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Microwave Loaded Line Phase Shifter Design for Beam-steering Applications in Adaptive Array Antenna System

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Abstract: - In this scholarly work, we present innovative design for Loaded Line Phase Shifter (LLPS) which is tailored for the dynamic requirements of beam-steering adaptive antenna arrays. This phase shifter plays a pivotal role by installing a precise 90º phase shift into the elements of the adaptive array, enabling beam switching in diverse directions. In the absence of the Loaded Line Phase Shifter, the S-Parameter values, specifically S11 and S21, are recorded at 158.88º and -23.72º, respectively. Upon integrating the LLPS into the transmission line, a remarkable transformation occurs with S11 and S21 values transitioning to -143.28º and -53.03º, correspondingly. These results hold great promise for the practical applications of adaptive antenna arrays.

Keywords: Adaptive Array Antenna, Loaded Line Phase Shifter, Beam-steering, Switching Speed, Phase Shift, Microwave.

1. INTRODUCTION:

A phase shifter is a crucial component within a transmit/receive module used in RF (Radio Frequency) and microwave systems. It finds extensive applications in different types of equipment, including phase discriminators, BFNs (Beam-forming Networks), Microwave power dividers, balanced RF amplifiers, and beam-switching arrays [1-3].

A phased antenna array is characterized by having a large number of antenna elements that radiate signals to create a focused electromagnetic beam. The key feature of a phased array antenna is its ability to electronically steer the direction of the radio beam by actively adjusting the relative phase of individual antenna elements [4-6]. Phase shifters play a fundamental role in enabling this capability, allowing for beam scanning and the reconfiguration of the beam's shape.

In practical applications, such as avionics TCAS (Traffic Collision Avoidance System) antennas, phased antenna arrays consist of multiple individual elements. Each of these elements require a dedicated phase shifter to apply the required phase shift, which is essential for steering the antenna beam in a specific direction. Additionally, in some avionics systems utilizing amplitude mono pulse techniques, a phase shifter is used to switch between different directional and Omni-directional antenna modes [7-10].

In summary, phase-shifters are important component in RF and microwave systems, especially in phased array antennas, where they enable the precise control and manipulation of the antenna beam's direction and shape for applications such as radar and avionics systems [11].

Phase shifter specifications encompass a range of factors that designers must carefully consider. These specifications include factors such as cost, physical size, and various technical requirements. In the context of RF and microwave printed phase shifters, specific technical specifications play a critical role in determining their performance and suitability for a given application [12]. Some of these key technical specifications are viz; range of frequency, phase change, bandwidth, switching speed, insertion loss, capacity of power handling, accuracy, Voltage Standing Wave Ratio, and harmonic levels.

Designers typically assign consecutive integer values as weighing coefficients to each of these parameters when

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determining the overall performance of a phase shifter. The maximum allowable value for these coefficients is generally limited to the total number of parameters being considered [13].

The selection of an appropriate phase shifter depends on factors such as the type of transmission line, prototype manufacturing, and weighing factor the assigned to these parameters. In many cases, to minimize cost and facilitate miniaturization, phase shifters are designed using microstrip transmission lines, which are well-suited for microwave and RF applications due to their compact size and cost-effectiveness [14].

Therefore, phase shifter specifications encompass a range of technical parameters that impact the design and performance of these critical components in RF and microwave systems. Designers carefully weigh these parameters to meet the requirements of a particular application while considering factors like cost and size. Opting for low-cost strip-line or slotted strip-line configurations is favourable desired transmission media for phase shifter design. The synthesis of a prototype phase shifter is depending upon system requirements as well as derived specifications [15-16]. The outcome of this synthesis process includes the physical parameters of the phase shifter and, if necessary, the values of lumped elements.

Electrical performance of the designed phase shifter is determined through analysis based on its physical dimensions [17]. Phase shifters are typically categorized into two types based on the desired output which is analog and digital. Digitally controlled bits are used to divide the phase into predetermined states, which is controlled by switching elements like PIN diodes and FETs. These digital phase shifters find applications in high-speed and current-controlled phase-shifting operations. On the other hand, analog phase shifters offer continuous phase shift control based on control inputs. While they are less affected by control element drift, they may exhibit degradation in insertion loss [18].

