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ANALYSIS AND DESIGN OF A SIX-PORT NETWORK BASED ON A MODIFIED SCHIFFMAN PHASE SHIFTER

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ABSTRACT

Purpose: This study presents a novel design of a six-port network based on a modified Schiffman phase shifter operating at a 90±2° phase shift.
Design/ Methodology/ Approach: The research methodology encompasses a comprehensive literature review, the analysis, design and simulation of the novel phase shifter, its integration into a six-port network, layout design and subsequent post-layout simulation, and comparative analysis to evaluate the new design's performance.
Findings: The schematic results showed an operational bandwidth from 5.52 GHz to 12.21 GHz, translating to a fractional bandwidth of 75.47% with a maximum phase error of ±1.8° for the 90° phase shift. Also, the post-layout simulation results from momentum demonstrated outstanding performance with an operation frequency band spanning from 5.52 GHz to 12.21 GHz, representing a factional bandwidth of 75.47% and ±2.1° phase error across the entire band. In addition, good impedance matching was achieved at all the ports well below -10 dB.
Research Limitation: This limitation acknowledges the inherent constraints in simulation-based research while recognising the need for future physical validation and testing.
Practical Implication: It also finds application in satellite communications, where beamforming enhances signal strength and quality by directing the signal towards specific locations on Earth, and antenna arrays for satellite uplink and downlink antennas adjust the beam direction and coverage area dynamically.
Social Implication: The social impact of this work includes high-performing communication devices for current and future generations, more accurate measurements, particularly wearable devices in healthcare for monitoring human vitals, weather monitoring systems, high-precision radar systems, wireless gadgets, high-data-rate communication systems, and Internet of Things (IoT) devices.
Originality / Value: The study contributes to the existing body of knowledge by introducing an innovative design that addresses the limitations of phase accuracy and bandwidth in Six-Port Networks.

Keywords: *Coupled line. hybrid coupler. shifter. single phase. six-port network*

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INTRODUCTION

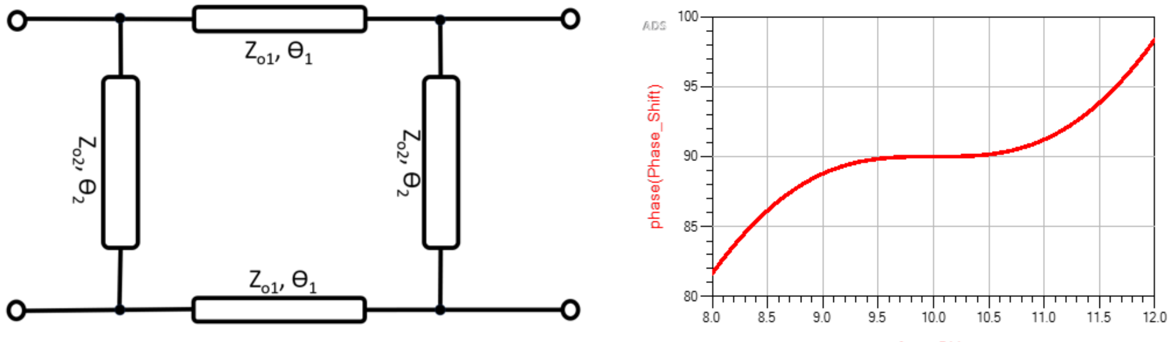
In recent years, the growing desire for low complexity, wideband, miniature, low-cost and low power consumption devices in microwave and wireless communications has led RF and microwave engineers to examine creative methods for the design of RF and microwave circuits (Bilal, Muhammad, & Mujahid, 2020) (Gyaang, Lee, & Kim, Analysis and design of harmonic rejection low noise amplifier with an embedded notch filter, 2020). This demand is no exception for designing a six-port network, particularly in sensitive applications areas such as transceiver design, instrumentation, direction finding and metrology, which are just a few examples.

