Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 8, S. 421-425, 4, 2024

Araştırma Makalesi

https://as-proceeding.com/index.php/ijanser
ISSN: 2980-0811

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 8, pp. 421-425, 4, 2024

Research Article

Adjustable Phase Shifter Design for Butler Matrix Feeding Network in 2.45 GHz Wireless Communication Applications

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(Received:16 May 2024, Accepted:26 May 2024)

(3rd International Conference on Engineering, Natural and Social Sciences ICENSOS 2024, May 16-17, 2024)

ATIF/REFERENCE: Heydarli, G. & Palandoken, M. (2024). Adjustable Phase Shifter Design for Butler Matrix Feeding Network in 2.45 GHz Wireless Communication Applications. *International Journal of Advanced Natural Sciences and Engineering Researches,* 8(4), 421-425.

Abstract – This study focuses on developing an adjustable voltage-controlled phase shifter design, specifically for integration with the Butler Matrix, which is used as a feed network for phased array antennas. The key element of the phase shifter design is varactor diodes. These diodes' capacitance can be varied by adjusting the DC voltage, allowing for up to a 100-degree phase shift. The design utilizes left-hand and right-hand transmission line methods for effective phase control. The varactor diodes in the design operate within a voltage range of 5 V to 15 V and offer ten distinct capacitance settings. Mitigating is the impact of the DC voltage on the RF signals at both the input and output, the design includes two interdigital capacitors. Additionally, two spiral inductors are incorporated to isolate the RF signals from the DC supply. The phase shifter is designed on an FR-4 substrate and is tuned to function at a frequency of 2.45 GHz, making it suitable primarily for Butler Matrix network applications in phased array antenna systems. The overall size of proposed phase shifter is 53.23 x 30 mm^2. The reflection coefficient and insertion loss are within acceptable limits for its intended use in a 2.45 GHz Butler matrix feeding network application.

Keywords – Butler Matrix, Phase Shifter, CRLH, Varactor Diodes, Phased Array Antenna

I. INTRODUCTION

Phase shifters have a many important roles in the architecture of modern communication systems, functioning as essential components that modulate the phase angle of transmission signals. These devices facilitate critical operations such as dynamically steering antenna beams, scanning geographical areas, and expanding signal reach in targeted directions. The operational effectiveness of phase shifters directly influences the performance of communication networks, making them indispensable in achieving high efficiency and broad coverage [1].

Ideal phase shifters are characterized by their low transmission losses and rapid response to phase alterations, ensuring minimal signal degradation and swift adaptability to network demands. Moreover, uniform loss profiles across all operational states prevent discrepancies in signal quality, thereby maintaining consistent communication standards [2]. The ability of phase shifters to operate bidirectionally adds further value, allowing for the seamless transmission of signals in multiple directions without the need for additional components [3].

The technological versatility of phase shifters is also reflected in their varied types, categorized by the common using control mechanisms: magnetic, mechanical, or electrical. Each type phase shifter offers distinct advantages and is suited for specific applications within different sectors of communication technology. This classification not only underscores the diverse applications of phase shifters but also highlights the ongoing innovations aimed at refining their functionality and integration into more complex systems [4].

As we look with comprehensively the implications of phase shifter technology, it becomes evident that their strategic implementation can significantly enhance the capabilities and efficiency of communication networks. This realization is crucial for advancing current technologies and fostering the development of new methodologies in signal processing and network design [5].

Phase shifters also can be highlighted as critical components within the feeding networks of phased array antennas. Among the most common of these feeding networks is the Butler Matrix (BM) network. The BM is extensively utilized in military and civilian radar systems, air traffic control systems, satellite communications, and recently in emerging high-frequency telecommunications networks such as 5G. This is particularly evident in applications where dynamic shaping and steering of antenna beams are crucial [6-9].

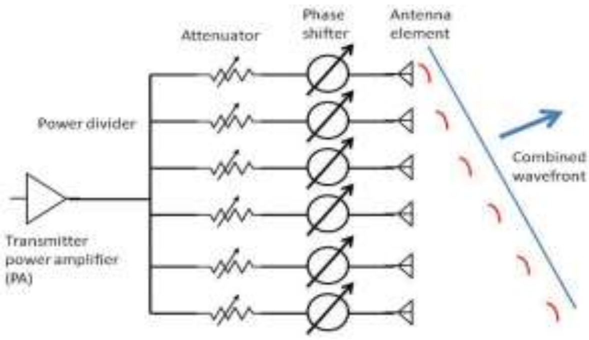

Fig.1 Phased array antenna system.

In BM feeding networks, phase shifters are used to control the beamforming capabilities of antenna arrays and to direct the antenna beams. This enables the adjustment of the signal's direction and width, thereby allowing the antenna array to achieve higher gain in a specific direction or to limit signal transmission towards undesirable directions. Additionally, phase shifters facilitate the antenna array's ability to adapt by reducing interference or unwanted signals from other directions [10-12].

