Directional Coupler Design and Performance Evaluation for Wireless Technologies

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Abstract: *Directional couplers are emerging technologies that play a significant role in enabling various wireless communication systems, such as mobile phones, wireless LANs, and Bluetooth-enabled devices. These couplers enhance key performance parameters, including isolation, directivity, and insertion loss. In this study, an updated analysis has been conducted through a comparative evaluation with previous work, focusing on isolation coefficient and return loss. The findings demonstrate that hybrid line directional couplers deliver optimal results across the frequency range of 0.1 GHz to 6 GHz, making them suitable for wireless applications. Notably, the third proposed design shows substantial improvements in bandwidth, insertion loss, and return loss (S11), especially in the lower range of the RFID frequency band. This design supports dual-band operation, covering 0.1 GHz to 2.283 GHz and 5 GHz to 6 GHz, achieving bandwidths of 2283 MHz and 510 MHz at center frequencies of 1.6 GHz and 5.3 GHz, respectively.*

Keywords: *Directional Couplers, Return loss, Insertion Loss, Coupling Factor, Isolation.*

I. Introduction

In the rapidly evolving domain of wireless communication, the demand for compact, efficient, and broadband microwave components has grown significantly. Among these, directional couplers play a vital role in signal routing, power monitoring, and isolation between circuits in high-frequency systems. Their ability to split or combine signals with minimal loss makes them essential in various applications, including mobile networks, satellite communication, radar systems, and RF front-end modules. Directional couplers are typically four-port passive devices that allow a fraction of the input signal to be coupled to a secondary output port while maintaining isolation from the remaining ports. Key performance parameters such as coupling factor, isolation, return loss, insertion loss, and bandwidth directly influence their effectiveness in real-world applications. Achieving an optimal balance among these parameters, particularly over a wide frequency range, remains a central design challenge—especially when size and fabrication constraints are also considered [1] – [3].

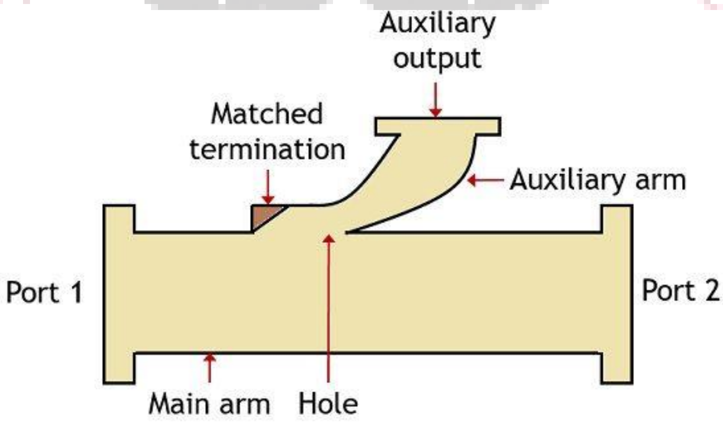

Figure 1: Directional Coupler.

Recent advancements have led to the development of various directional coupler architectures, including branch-line, Lange, and coupled-line couplers. However, each structure comes with its own limitations regarding bandwidth, size, and performance at lower frequency ranges. This study addresses these challenges by presenting the design and simulation of novel directional coupler configurations tailored for wireless applications. Utilizing HFSS (High Frequency Structure Simulator), the proposed designs focus on improving bandwidth and minimizing insertion and return losses without compromising compactness. The main objective of this work is to evaluate and compare multiple coupler configurations and identify the optimal structure that meets the performance demands of modern wireless systems. Special attention is given to hybrid structures that incorporate both cross-coupled and suspended lines to enhance overall performance across multiple frequency bands [4]–[7].

II. Related Work

This section provides a comparative overview of significant contributions related to the design and optimization of directional couplers.

