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Integrated Design of a 2.45 GHz Phased Array Antenna with MEMS-Based DMTL Phase Shifters

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ABSTRACT

This paper presents the design and simulation of a 2.45 GHz phased array antenna incorporating a 2-bit cascaded Distributed Micro-Electro-Mechanical Systems Transmission Line (DMTL) phase shifter, a 4-way Wilkinson power divider, and a 4-element patch antenna array. Each component was individually designed and optimized through full-wave electromagnetic simulation, then integrated into a complete radio frequency (RF) system for performance evaluation. The phased array enables dynamic beam steering within a range of −20° to +20° by adjusting the phase shift introduced by the DMTL phase shifters. A thermal analysis was also performed to assess the reliability of the antenna under operational conditions. Simulation results show that the antenna achieves a maximum gain of 10.56 dBi, demonstrating its suitability for compact and reconfigurable wireless systems.

1. Introduction

The development of 5G technology has carried significant advancements to wireless communication, promising faster speeds, ultra-low latency, and the ability to connect a massive number of devices. To realize the full potential of 5G networks, advanced antenna systems such as phased array antennas are required. These antennas offer beam steering capability which allows for targeted signal transmission to specific devices or coverage areas. Recently, Distributed MEMS Transmission Line (DMTL) phase shifters have attracted interest from researchers due to their low loss and wideband characteristic [1]. DMTL phase shifters enable real-time phase adjustments, permitting rapid beam steering for accurate tracking of user devices and optimizing communication links. Together, the integration of phased array antennas and DMTL phase shifters enhances signal quality, data rates, capacity, and connectivity, reshaping the wireless communication experience in the era of 5G.

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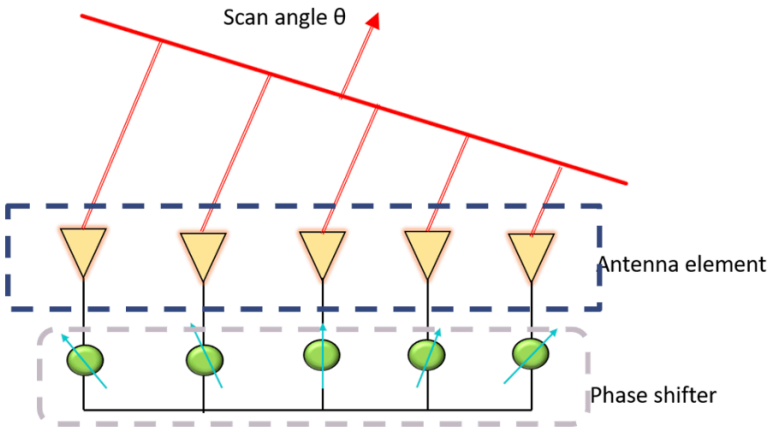

Fig. 1. Phase array antenna

In a phased array antenna as illustrated in Fig.1, precise control over the progressive phase between antenna elements enables electronic beam steering without the need for physical antenna movement. These systems can consist of several to thousands of elements, each individually fed by a phase shifter. Therefore, the development of efficient phased array antenna with phase shifters that exhibit low loss, low cost, low power consumption, and lightweight characteristics is vital [2,3].

Various solid-state phase shifters have been proposed for operation in the L and S bands [4-6]. However, these designs suffer from limitations such as limited bandwidth, high insertion loss, and constant phase shift over frequency, rendering them unsuitable for wideband applications. On the other hand, RF microelectromechanical systems (MEMS) technology offers compact and cost-effective solutions by integrating multiple micro components onto a single chip. The development of true time delay (TTD) type phase shifters using MEMS technology has gained momentum due to their low loss [7-9]. These phase shifters can be categorized into two main groups: switched line phase shifters and distributed MEMS transmission line (DMTL) phase shifters. Switched line phase shifters involve switching between transmission lines of unequal length to achieve desired phase shifts, while DMTL phase shifters are realized by periodically loading a high impedance transmission line (>50 Ω) using MEMS switches. The actuation of switches increases the distributed capacitance on the transmission line, causing a decrease in line impedance and phase velocity, thereby providing a differential phase shift. The distributed technique is particularly advantageous for wideband applications. A true-time delay module, such as the distributed MEMS transmission line (DMTL) phase shifter, is essential to avoid beam squint in wideband radar applications, as reported in Ong *et al*., [10]. Several phased array antenna employing DMTL phase shifters have been proposed [7-9],[11]. However, these designs were specifically designed for operation in the X-band to Ku-bands.

This paper presents the design and simulation of a phased array antenna that operates at 2.45 GHz through co-simulation technique using ANSYS Electronic Desktop (AEDT). The phased array antenna comprises of 2-bit cascaded Distributed Micro-Electro-Mechanical Systems Transmission Line (DMTL) phase shifter, a 4-way Wilkinson power divider, and 4-element patch array antenna.