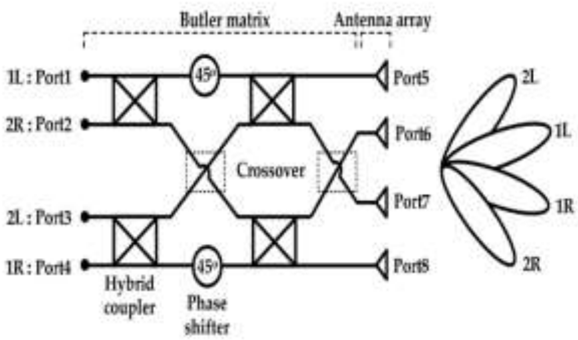

Fig.2 Butler Matrix feeding network.

In this study, a compact adjustable voltage-controlled phase shifter is designed and investigated. The designed phase shifter using the CRLH transmission lines technique is proposed. In this article adjustable voltage-controlled phase shifter design has been presented for use in Butler matrix feeding networks designed for 2.45 GHz wireless communication applications.

II. Materials and Method

A new design of a varactor diode-based voltage-controlled phase shifter has been developed, specifically designed to operate at 2.45 GHz with the capability of achieving up to 100 degrees of phase shift. This design utilizes both right-hand and left-hand transmission line techniques. To isolate DC voltage at the phase shifter's inputs and outputs, an interdigital capacitor was specially integrated into the system. Additionally, a spiral inductor was incorporated to mitigate the effects of RF signals at the DC ports. These design choices significantly enhance the device's functionality and performance, illustrating the critical role of sophisticated component integration in the development of advanced phase shifting technologies.

A. *Design of Phase Shifter*

The design of the adjustable voltage-controlled phase shifter shown in Fig 3 uses a complex arrangement of left-handed (LH) and right-handed (RH) transmission lines [13]. This phase shifter model provides improved flexibility and electronic controllability capability over the desired phase shifting ranges, making it suitable for a variety of advanced communication applications.

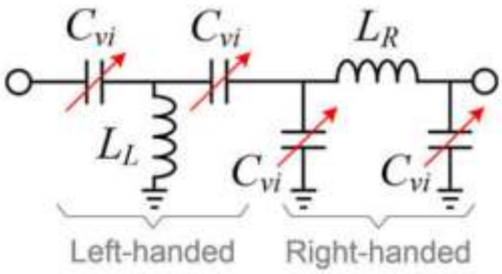

Fig. 3 Proposed phase shifter circuit model [1].

In the design, the inductor values for the right-handed and left-handed transmission lines have been calculated. To adjust the capacitive values, four varactor diodes, whose capacitance values vary between 0-20 V supply voltages, have been used. The designed phase shifter has the capability to shift phase by 100 degrees. For this circuit, operating at a resonance frequency of 2.45 GHz, the L_L value was calculated as 3.59 nH and the L_R value as 3.06 nH. In the design, interdigital capacitors used to block DC voltage at the input and output ports were calculated to be 20 pF, while the value of the spiral inductor was determined to be 30 nH. The designed circuit is shown in Figure 4.

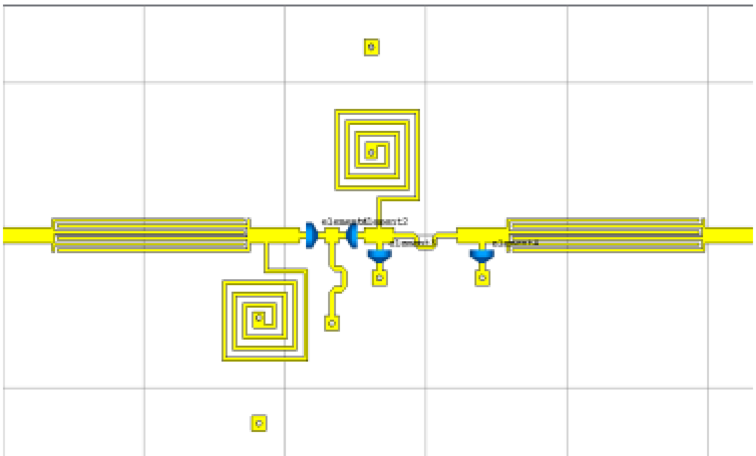

Fig. 4 The top side of designed phase shifter.