In [8], the authors investigated forward-wave coupling in uniform symmetrical coupled lines, a phenomenon that occurs when the even- and odd-mode phase velocities differ. They developed both symmetric and asymmetric broadband couplers using a multi-mode resonator (MMR), which supports resonance at four distinct frequencies. Notably, three of these modes contribute significantly to bandwidth enhancement. The coupling strength can be adjusted by altering the gap between the coupled lines, and the operational bandwidth is tunable through impedance ratio variations. A 10 dB forward-wave directional coupler was successfully designed for the 4–8 GHz frequency range, offering benefits such as compact size, single-layer construction, and elimination of bond wires.

In [9], the authors addressed the growing interest in microwave circuit designs employing differential excitation, which contrasts with the conventional single-ended configurations. Differential architectures offer improved suppression of common-mode interference, as such noise typically propagates identically through all conductors. The study introduces a balanced directional coupler and presents a novel edge-coupled stripline structure along with relevant physical parameters. The approach builds upon multi-section designs utilizing asymmetric couplers for enhanced performance.

The work in [10] focuses on branch-line directional couplers, which are widely used in microwave systems. While traditionally designed for single-ended operation, the paper highlights a shift toward differentially fed circuits due to their enhanced common-mode rejection. A differential branch-line coupler was developed using a two-conductor, substrate-integrated transmission line technique. To expand the bandwidth, a four-branch topology was employed, and the transmission line impedances were optimized for practical implementation.

In [11], a novel full-band square waveguide coupler was proposed, capable of coupling TE10 and TE01 symmetrical modes. This configuration comprises a pair of rectangular waveguide directional couplers rotated 90° relative to each other and integrated into a square waveguide through dedicated junctions. The device operates across the 10–18.9 GHz band and is optimized for polarization control. The prototype achieves a coupling level of 31 dB with a flatness of ±3.8 dB and superior cross-polarization isolation exceeding 50 dB throughout the band, making it suitable for circular polarization applications.

III. Problem Definition

In the design of directional couplers, achieving an optimal balance between compact size, high directivity, and wide operating bandwidth remains a significant challenge. Despite advancements in design methodologies, it is still difficult to realize a compact structure without compromising on performance. This research addresses these limitations through the implementation of a hybrid line directional coupler, aimed at enhancing overall performance while maintaining a reduced physical footprint.

IV. Problem Definition

The directional coupler designs proposed in this work have been simulated using ANSYS HFSS over a frequency range of 0.1 GHz to 6 GHz, targeting wireless communication applications. All three designs are developed on an FR4 substrate due to its cost-effectiveness and widespread use in RF systems. Among the three configurations, the third design demonstrates superior performance in terms of bandwidth and return loss, making it the most promising for practical implementation.

Design 1: Cross-Coupled Line Directional Coupler

The first model incorporates cross-coupled lines between both feed lines to enhance coupling characteristics. The simulation parameters analyzed include coupling factor (S31), isolation (S41), return loss (S11), insertion loss (S21), VSWR, and operating bandwidth (in MHz). These results are summarized in Table 1.

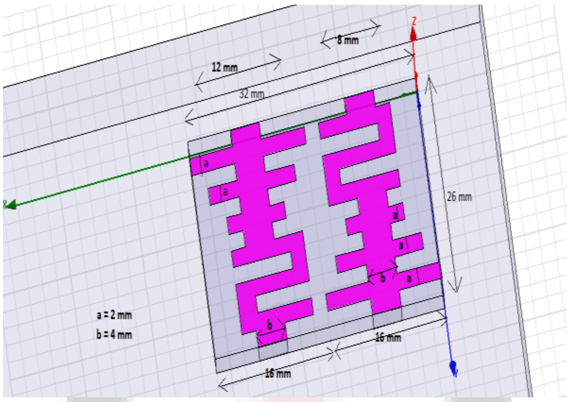

Figure 2: Top View of Cross Couple LineDirectional Coupler for Design1.

Figure 3: Ground of design 1.