In addition, the necessity for high data rates for current applications to execute activities such as real-time communication has demanded wider bandwidths to accommodate broadband equipment, enabling faster data transfer. Furthermore, the implementation of 5G and advancements in future generations of communication technologies (such as 6G) (Morandini, 2024) demand devices that can operate efficiently across a wide frequency band Gyaang, Lee, Mauludin, & Kim (2021); Gyaang, Lee, & Kim (2020). These require significantly more efficient power usage and wideband capabilities. Six-port networks combine ultra-wideband (UWB) capabilities, simplicity, and adaptability to provide efficient solutions for demanding projects in various applications, making them critical components in current microwave and wireless systems.

A six-port network uses complex transmission lines, directional couplers, power dividers, and other passive or active components to offer precise signal processing and measurement. These networks are particularly valued for their ability to simultaneously analyse various signal parameters, including amplitude, phase, frequency, and time delay, with high precision and efficiency.

The earliest six-port network suggested by Engen (Engen, 1980) included a power divider and a hybrid coupler. Diverse designs have evolved, and the architecture chosen is always determined by the applications and performance constraints (Luzzatto & Haridim, 2016). The power divider's typical function is dividing input power into two halves along the signal lines. The Wilkinson power divider (Wu, Liu, & Xue, 2010) is a well-known device that can distribute power across an extensive frequency range.

Hybrid couplers accomplished a flawless 90° phase shift, especially at the design frequency. They also provide enough isolation between the input and isolated ports. Hybrid couplers are useful for applications requiring phase shift across a narrow range of operative frequencies. However, their high phase variation beyond 10% bandwidth of the specified frequency (Abdulbari, et al., 2021) makes them unsuitable for wideband applications. The phase response of a conventional hybrid coupler is shown in Figure. 1 (a) is given in Figure 1 (b). As can be seen in the plot, there is a sharp phase deviation at about 500 MHz from the centre frequency, giving it an operational bandwidth of about 1 GHz.



(a) (b)

Figure 1: Conventional Hybrid Coupler (a) block diagram and (b) Phase response

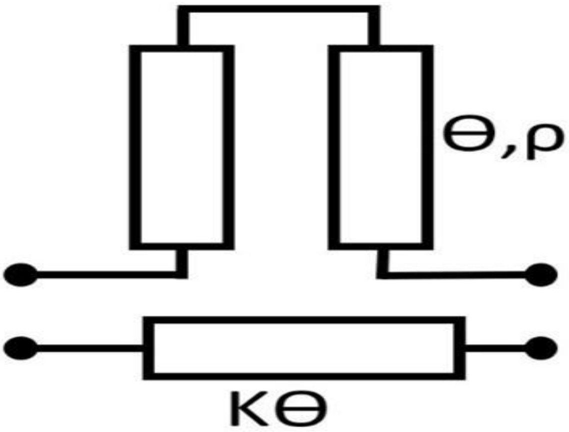


Figure 2: Block diagram of a conventional Schiffman phase shifter

LITERATURE REVIEW

To improve bandwidth performance, several architectures have been investigated over the years, including an N-section hybrid coupler architecture (An, et al., 2022), Schiffman phase shifter proposed by Bernard M. Schiffman (Schiffman, 1958), capacitive compensation (Dydyk, 1990), optimal positioning of capacitors for capacitive compensation (Muller, Pham, & Jacob, 2011), hybrid type of Schiffman (Hussain, Rashid, & Ullah, 2013) and the use of high-pass network (Huang & Lu, 2015).