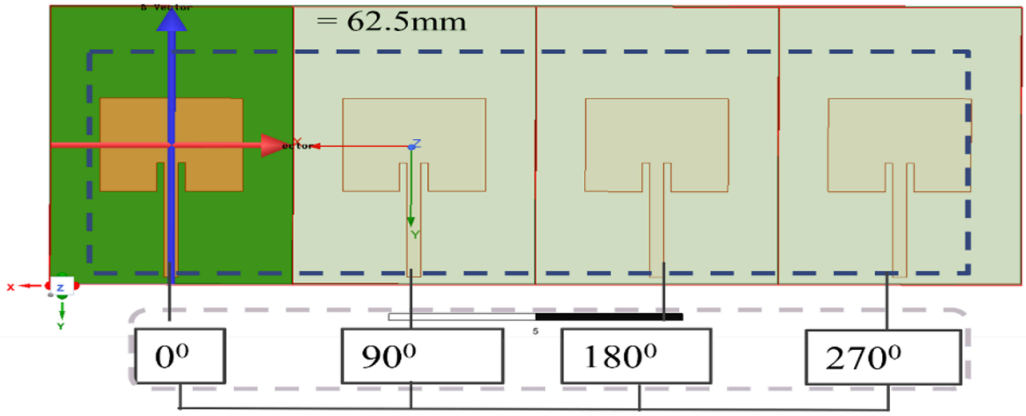

Fig. 2. Element patch array antenna with phase shifter

The DMTL phase shifter employs 16 shunt switches loaded on a co-planar waveguide (CPW) transmission line, enabling discrete phase shifts of 0° and 90° at 2.45 GHz, as illustrated in Fig. 2. Each component of the phased array system was first simulated independently in ANSYS HFSS to evaluate its RF characteristics such as insertion loss, return loss, and phase shift. To assess the overall performance of the system, a co-simulation method was used where these components were integrated in ANSYS Nexxim to perform beam steering. Finally, the reliability of the antenna array was evaluated via electrothermal simulation using ANSYS Icepak to observe the effect of input power to the temperature of the antenna array.

2. Design and Simulation Workflow

The simulation of the 4-element phased array antenna at 2.4GHz integrated with Wilkinson power divider and DMTL phase shifters was carried out through co-simulation approach in AEDT. The co-simulation method allows for a quick evaluation of the phased array antenna system based on the independent design of MEMS phase shifter, power divider, and array antenna. The co-simulation workflow for the phased array antenna system is outlined in Fig. 3. Through co-simulation, the input to the phased array antenna can be changed to observe the beam steering performance. Temperature distribution on the array antenna structure was later analyzed based on the electromagnetic loss from ANSYS HFSS when coupling with ANSYS Icepak.

2.1 DMTL Phase Shifter

A DMTL phase shifter is a two-port network designed to alter the phase or delay an RF signal that passes through it. It consists of a transmission line (TL) that is periodically loaded with MEMS (Micro-Electro-Mechanical Systems) shunt switches or bridges as shown in Figure 4. These MEMS bridges can be actuated by applying voltage to them. By controlling the voltage, the state of the switches and consequently the capacitance can be tuned, thereby modifying the phase shift experienced by the RF signal as it travels through the transmission line. In other words, the phase shift can be adjusted according to the desired requirements by controlling the state of the MEMS switches through the application of voltage[12].