The directional coupler is constructed on an FR4 substrate with a dielectric constant of εr = 4.4 and thickness of 1.6 mm. The structure spans 32 mm × 26 mm, using copper (PEC in HFSS) for the conductive paths. Three cross-coupled lines, each connected to the feed lines, are implemented with lengths of 16 mm, 12 mm, and 8 mm, and thicknesses of 2 mm (denoted by 'a'). The feed lines (denoted by 'b') also use rectangular copper sections. A detailed top view is illustrated in Figure 2, while the bottom view of the substrate layout is presented in Figure 3.

Design 2: Reduced Cross-Coupled Line Directional Coupler

The second design maintains the same overall footprint of 32 mm × 26 mm, but modifies the cross-coupling strategy. Unlike the first design, only one feed line includes cross-coupled sections, again measuring 16 mm, 12 mm, and 8 mm, but with 2 mm spacing between them. The feed line width in this case is 4 mm, spanning the full height of 26 mm. This design seeks to analyze the impact of reduced cross-coupling on bandwidth and isolation. A visual representation of this configuration is provided in Figure 4.

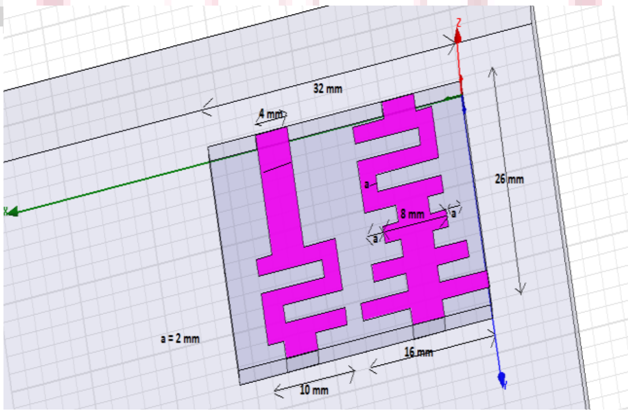

Figure 4: Top view of the 2nd Design of Reduced Cross Coupled Line DirectionalCouplerModel.

V. Simulation Results

The simulation results of the proposed directional coupler designs were obtained using ANSYS HFSS. Each design was analyzed based on key performance parameters such as bandwidth, insertion loss (S21), return loss (S11), coupling factor (S31), isolation (S41), and VSWR.

Table I: Simulation Results for the First Proposed Cross-Coupled Line Directional Coupler

Radiating Frequency (GHz)	**Return Loss S11 (In dB)**	**Insertion Loss (S21)**	**Bandwidth (MHz)**	**VSWR**	**Coupling parameters S31 (dB)**	**Isolation parameters S41 (dB)**
0.1	-22.32	-0.97	500	1.16	-47.52	.46.56
3.6	-22.75	-0.73	400	1.15	-25.34	-33.21

From the simulation of the first design, dual-band operation was observed with bandwidths of 500 MHz and 400 MHz, centered at 0.1 GHz and 3.6 GHz, respectively. The insertion loss recorded at 0.1 GHz was -0.97 dB. Other performance parameters including return loss and coupling were also evaluated at these center frequencies.

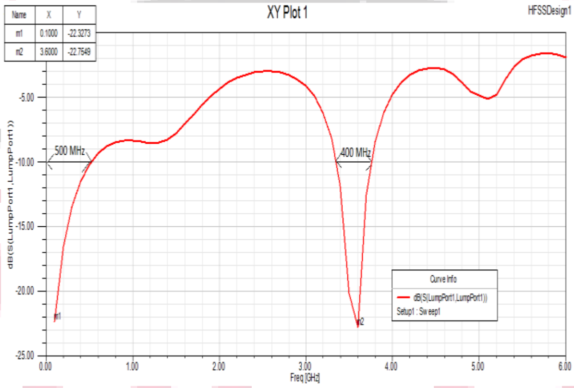

Figure 5: Return loss of simulation result for Design 1.