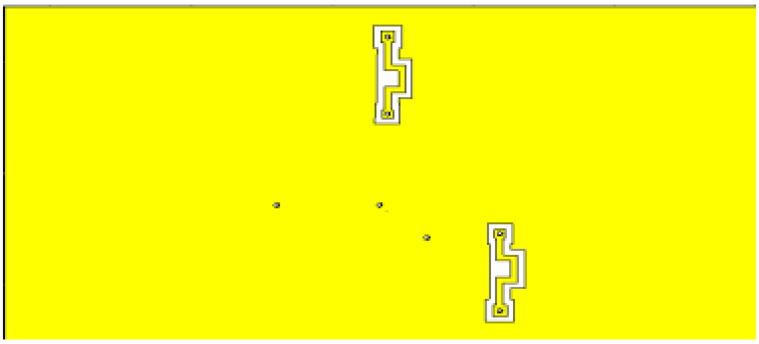

Fig. 5 The bottom side of designed phase shifter.

III. RESULTS

The performance of the designed phase shifter is presented in Figures 5. Before taking measurements, a look-up table for the capacitance versus voltage (C-V) characteristics of the varactors were created according to SMV2020. The capacitance values were set based on this C-V curve needed for the simulation. The bias voltages correspond to capacitance values ranging from 0.35 pF at 20 V to 1.12 pF at 5.8 V. The phase shifter achieves a frequency response while ensuring optimal matching and minimal insertion loss. Specifically, at 2.4 GHz, the return loss is below 10 dB, and the insertion loss S_{21} averages 2.3 dB. Throughout the 2.45–2.5 GHz bandwidth the maximum phase error of 22 degrees or less has been obtained.

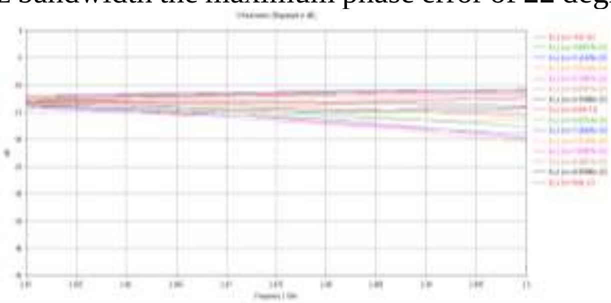

Fig. 6 S_{11} graphic of designed phase shifter.

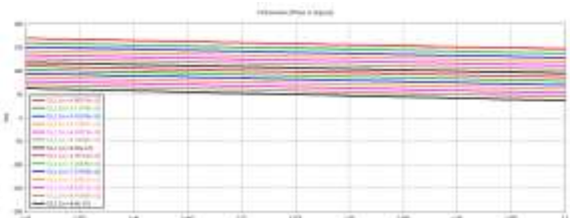

Fig. 7 S_{21} phase graphic of designed phase shifter.

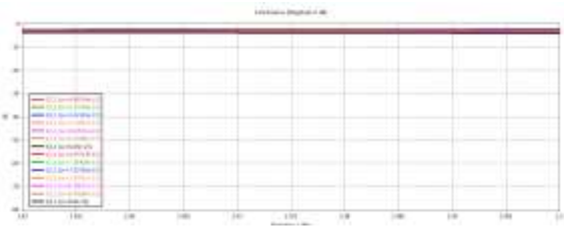

Fig. 8 S_{21} graphic of designed phase shifter.

IV. DISCUSSION

The varactor diode-based adjustable phase shifter presented here marks a significant step forward in the control and flexibility of phase management in communication systems. However, future enhancements are crucial for achieving broader applicability and performance optimization in even more demanding environments.

One of the main goals for future development is the reduction of phase error, which currently stands at less than 22 degrees within the narrow bandwidth of 2.45–2.5 GHz. Reducing this phase error further would lead to more precise beamforming capabilities, critical for applications such as targeted communication links and radar detection systems where accuracy is paramount. Enhanced phase accuracy would enable sharper beam pointing and reduced side lobes, thereby minimizing potential interference and maximizing the effective use of the spectrum. Additionally, expanding the operating bandwidth of the phase shifter is another critical area for enhancement. The current bandwidth, while effective for specific applications, limits the phase shifter's utility across different frequency ranges. By increasing the bandwidth, the phase shifter could be made suitable for a wider array of applications, from broadband wireless communications to multifunctional radar systems. A broader bandwidth would also facilitate the handling of higher data rates, which are increasingly important in the era of 5G and beyond.

V. CONCLUSION

The designed varactor diode-based adjustable phase shifter demonstrates significant potential for enhancing the capabilities of phased array antenna systems, specifically within Butler matrix feeding networks. By providing precise control over phase adjustments, this phase shifter facilitates more accurate beam steering and beam forming, which are critical for optimizing the performance of phased array systems. The ability of the phase shifter to adjust the phase up to 100 degrees with minimal insertion loss and a maximum phase error of less than 22 degrees at specific operating frequencies (2.45–2.5 GHz) ensures that it can seamlessly integrate into existing and future high-frequency communication platforms. This integration is particularly beneficial in applications requiring rapid, dynamic changes in the antenna pattern, such as in radar systems, satellite communications, and 5G networks.

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