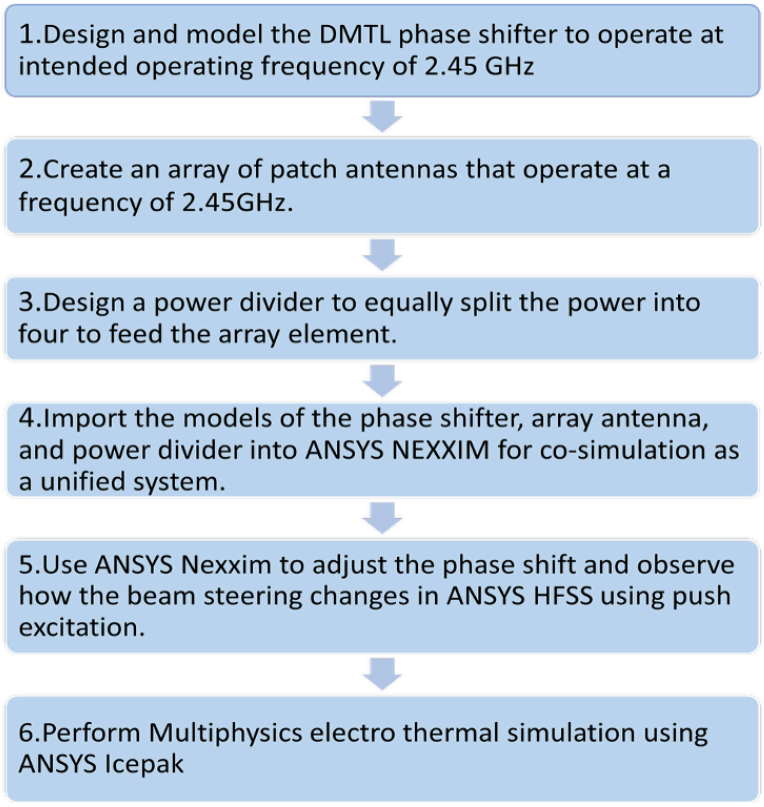

Fig. 3. Simulation workflow

The capacitance of the MEMS switches can be calculated based on parallel plate [13]

$$C_{pp} = \frac{\varepsilon_o A}{g_o + \frac{t_d}{\varepsilon_r}} \quad (1)$$

Where ε_o = 8.854 is the permittivity of free space, A is the contact area between the plate, g_o is the initial gap and t_d is dielectric thickness and ε_r is the dielectric constant of dielectric layer.Fig.5 shows the complete structure of DMTL phase shifter used in this study. It comprises 16-unit cells

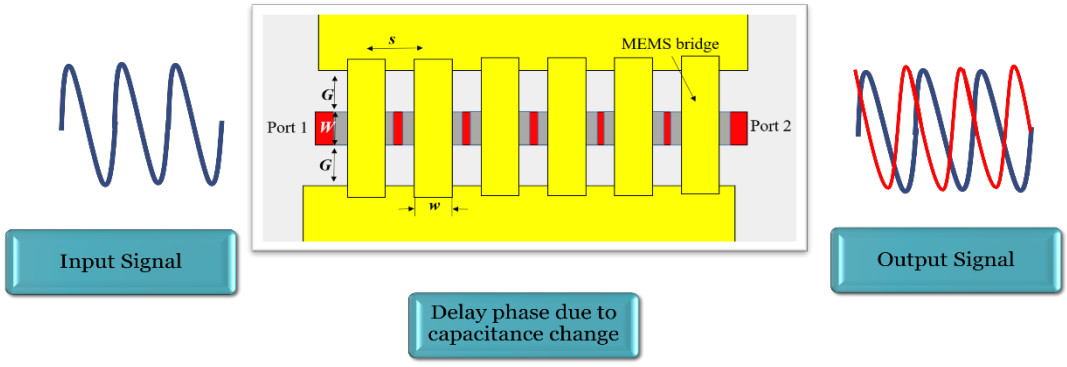

Fig. 4. Working principle of DMTL phase shifter

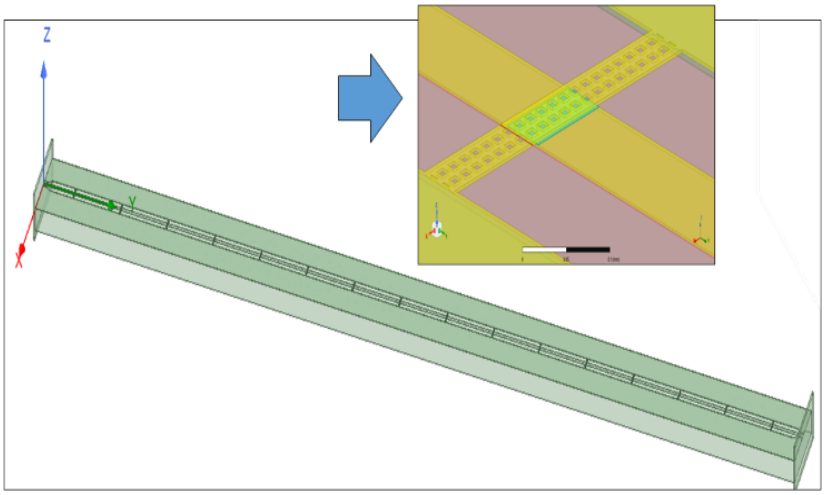

Fig. 5. DMTL phase shifter

representing 0° during upstate and 90° during downstate at 2.4GHz. The spacing between two adjacent switches denoted as S, is 1850µm and is defined by [13]:

$$S = \frac{Z_d c}{\pi f_b Z_o \sqrt{\varepsilon_{r,eff}}} \tag{2}$$

Where Z_d represents the distributed impedance of the DMTL in the down-state, Z_o is the characteristic impedance of the unloaded transmission line, c is the speed of light, ε_{eff} is the effective dielectric constant of the unloaded line, and f_B denotes the Bragg frequency, given by[13]

$$f_B = \frac{2}{2\pi\sqrt{sSL_t(sC_t+C_b)}} \tag{3}$$

The Bragg frequency is the cutoff frequency which in this design it is set to be 10 times the operating frequency, $f_o$of 2.4GHz. This ensures that the down-state capacitance of the MEMS shunt switches remains sufficiently low to prevent the formation of a short-circuit condition, thereby avoiding reflective switch behavior.

