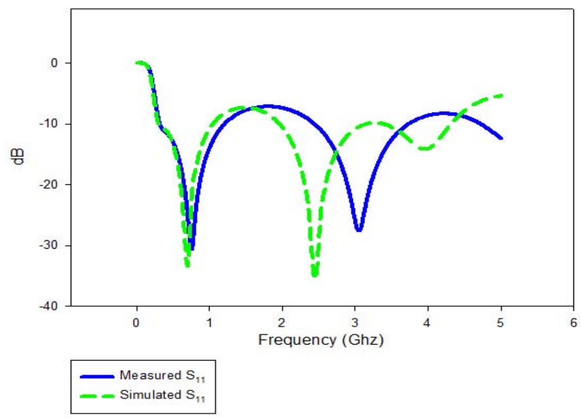


Fig. 10. Calculated return loss (S_{11}) at switch ON mode.

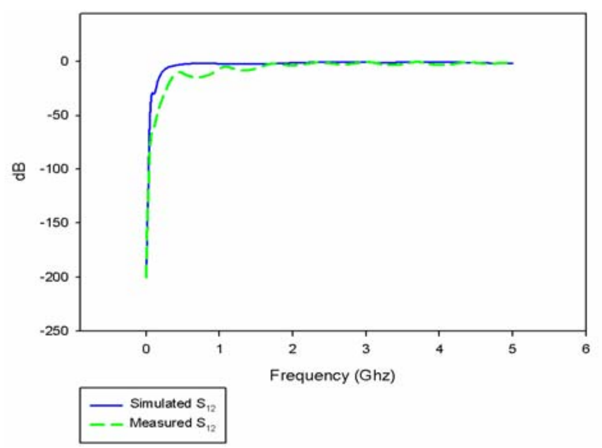


Fig. 11. Calculated transmission loss (S_{12}) at switch ON mode.

3.3.2 Transmission loss (S_{12}) at ON state

According to the theory, the transmission loss is defined as the ratio of the power at one point in a transmission system to the power at a point farther along the line, which is usually expressed in decibels. The actual power is lost in transmitting a signal from one point to another through a medium or along a line. It can be observed from the simulations results presented in Fig. 11, the PIN diode switching circuit's optimum operation with the maximum voltage or power transfer occurs at the frequency of 2.45 GHz. The transmission loss (S_{12}) for this design is -0.2543 dB and it is acceptable because the transmission loss (S_{12}) is relatively low (S_{12} <0.25 dB). It can be also found, the measured transmission loss is approximately the same with the simulation, which is -1.2259 dB. By comparing the obtained results, it can be observed that, both results are acceptable since the minimum requirement has been achieved in this study.

4. Conclusions

An integration of PIN diode switching circuit with the Butler Matrix has been successfully designed and simulated in this paper. The PIN diode switching circuit is proven operable, with a sufficient amount of return loss and radiation characteristic. The proposed design of PIN diode switching circuit achieves the best return loss at the desired frequency of 2.45 GHz. Although the measurement results occur shifting of frequency in some cases, the range of operating frequency is still in the wireless band. It is found that the array PIN diode switching circuit can operate properly with the Butler Matrix and the obtained results show that the radiation pattern of each output of the integrated Butler Matrix with PIN diode switching circuit is approximately the same with the theory of radiation pattern of Butler Matrix.

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