Obtaining a phase shift over a wideband, such as an FBW, beyond 70% utilising the multi-sectioned hybrid coupler remains challenging for circuit designers. Also, the pin diode phase shifters are known for their flat phase shift of not more than 1°, but they require at least two pin diodes working in a low-pass/high-pass arrangement to accomplish the appropriate phase shift. Their working bandwidth is quite restricted, rendering them unsuitable for wideband operations. Standard Schiffman phase shift, while its capacity to produce a vast range of operative frequencies, produced a pretty substantial phase error, making it unsuitable for delicate applications. Furthermore, the standard Schiffman phase shifter shown in Figure 2 is a differential phase shifter comprised of two distinct transmission lines, one of which is folded (coupled) to be dispersive. The phase variation across the two lines can often be made practically constant over a large bandwidth by selecting the right length and degree of coupling (Karmakar & Bialkowski, 1999). It uses the even and odd mode impedance ratio and the coupling impact of the coupled line to attain phase synchronisation throughout its operation band.

This technique, however, restricts the possibility of having a very low phase error given that both the impedance ratio and coupling effect are bound by the minimum permissible separation between the coupled lines for manufacture, which required further research that has been conducted in this field over the years. The phase difference between them can be almost constant over a broad bandwidth through the proper selection of the length of these lines and the degree of coupling. To achieve a tight coupling in the coupled line, the even and odd mode impedance ratio of (1) must be set to a value less than 2 (Schiffman, 1958) as shown in the various classes of Schiffman phase shifters.

The drawback of this technique is that it limits the operational bandwidth. Secondly, the impedance ratio or coupling effect, although helping in achieving the flat phase performance, also results in a fabrication constraint requiring a minimum allowable spacing between the coupled lines, which results in a tricky trade-off that is often difficult to achieve. Thirdly, the characteristic impedance must be chosen with the input and output impedances in mind and thus cannot be selected arbitrarily.

$$\rho = \frac{Z_{even}}{Z_{odd}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Due to the above design constraints of the conventional Schiffman, several modified Schiffman phase shifters have since evolved. A modified ground plane of the coupled line was presented in (Guo, Zhang, & Ong, Improved wide-band Schiffman phase shifter. , 2006). This resulted in an improved even-mode impedance while at the same time decreasing odd-mode impedance. The results showed a 1.0 to 3.5 GHz bandwidth with a phase derivation within ±5° only possible over 1.7 to 2.9 GHz, or 70%. However, this technique uses a try-and-error approach since there is no theoretical basis to back the exact area of the ground plane to cut for the corresponding even/odd mode impedance the designer wishes to achieve.

Capacitive compensation of the coupled line Muller, Pham, & Jacob (2011); Dydk (1990) was introduced to improve the coupling effect of the coupled line. The authors (Muller, Pham, & Jacob, 2011) discussed the compensation for phase velocity differences in coupled line microstrip couplers utilising parallel capacitances. They present an accurate design synthesis for the phase velocity compensation and several design examples. They argued that the directivity-bandwidth performance is significantly improved by optimising the positions of capacitances along the coupled line structure in directional couplers. The parasitic even-mode capacitance was considered throughout the analysis using a realistic model. The authors (Dydyk, 1990) also presented an accurate design of microstrip directional couplers with high directivity using capacitive compensation. It utilised symmetry analysis and equivalence principles to develop closed-form solutions of the compensating capacitance and a new odd mode characteristic impedance necessary to realise an ideal microstrip directional coupler. The approach generated accurate quadrature microstrip directional coupler designs that were valid for tight and loosely coupled sections.

The drawback, however, is that the exact position of the compensation capacitance cannot be determined. Additionally, the compensation did not present much impedance variation to achieve an ultra-wide bandwidth performance. Furthermore, lump components are known to change behaviour when operating at higher frequencies and can present more significant loss than transmission lines; hence, this technique is only accurate at low frequencies.

Hussain, Rashid, and Ullah (2013) and Huang and Lu (2015) introduced a hybrid type of Schiffman phase shifter. Hussain et al. (2013) intimated that the new hybrid type of phase shifter used Schiffman lines for both the primary and reference lines. Compared with existing designs, it could achieve a much smaller phase shift error over a broader frequency range (2.85-17.15 GHz) with a minimal error of ±5°.