The proposed phase shifter is implemented on a high resistivity silicon substrate with a thickness of 525 µm and resistivity of 10 kΩ·cm. This choice helps minimize losses caused by the underlying substrate. To achieve a return loss of -18 dB per bit, the loaded impedances of the transmission lines (TL) are set to 60 Ω (up-state position) and 42 Ω (down-state position). This ensures that all states have return losses better than -10 dB across the operating band. The key design parameters are summarized in Table 1. The RF performance analysis of the phase shifter was conducted using ANSYS HFSS.

Table 1
DMTL phase shifter parameters table

Parameters	Value
Z_o	65Ω
Z_u	60Ω
Z_d	42Ω
CPW (G/W/G)	136/100/136 µm
Thickness of CPW	2 µm
Distance between beam, s	1850µm
Beam dimension (w x L)	50 × 372µm
Thickness of beam	1 µm
Air gap	1.5 µm
Bragg freq, f_{Bragg}	10 f_o
Upstate capacitance, C_{lu}	45.38fF
Downstate capacitance,C_{ld}	363.014fF
Capacitance ratio, C_r	8
Cells	16

2.2 Microstrip Antenna Array

A single-unit patch antenna operating at a frequency of 2.4 GHz was developed in Ansys HFSS. Microstrip patch antennas function as resonant cavities where the patch radiates due to fringing fields at the edges. The resonant frequency of the antenna is determined primarily by the length of the patch. For a rectangular patch, the resonant frequency (f_o) for the dominant TM_{10} mode can be approximated by[13]:

$$\boldsymbol{f_o = \frac{c}{2L\sqrt{\varepsilon_{eff}}}} \quad (4)$$

Where c is speed of light, L is the effective length of the patch, and $\boldsymbol{\varepsilon_{eff}}$ is the effective dielectric constant. Fig. 6 and Table 2 show the design parameter used for the single patch antenna. Then, a 4-element antenna array was created from the unit cell. This array was simulated using Finite array Domain Decomposition Method (FADDM), an efficient technique that partitions the finite array into subdomains to account for mutual coupling while maintaining computational efficiency.

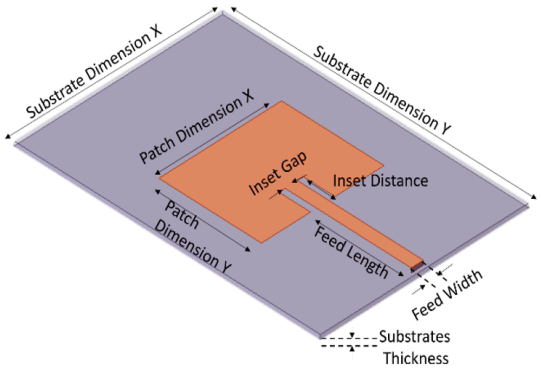

Fig. 6. A single unit patch antenna 2.4GHz

Table 2
2.4GHz patch antenna parameter

Parameters	Value (cm)
Frequency	2.4GHz
Patch Dimension X	1.19
Patch Dimension Y	0.91
Substrate Material	FR-4
Substrate Dimension X	2.7
Substrate Dimension X	2.87
Substrate Thickness	0.1575
Feed Width	0.493
Feed Length	0.914
Inset Distance	0.276
Inset Gap	0.247

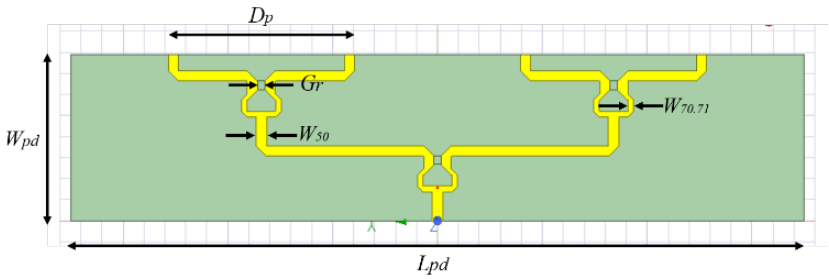

Fig. 7. 4-way Wilkinson power divider

2.3 Wilkinson Power Divider

The Wilkinson power divider plays a critical role in RF systems by providing efficient power division and signal distribution. Its design and performance greatly impact the overall functionality and efficiency of RF circuits [14]. The Wilkinson power divider is based on the principle of quarter-wave impedance transformers and resistive terminations. It consists of a transmission line with two impedance-matched resistive terminations connected to the outputs and a branch line connected to the input [15]. In this work, a 4-way Wilkinson power divider was designed as a feeding network for the antenna array. The characteristic impedance of the Wilkinson power divider, *Z0* is set to 50 Ω to match with the impedance of the antenna port. The distance between the output ports is also set to match the separation distance in the proposed antenna array. The optimized design of the 4-way Wilkinson power divider is shown in Fig. 7. The values of the parameters of the structure is given in Table 3.