In digital phase shifters, switching elements like PIN diodes are manipulated by adjusting the bias voltage from forward to reverse and vice versa. In MMIC (Monolithic Microwave Integrated Circuit) design, open FETs are used as switching elements [19]. GaAs (Gallium Arsenide) phase shifters are compact and suitable for thin-film semiconductor manufacturing but are costly.

Analog phase shifters utilize control elements such as varactor diodes, which offer electrically variable capacitance when operated in reverse-biased mode. They can achieve significant phase shifts and high speeds while requiring fewer diodes than digital counterparts [20]. However, they have less accuracy, narrower bandwidth, and lower power handling capabilities (typically less than 1W). In analog phase shifters Schottky diodes are also used with challenges such that power handling and matching in broadband networks.

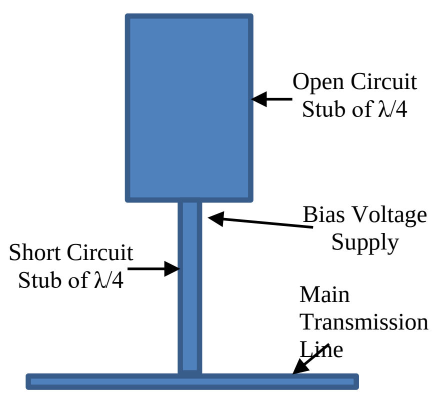

Fig.1. Layout of Loaded Line Phase Shifter

Microwave phase shifters can be implemented through various methods, like loaded line, switched-line, switched N/W, and reflection types [21]. Among the various phase-shifting techniques, the switched-line phase shifter emerges as an elegant and practical solution. It capitalizes on disparities in time delays between two direct signal paths to attain the desired phase shift. The fundamental structure of this design comprises key components such as phase elements, switch elements, and a dedicated control network. The selection of appropriate switch elements is contingent upon the precise prerequisites of the phase shifter, often correlated with the length of the utilized transmission line. Notably, switched-line phase shifters exhibit nearly linear frequency-dependent phase shifts, enabling operation across a wide frequency range while maintaining stability over time and temperature [22].

This paper has been organised as; design of Loaded Line Phase Shifter (LLPS) using CST Microwave Studio is explained in section two. Third section presents simulation results of LLPS for S11 and S21. Final section is used to conclude all research work.

2. ANALYSIS OF LOADED LINE PHASE SHIFTER

Loaded line phase shifters (LLPS) incorporate shunt reactance, typically in the form of inductors or capacitors, to induce a phase shift in the signal. The schematic of a conventional LLPS is illustrated in Fig. 1. Each segment of the loaded line phase shifter comprises a λ/4 transmission line symmetrically loaded at its terminations with small susceptance, strategically arranged to cancel out reflections resulting from the λ/4 separation. This design characteristic ensures a favourable impedance match for the phase shifter section in both of its control states. These values are manipulated using semiconductor devices, such as PIN diodes.

The required phase shift is achieved by changing the electrical dimensions through the actuation of PIN diodes. The loading admittance of these elements is controlled through these switching diodes, allowing for the electrical extension or contraction of the transmission line. Designing a loaded line phase shifter utilizing micro-strip lines necessitates the knowledge of the line impedance (Z_T) of the quarter-wave transformer (λ/4 line) and the electrical length (βl) of the short stub. When two susceptances are separated by λ/4 spacing, it results in a broader bandwidth [15].

The LLPS offers the advantages of simplicity and low insertion loss when applied for phase shifts less than 45°. To enhance insertion loss performance, the utilization of lower-loss dielectric materials is recommended. However, a notable drawback of this phase shifter type becomes evident when dealing with larger phase shift requirements, as it necessitates high values of susceptance, leading to an increase in insertion loss.