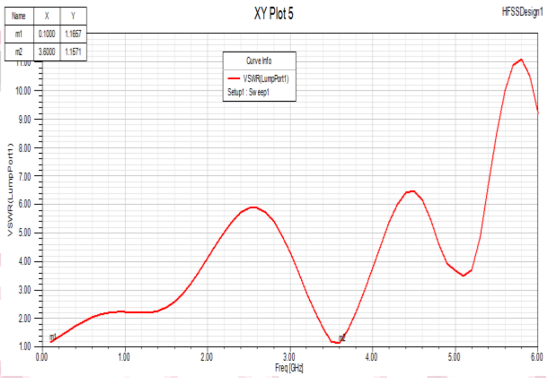

Figure 6: VSWR in dB of simulation result for Design 1 at Port 1.

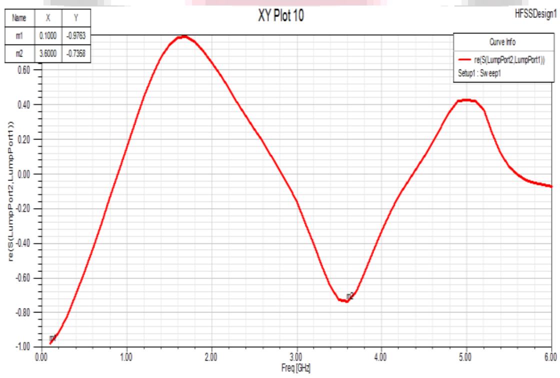

Figure 7: Insertion Loss of simulation result for Design 1

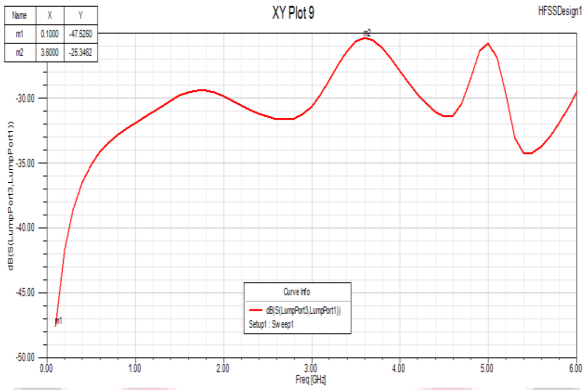

Figure 8: Coupling Factor Coefficient S31of simulation result for Design 1.

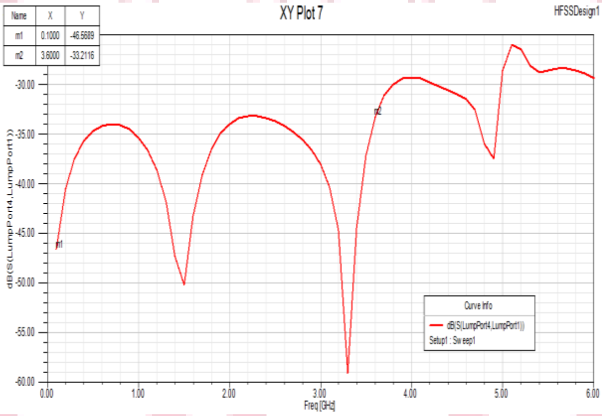

Figure 9: Isolation Coefficient S41of simulation result for Design 1.

Table 2: Simulation Results for the Second Proposed Reduced Cross-Coupled Line Directional Coupler

Radiating Frequency (GHz)	Return Loss S11 (In dB)	Insertion Loss (S21)	Bandwidth (MHz)	VSWR	Coupling parameters S31 (dB)	Isolation parameters S41 (dB)
1.6	-28.19	0.72	2200	1.08	-32.33	-43.34
5.3	-23.89	0.48	500	1.13	-35.84	-35.42

The second design demonstrated improved bandwidth performance, achieving 2200 MHz and 500 MHz at 1.6 GHz and 5.3 GHz, respectively. The best insertion loss was noted as -0.72 dB at 1.6 GHz, while the minimum return loss achieved was -28.19 dB, as illustrated in Figure 10.