Table 3
Geometrical parameter of the 4-way Wilkinson power divider

Parameters	Value
Length, *Lpd*	350mm
Width, *Wpd*	79mm
Port separation distance, *Dp*	84mm
Feedline width for 50Ω TL, *W50*	4.93mm
Feedline width for 70.71Ω TL, *W70.71*	2.78mm
Branches gap, *Gr*	3.42mm
Resistor 1	100Ω
Resistor 2	100Ω
Resistor 3	100Ω

2.4 Co-simulation

To quickly analyze the performance of the phased array system, the three independently designed RF components presented earlier were then integrated and simulated together using co-simulation in AEDT. Co-simulation refers to the combination of different software tools to analyze a complex RF system. In AEDT, co-simulation between ANSYS HFSS and ANSYS Nexxim is commonly employed for RF systems.

The design files of DMTL phase shifter, array antenna and power divider from ANSYS HFSS were seamlessly transferred to ANSYS Nexxim, a circuit simulator in AEDT. This integration greatly simplifies the data exports between the two software tools. In Nexxim, the HFSS model is represented as a box with a port, as illustrated in Fig. 8.

The co-simulation environment enables the interaction between HFSS and Nexxim. Electrical signals from Nexxim are fed back to HFSS to update the electromagnetic fields within the RF components. This iterative process allows for a quick and accurate analysis of the phased array antenna. The beam forming created from phase array antenna based on the phase shifting can then be analyzed. Three unit DMTL phase shifters are connected in series to provide 0° , 90°, 180°, 270° phase shift to each of the antenna element respectively to steer the beam of the array antenna.

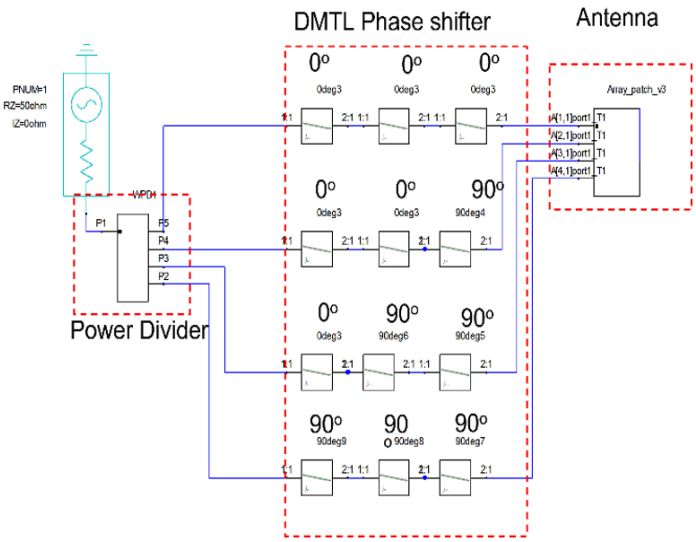

Fig. 8. Co-simulation in ANSYS Nexxim

2.5 Thermal Analysis

Thermal analysis of the 4-element patch antenna array was performed using ANSYS Icepak in AEDT. The electrothermal study is particularly crucial for 5G applications, especially at high frequencies in base stations. ANSYS HFSS is used to determine the amount of electromagnetic power generated by the source, while Icepak provides valuable information such as temperature distribution and heat flow.

To begin the simulation, an explicit model of the antenna array is created in ANSYS HFSS and a power of 30mW is applied to the array. Once the HFSS simulation is completed, the model is transferred into ANSYS Icepak for thermal analysis. Steady-state analysis is chosen as the solution type. For the boundary conditions, opening boundaries are assigned as the inlet and outlet, while the substrate, antenna, and ground are assigned as EM loss boundaries as shown in Fig. 9.