When selecting between elements for susceptance, capacitors prove to be the superior choice over inductors in the context of a LLPS. Shunt capacitor elements effectively increases electrical length of a transmission line, while shunt inductance has the opposite effect, causing electrical shortening [23]. The major performance parameters of microwave Phase Shifters are, Frequency Range, Bandwidth, Phase Change (Δj), Insertion Loss, Switching Speed, Power Handling, Accuracy and Resolution, VSWR or Return Loss, Harmonics Level.

The relationship between the propagation constant, phase shift, delay, and wavelength is fundamental in understanding phase shifters. In a transmission line, the propagation constant is a complex number, composed of two parts. The real component represents the attenuation constant, indicating how the signal amplitude decreases as it travels along the line. The imaginary component, denoted as βx, is the phase constant in radians per unit length, indicating the phase difference between the voltage at the sending end and a point at distance x.

A phase shift of 360 degrees (2π radians) corresponds to one wavelength, which marks the separation between consecutive zero-crossings on a waveform, as depicted in the figure. The wavelength (λ) is defined as the distance (x) required for the phase angle βx to increase by 2π radians, expressed as λ = 2π/β. A phase shift can also be seen as a delay, and the relationship between phase shift and time delay is captured by equation (1).

$$Timedelay(seconds) = \frac{[Phaseshift\ (0)]}{[360\_frequency(Hz)]} \dots\dots\dots\dots\dots\dots\dots (1)$$

The time delay experienced in a transmission line is directly proportional to the reciprocal of the propagation velocity (υp). This time delay, in terms of the delay introduced per unit distance (X), is quantified by equation (2)

$$Timedelay = \frac{\text{X}}{vp} = \frac{\beta x}{\omega} \dots\dots\dots\dots\dots\dots\dots (2)$$

Where,

X is distance,

vp is phase velocity,

βx is phase angle,

ω is radial frequency

Group delay, a vital parameter, represents the mean time delay encountered by signals within a defined narrow frequency band as they traverse a circuit. This group delay is proportionate to the rate of phase shift experienced at each specific frequency of interest, and it can be quantified using equation (3)

$$Groupdelay(seconds) = \frac{1}{36} \text{x} \frac{\Delta J}{\Delta f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where,

ΔJ is total phase change, and

Δf is frequency range,

Loaded line phase shifters employ shunt reactance components, such as inductors or capacitors, to introduce phase shifts into the circuit. Each segment of a loaded line phase shifter consists of a λ/4 transmission line that is symmetrically loaded at its ends with small susceptance elements, strategically positioned to mutually cancel out any reflections arising from the λ/4 separation. This design feature ensures an excellent impedance match for the phase shifter section in both of its control states.

Designing a loaded line phase shifter utilizing microstrip lines involves the consideration of two key parameters: the characteristic impedance (Zo) of the quarter-wave transformer (λ/4 line) and the electrical length (βl) of the short stub. By maintaining λ/4 spacing between two susceptance values, a broader bandwidth is achieved, enhancing the phase shifter's performance. A visual representation of the design layout of a loaded line phase shifter can be observed in Fig. 2.

3. DESIGN STEPS AND RESULTS OF LLPS

Calculations and simulation of Loaded Line Phase Shifter (LLPS) for beam-steering array applications is carried out using CST software. For this LLPS, design steps are as given below:

1. For loaded line phase shifter series LC tank circuit is used where C acts as open circuit stub with λ/4 length which is low impedance line and L acts as a short circuit stub with λ/4 length which is high impedance line.
2. For input/output 50 W lines, width Wo is calculated which is 3 mm using equation (4)
3. Choose ZL = 120 W for 8 nH inductive line and calculate width WL.
4. Choose ZC = 20 W for 2.2 PF capacitive line and calculate width WC.
5. For a given inductance L calculate the length of an inductive line using equation

$$l_L = \frac{\lambda H}{2\pi} sin^{-1}(\frac{\omega L}{Z_L}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where,

l_L is length of inductive line,

ω is frequency,

L is inductance (8 nH),

Z_L is impedance of inductive line,

λ is wavelength at 3.6 GHz,

H is distance between stripline and ground (1.6 mm)