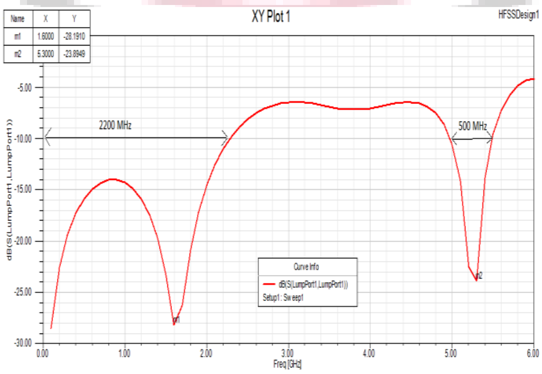

Figure 10: Isolation Coefficient S41of simulation result for Design 1.

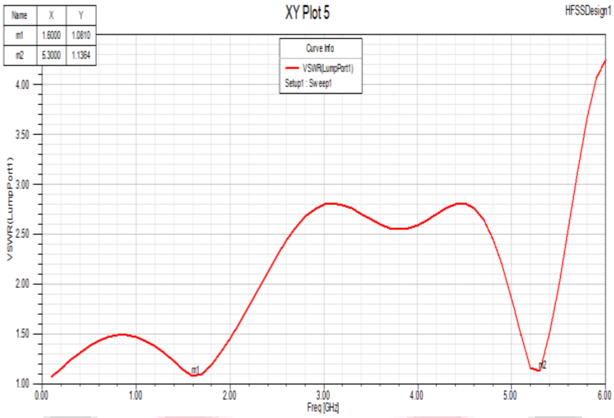

Figure 11: Isolation Coefficient S41of simulation result for Design 1.

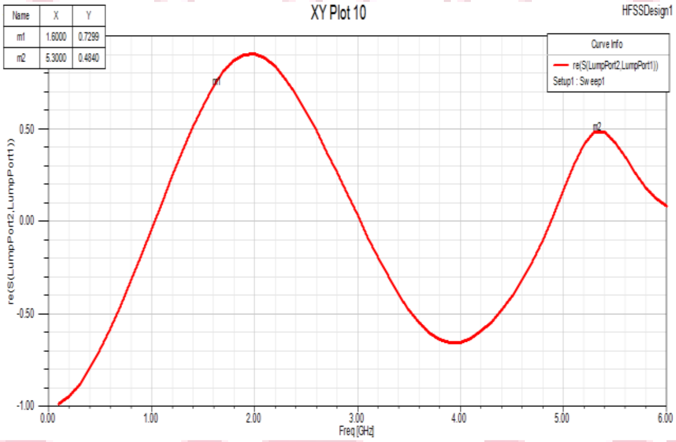

Figure 12: Isolation Coefficient S41of simulation result for Design 1.

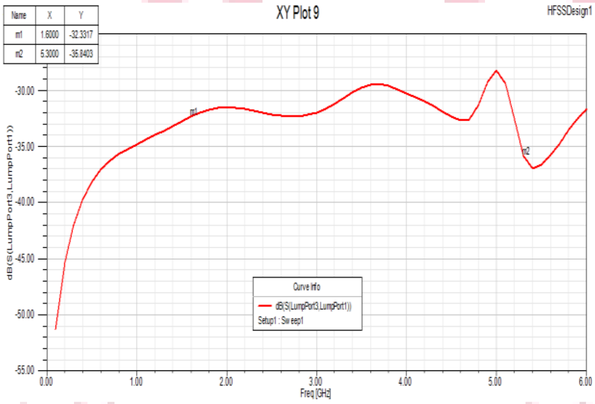

Figure 13: Isolation Coefficient S41of simulation result for Design 1.