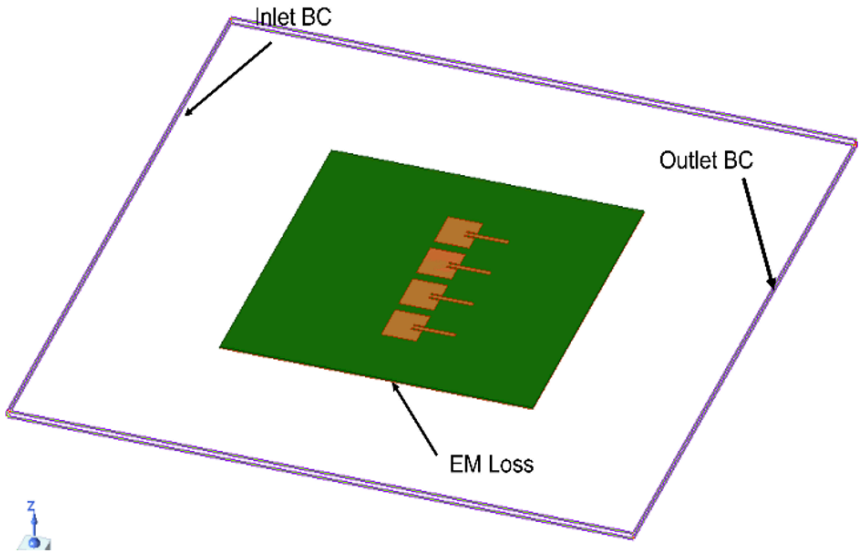

Fig. 9. Thermal boundary condition in ANSYS Icepak

3. Result and Discussions

3.1 DMTL Phase Shifter

The performance of DMTL phase shifter was characterized in terms of return loss, insertion loss and the amount of phase shift. Figure 10 illustrates the simulated return losses for upstate and downstate for the DMTL phase shifter. It demonstrates that the return losses across the 2 GHz to 4 GHz range are less than -10 dB which show good impedance match. This achievement was made possible by selecting loaded impedances of 60 Ω (upstate) and 42 Ω (downstate), resulting in a per-bit loss of -1.8 dB. The insertion loss at 2.45 GHz, depicted in Figure 11, are -0.68dB and -0.86 dB for 0° and 90° respectively. The simulated phase shifts for a single unit DMTL phase shifter are shown in Fig. 12.