6. For a given capacitance C calculate the length of a capacitive line using equation (5)

$$l_c = \frac{\lambda H}{2\pi} sin^{-1}(\sin^{-1} \omega c Z_C) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

7. From the above equations, calculated width of the capacitive line, WC is 9.012 mm and length LC is 11.10 mm for 20 W.
8. From the above equations, calculated width of the inductive line, WL is 0.408 mm and length LC is 12.11 mm for 90 W.
9. S-parameter values observed from Fig.3. are S11 without phase shifter is 158.88°, S21 without phase shifter is -23.72°, S11 with phase shifter -143.28°, S21 with phase shifter -53.034°
10. Structure layout for LLPS is presented in Fig.2. Overall Phase Shift obtained with this LLPS is only -29.31° which is indicated in Fig.3.

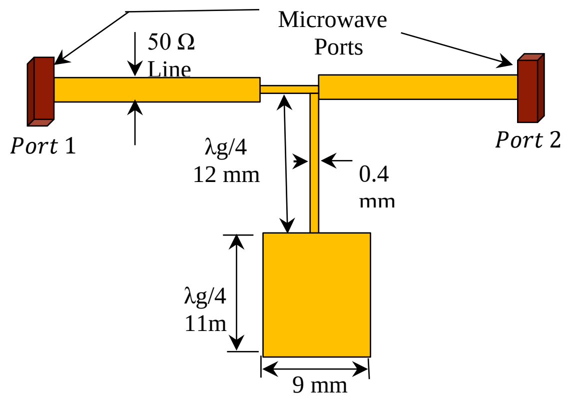

Fig.2. Layout of Loaded Line Phase Shifter using CST

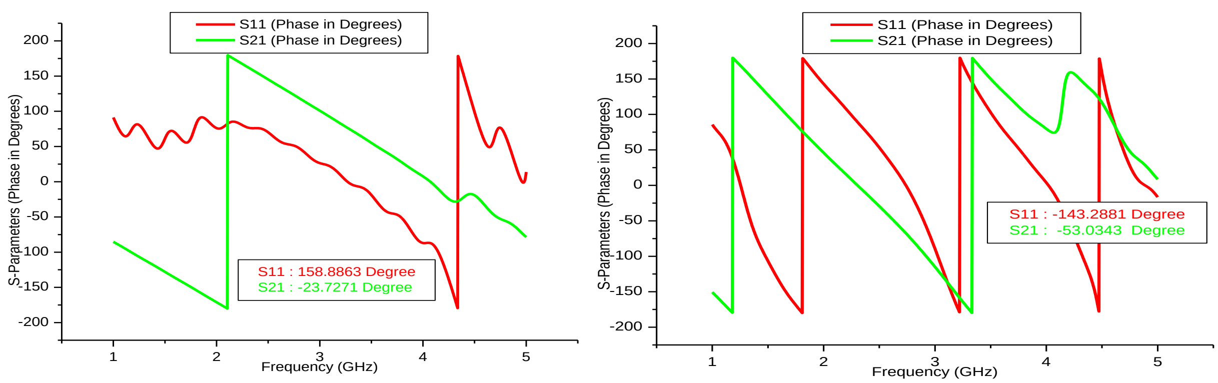

Fig. 3. S-Parameters S11= -153.88º and S21= -23.72º without LLPS (Left) and S11= -143.28º and S21 = -53.03º with LLPS (Right)

Table1: Design Specification and Result Analysis of LLPS

Sr.No.	Parameter	Value
1	Impedance for Inductive Line ZL	120W
2	Width for Inductive Line WL	0.408 mm
3	Length for Inductive Line LL	12.11 mm
4	Impedance for Capacitive Line ZC	20W
5	Width for Capacitive Line WC	9.012 mm
6	Length for Capacitive Line LC	11.10 mm
7	S11Without Phase Shifter	158.88º
8	S21Without Phase Shifter	-23.72º
9	S11With Phase Shifter	-143.28º
10	S21With Phase Shifter	-53.034º