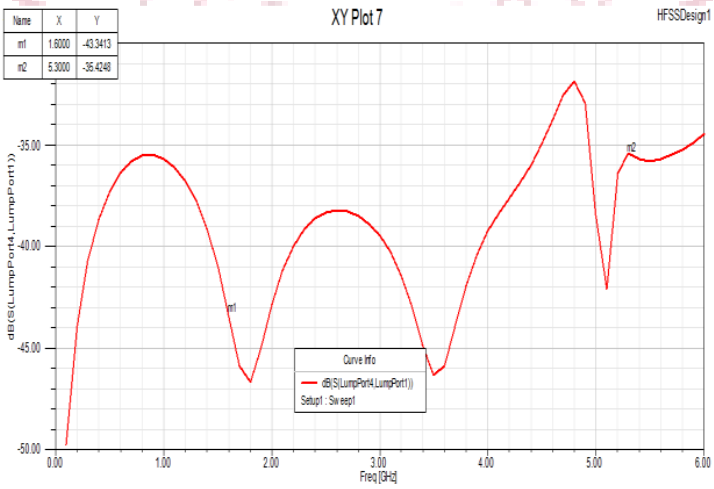

Figure 14: Isolation Coefficient S41of simulation result for Design 1.

Table 3: 3rdDesign Hybrid Line Directional Coupler.

Radiating Frequency (GHz)	Return Loss S11 (In dB)	Insertion Loss (S21)	Bandwidth (MHz)	VSWR	Coupling parameters S31 (dB)	Isolation parameters S41 (dB)
1.6	-28.19	0.72	2283	1.05	-31.74	-36.76
5.3	-23.89	0.43	510	1.08	-20.17	-26.75

The third design, based on a hybrid structure combining cross-coupled and suspended lines, showed dual-band operation with bandwidths of 2283 MHz at 1.6 GHz and 510 MHz at 5.3 GHz. An insertion loss of -0.72 dB and return loss of -28.19 dB were recorded at 1.6 GHz, indicating superior performance in the lower frequency range compared to the previous two designs.

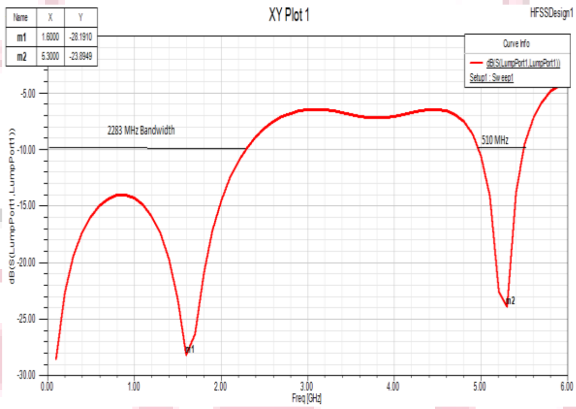

Figure 15: Isolation Coefficient S41of simulation result for Design 1.

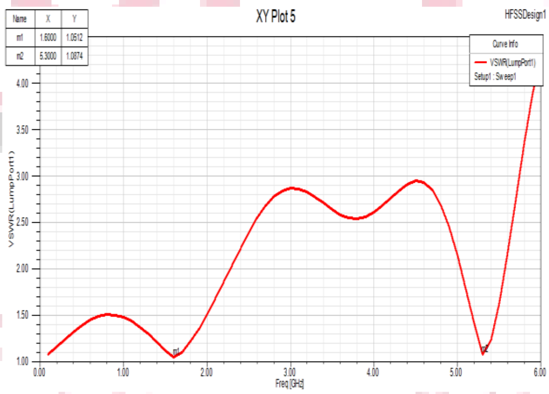

Figure 16: Isolation Coefficient S41of simulation result for Design 1.