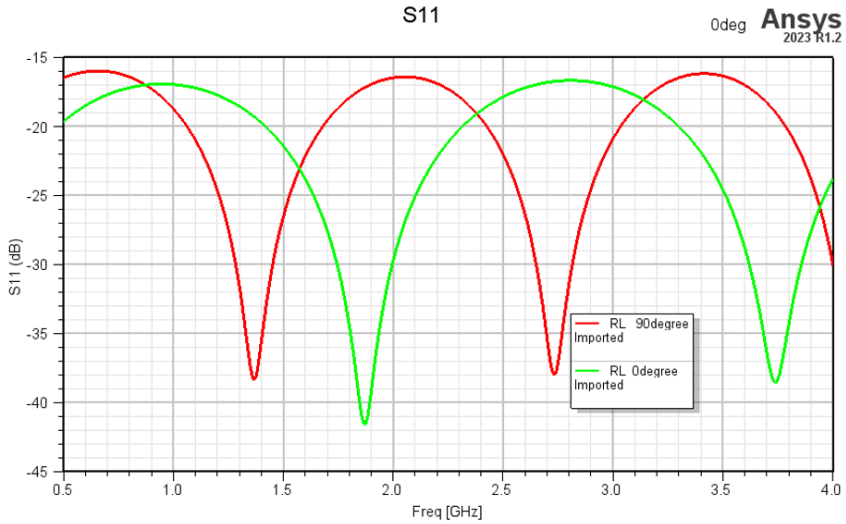

Fig. 10. Return loss of DMTL phase shifter

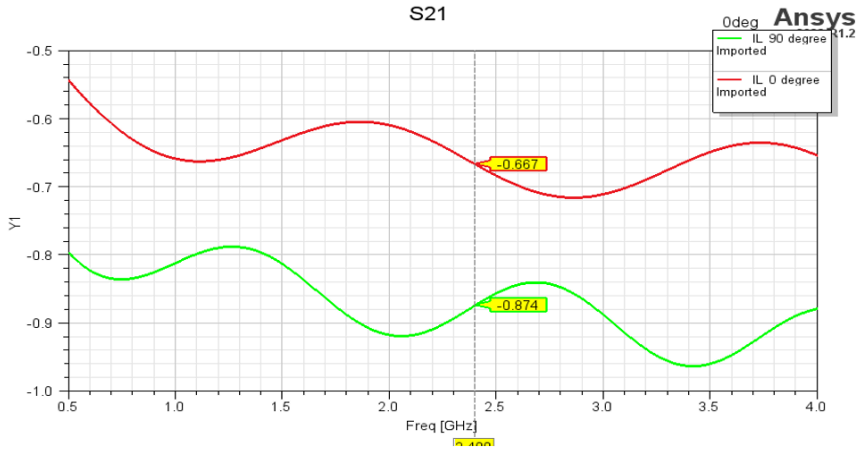

Fig. 11. Insertion loss of phase shifter

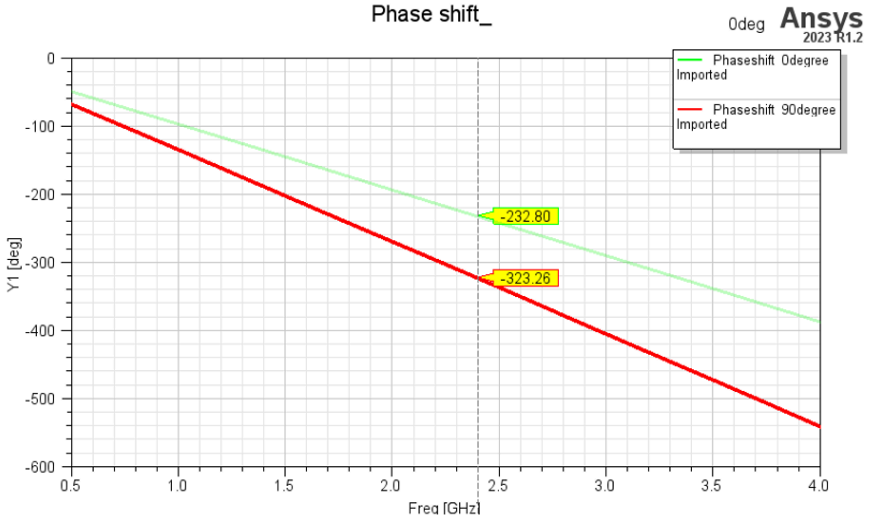

Fig. 12. Phase shift of DMTL phase shifter

3.2 Patch Array Antenna

The return loss and the radiation pattern of the microstrip array antenna and the radiation pattern of the microstrip array antenna shown in Fig.13 and Fig.14 respectively. Based on the figures, the reflection coefficient of the array antenna at its operating frequency of 2.4GHz is-15.84dB while the simulated gain is 10.5dBi.