4. CONCLUSION

In this research work, we have presented innovative design for Loaded Line Phase Shifter (LLPS) which is very useful for the dynamic requirements of beam-steering adaptive antenna arrays. This phase shifter plays a pivotal role by installing a precise 90º phase shift into the elements of the adaptive arrays, enabling beam switching in diverse directions. In the absence of the

Loaded Line Phase Shifter, the S-Parameter values, specifically S11 and S21, are recorded at 158.88º and -23.72º, respectively. Upon integrating the LLPS into the transmission line, a remarkable transformation occurs with S11 and S21 values transitioning to -143.28º and -53.03º, correspondingly. Therefore, an aggregate phase shift of -29.31º has been achieved. This result holds great promise for the practical applications of adaptive antenna arrays.

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REFERENCES

[1] Dipali Bansal, M. Tripathy, S. Padhi, "Adaptive Beamforming Method based Optimal Smart Antenna Selection with RSC Algorithm in 5G system", IEEE Wireless Antenna and Microwave Symposium (WAMS), 5 June 2022 Business, Computer Science.

[2] Errifi, H.; Baghdad, A.; Badri, A.; Sahel, A. Electronically reconfigurable beam steering array antenna using switched line phase shifter. In Proceedings of the 2017 International Conference on Wireless Networks and Mobile Communications (WINCOM), Rabat, Morocco, 1–4 November 2017; pp. 1–6.

[3] Djerafi, T.; Fonseca, N.J.G.; Wu, K. Planar Ku-band 4 × 4 Nolen matrix in SIW technology. IEEE Trans. Microw. Theory Tech. 2010, 58, 259–266

[4] Vidya P. Kodgirwar, Shankar B. Deosarkar, Kalyani R. Joshi, Aarti J. Vyavahare, "Design of Adaptive Array with E-Shape Slot Radiator for Smart Antenna System", Progress in Electromagnetic Research, Cambridge, USA, 2020.

[5] Vidya P. Kodgirwar, Shankar B. Deosarkar, Kalyani R. Joshi, "Design of Dual Band Beam Switching Array for Adaptive Antenna Applications using Hybrid Directional Coupler and E-Shape Slot Radiator", Wireless Personal Communication by Springer Nature.

[6] Vidya P. Kodgirwar, Shankar B. Deosarkar, and Kalyani R. Joshi, "Design of beam steering-switching array for 5G S-band adaptive antenna applications–part-I and part-II", IETE Journal of Research, ISSN-0377-2063, DOI:10.1080/03772063.2020.1732843, p-1-13, Nov.2020.

[7] Shankar B. Deosarkar, Vidya P. Kodgirwar and Kalyani R. Joshi, "Design of Microstrip Line BPF and Preamplifier for Adaptive Antenna System", Computing in Engineering and Technology, Advances in Intelligent Systems and Computing 1025, https://doi.org/10.1007/978-981-32-9515-5_67, 17 October 2019.

[8] Bousbia, L.; Ould-Elhassen, M.; Mabrouk, M.; Ghazel, A. New synthesis of tunable filter and phase shifter used for phased array antennas applications. In Proceedings of the 2014 International Conference on Multimedia Computing and Systems (ICMCS), Marrakech, Morocco, 14–16 April 2014; pp. 1348–1353.

[9] Siti Nailah Mastura Zainarry, Student Member, IEEE, Nghia Nguyen-Trong, Member, IEEE, and Christophe Fumeaux, Senior Member, IEEE," A Frequencyand Pattern-Reconfigurable two-element Array Antenna", IEEE Antennas and Wireless Propagation Letters, Vol. 17, NO. 4, April 2018.

[10] Zheng Gan, Zhi-Hong Tu, and Ze-Ming Xie, "Pattern-Reconfigurable Unidirectional Dipole Antenna Array Fed by SIW Coupler for Millimeter-Wave Application", IEEE Access, Vol 6, 2018.

[11] Bartlett, C.; Salem Hesari, S.; Bornemann, J. End-fire substrate integrated waveguide beam-forming system for 5G applications. In Proceedings of the 2018 18th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM), Waterloo, ON, Canada, 19–22 August 2018; pp. 1–4.