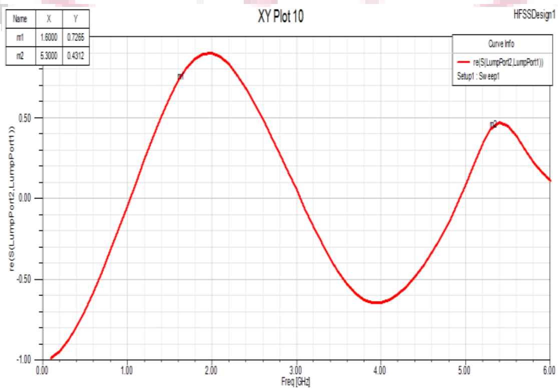

Figure 17: Isolation Coefficient S41of simulation result for Design 1.

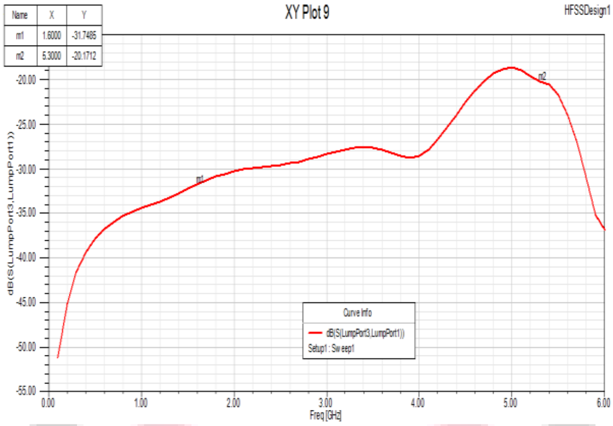

Figure 18: Isolation Coefficient S41of simulation result for Design 1.

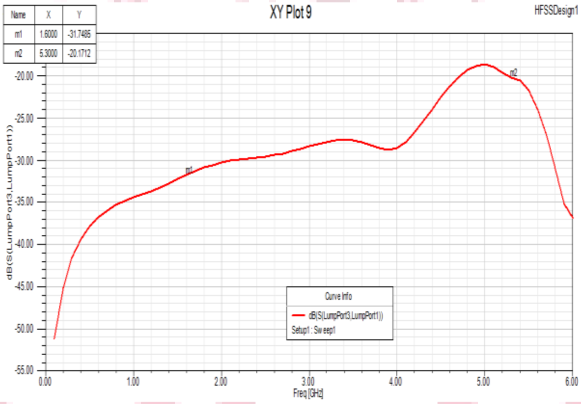

Figure 19: Isolation Coefficient S41of simulation result for Design 1.

VI. Conclusion and Future Work

This study presents the design and simulation of three directional couplers for broadband wireless applications using HFSS. Among the three designs, the third proposed configuration demonstrated the best overall performance in terms of bandwidth, insertion loss, and return loss, while maintaining acceptable values for other critical parameters. Design 1 achieved dual-band operation at 0.1 GHz and 3.6 GHz, offering bandwidths of 500 MHz and 400 MHz, respectively, with a return loss of -22.75 dB. Design 2 showed improved performance, achieving wider bandwidths of 2200 MHz and 500 MHz at 1.6 GHz and 5.3 GHz, respectively, and a return loss of -28.19 dB. Building upon the strengths of the previous designs, Design 3 adopted a hybrid structure that combines cross-coupled and suspended lines. This design further enhanced the bandwidth to 2283 MHz and 510 MHz for center frequencies of 1.6 GHz and 5.3 GHz, respectively, while also achieving excellent insertion and return loss characteristics.

The results clearly indicate that modifications to the cross-coupled structure positively influence bandwidth and return loss. Moreover, integrating different coupling mechanisms, as done in the hybrid configuration, significantly improves the overall performance of the directional coupler. Future research will focus on optimizing key performance metrics, including bandwidth, insertion loss (S21), coupling factor (S31), isolation (S41), and return loss (S11), particularly within the lower frequency range. These enhancements will be targeted toward applications in RFID systems and emerging wireless communication technologies.

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