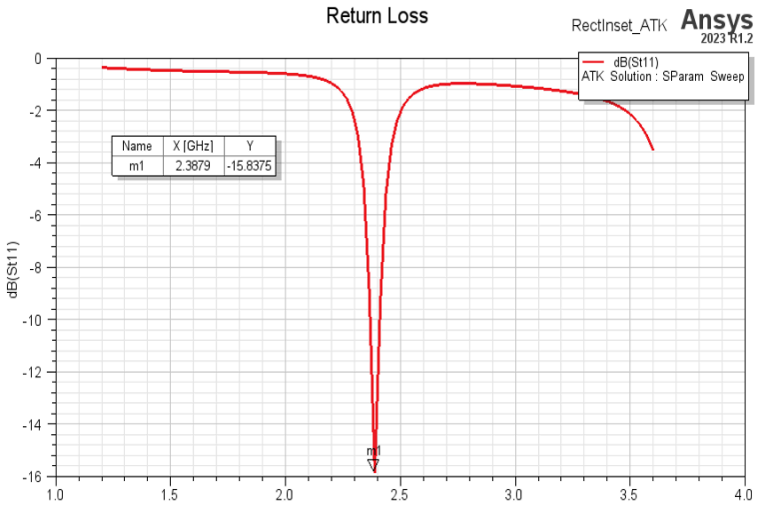

Fig. 13. Reflection coefficient of the patch array antenna

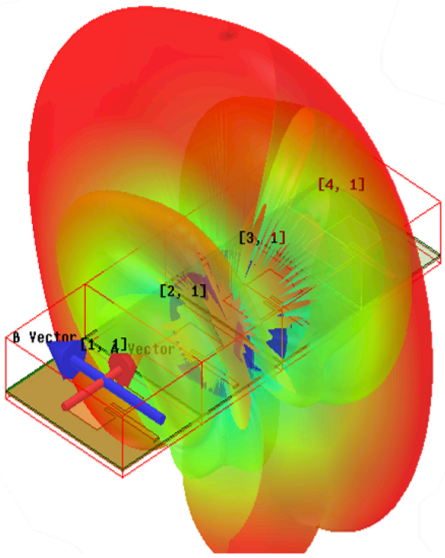

Fig. 14. Radiation pattern of 4 element patch array antenna

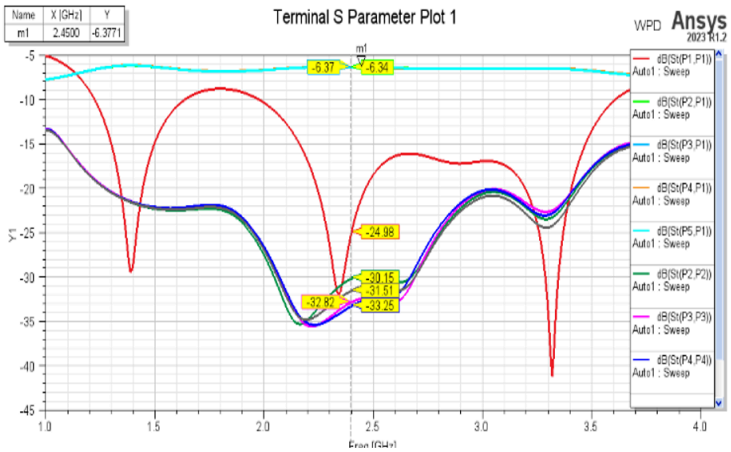

Fig. 15. S parameter for Wilkinson Power Divider

3.3 Wilkinson Power Divier

Figure 15 shows simulated results for the 4-way Wilkinson power divider. The S11 result for each port indicates that it is well matched to 50Ω, as it remains below −10 dB across the operating frequency. The transmission coefficient, S21, between the input port, P1, and the output ports (P2, P3, P4, P5), ranges from -6.35 dB to 6.37 dB. The insertion loss is around 0.36dB for all the ports.

3.4 Co-simulation

The performance of the phased array system was evaluated based on its beam forming capability. Through co-simulation, the devices were integrated together in ANSYS Nexxim. By varying the progressive phase shift, the main beam for the array antenna can be steered in a different direction. The progressive phase shift is set to 90° between the antennas. Figure 16 shows that the main beam of the antenna array shifts to -20° and 20° respectively. More direction can be achieved by adding more antenna elements as well as increasing the number of bits of the DMTL phase shifter. The return loss for all three beam steering angles at 2.4GHz are provided in Table 4.

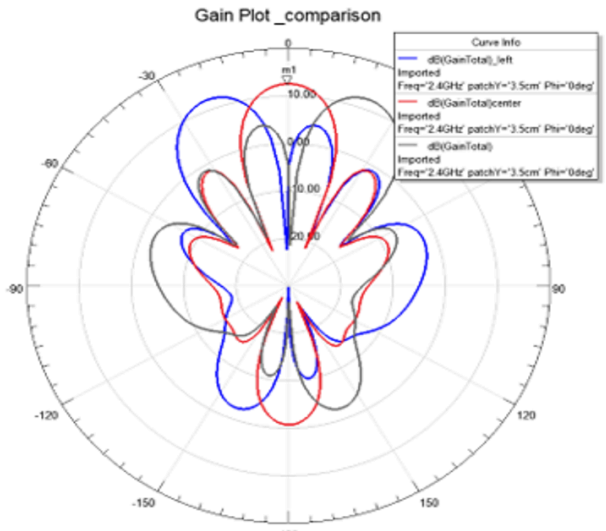

Fig. 16. Beam steering of patch array antenna

3.5 Thermal Analysis

Based on the EM loss data obtained from HFSS, the temperature distribution was then calculated in ANSYS Icepak. EM loss, also known as power loss, occurs due to the power dissipated by the device and is influenced by the temperature-dependent materials used in the model. It should be noted that this paper does not consider any external power or heat contribution from other components in the simulation. The total EM loss for this phased array antenna is calculated to be 0.007256W for an input power of 30mW, resulting in maximum temperature of 20.019°C as shown in Figure 3. Based on these findings, it can be concluded that an input power level up to 30mW could be used for this phased array antenna system.

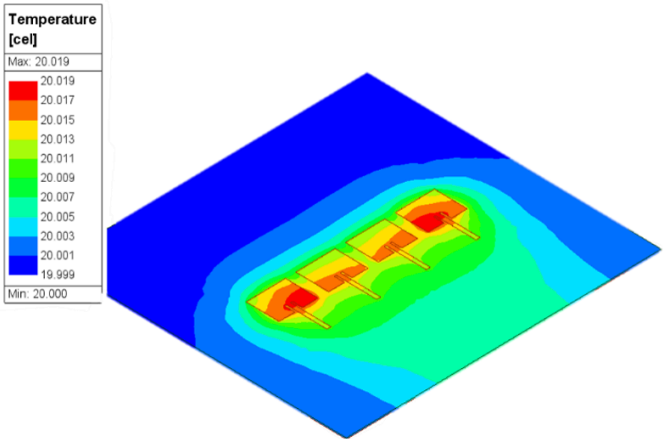

Fig. 17. Temperature distribution in ANSYS Icepak

4. Conclusion

In conclusion, this study successfully simulated a phased array antenna that operates at 2.4GHz using co-simulation approach in AEDT. The design process involved optimizing the antenna, phase shifter, and Wilkinson power divider independently, enabling efficient optimization of each component. Subsequently, co-simulation method was employed to simulate the entire design, ensuring quick and accurate analysis and evaluation of the overall system performance. Furthermore, multiphysics simulation was conducted to analyze the temperature distribution of the patch array antenna.

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