[12] Nikfalazar, M.; Mehmood, A.; Sohrabi, M.; Mikolajek, M.; Wiens, A.; Maune, H.; Kohler, C.; Binder, J.R.; Jakoby, R. Steerable dielectric resonator phased-array antenna based on inkjet-printed tunable phase shifter with BST metal-insulator-metal varactors. IEEE Antennas Wirel. Propag. Lett. 2016, 15, 877–880.

[13] Alfredo Catalani, Giovanni Toso, Piero Angeletti, Mario Albertini and Pasquale Russo, "Development of Enabling Technologies for Ku-Band Airborne SATCOM Phased-Arrays", Electronics 2020, 9(3), 488; https://doi.org/10.3390/electronics9030488 - 16 Mar 2020.

[14] Yongzhen Li, Zhanling Wang, Chen Pang and Xuesong Wang, "A Low Cross-Polarization Configuration Method for Phased Array Radar Antenna", Electronics 2020, 9(3), 396; https://doi.org/10.3390/electronics9030396 - 27 Feb 2020.

[15] Vidya P. Kodgirwar, Shankar B. Deosarkar, Kalyani R. Joshi, "Design of Beam Steering-Switching Array for 5G S-Band

Adaptive Antenna Applications (Part-I and Part-II)", IETE Journal of Research, Manuscript Id: TIJR- 2019-0951, ISSN(P): 0377-2063 11 March 2020.

[16] Weijian Si, Zhanli Peng, Changbo Hou and Fuhong Zeng, "Design of Novel Nested Arrays Based on the Concept of Sum-Difference Coarray", Electronics 2020, 9(1), 115; https://doi.org/10.3390/electronics9010115 - 07 Jan 2020.

[17] Shuli Shi, Yougen Xu, Junpeng Zhuang, Kang Zhao, Yulin Huang and Zhiwen Liu, "Tri-polarized Sparse Array Design for Mutual Coupling Reduction in Direction Finding and Polarization Estimation", Electronics 2019, 8(12), 1557; https://doi.org/10.3390/electronics8121557 - 17 Dec 2019.

[18] Zhanling Wang,Chen Pang,Yongzhen Li andXuesong Wang, "Bias Correction to Antenna Frequency Response for Wideband Polarimetric Phased Array Radar", Electronics 2019, 8(10), 1075; https://doi.org/10.3390/electronics8101075 - 23 Sep 2019

[19] Massimiliano Comisso, Gabriele Palese, Fulvio Babich, Francesca Vatta and Giulia Buttazzoni, "3D Multi-Beam and Null Synthesis by Phase-Only Control for 5G Antenna Arrays", Electronics 2019, 8(6), 656; https://doi.org/10.3390/electronics8060656 - 11 Jun 2019.

[20] Massimiliano Comisso, Gabriele Palese, Fulvio Babich, Francesca Vatta and Giulia Buttazzoni, "3D Multi-Beam and Null Synthesis by Phase-Only Control for 5G Antenna Arrays", Electronics 2019, 8(6), 656; https://doi.org/10.3390/electronics8060656 - 11 Jun 2019.

[21] Wei Hu, Guangjun Wen, Daniele Inserra, Yongjun Huang, Jian Li and Zhizhang (David) Chen,"A Circularly Polarized Antenna Array with Gain Enhancement for Long-Range UHF RFID Systems", Electronics 2019, 8(4), 400; https://doi.org/10.3390/electronics8040400 - 03 Apr 2019.

[22] Tao Wu, Xiaofeng Zhang, Yiwen Li, Zhenghong Deng and Yijie Huang, "On Spatial Smoothing for DOA Estimation of 2D Coherently Distributed Sources with Double Parallel Linear Arrays", Electronics 2019, 8(3), 354; https://doi.org/10.3390/electronics8030354 - 23 Mar 2019.

[23] Ding, Y.; Wu, K. Varactor-tuned substrate integrated waveguide phase shifter. In Proceedings of the 2011 IEEE MTT-S International Microwave Symposium, Baltimore, MA, USA, 5–10 June 2011; pp. 1–4