Although the bandwidth was improved compared to other techniques, the phase deviation is relatively high for sensitive applications. The second approach (Huang & Lu, 2015) presented a method to realise a broadband 90 differential phase shifter using a high-pass network with a coupled line section for reducing the phase error to less than ±2°.

The proposed phase shifter operated as a high-pass network at low frequency and a coupled line at high frequency. By this approach, the coupled line did not require tight coupling. Moreover, by adjusting the ratio of even/odd mode impedances of the coupled line, the return loss could be improved, and the limitation of fabrication was also relaxed. (Karmakar & Bialkowski (1999); Jackson, (2018); Zohuri, (2020); Kızıltaş, (2013).

Also, at low frequencies, the return loss and phase error can be improved by adjusting the values of the filter inductor and capacitor and the impedance of the coupled line, which subsequently relaxes the limitation of fabrication. However, the technique still depends on the impedance ratio at a high frequency of operation. This means that the compensation only works for low frequencies, hence not suitable for applications operating at high frequencies.

Other techniques included the use of artificial neural networks (An, et al., 2022) and (Gyaang, Abdul-Rahman, Gookyi, Jang, & Lee, 2023) to predict and compensate for the phase error, which has similar behaviour to capacitive compensation, multi-sectioned coupled lines approach (Yin, et al., 2015) which achieved a phase shift of less than 1° and a bandwidth performance of 20.4%. The structure (Yin, et al., 2015) is bulky and presents an increased loss despite the low bandwidth. An improved Schiffman phase shifter with two C-section coupled lines that separately operate in the first and second phase periods was presented in (Geyikoglu, Koc Polat, & Cavusoglu, 2020) and (Qiu, Zhu, & Lyu, 2019). Theoretical models and analyses of their performance were presented. For the first and second phases, respectively, a phase shift deviation of ±3° across a fractional bandwidth of 33.6% and 36.7% at 90° and 150° phase shifts was achieved. However, the bandwidth is still woefully inadequate for broadband operations.

This work proposes a novel technique for designing a modified Schiffman phase shifter with improved phase error and bandwidth performance. The design synthesises the even mode excitation of a coupled line to improve the impedance ratio (ρ), enhancing the phase performance while overcoming the fabrication constraints of a minimum coupled line space. The simulation results from the design were found to correlate with those predicted from the theoretical equations.

METHODOLOGY

A thorough review of the literature, the design and modelling of the new phase shifter, and a performance comparison study will all be included in the research. Consideration will be given to important performance standards, and the research goal is to improve telecommunications significantly. This study design aims to methodically address the important elements involved in creating and evaluating a high-performance Six-Port Network. This updated Schiffman Phase Shifter is predicted to address current problems with bandwidth and phase precision, which makes the study extremely pertinent to the advancement of telecommunications technology. The research is thorough, and the conclusions are reliable and applicable thanks to the technique, which combines extensive design, simulation, and comparative analysis. The structured approach ensures a comprehensive analysis of all noteworthy variables impacting network performance, furnishing a robust groundwork for forthcoming investigations and pragmatic implementations.

Modified Schiffman Phase Shifter Design

The traditional Schiffman phase shifter consists of two transmission lines, one folded to form a coupled section to create dispersion when a signal passes through it as shown in Figure. 2. Hence, a coupled line is formed, consisting of two conductive strips placed in close proximity to each other. In its standard operation, as shown in Figure. 3 (a), a voltage is applied to one of the strips, and an electromagnetic wave is generated that travels along the line. Similarly, differential signals (Figure. 3 (b)) or common mode signals (Figure. 3 (c)) can be used to excite the coupled line to vary the even/odd mode impedances of the line. Since the two lines are designed to be very close, a level of coupling exists between these lines, which closely relates to the differential/common mode excitation and consequently results in differential and common modes of propagation. A detailed analysis of the impedance and propagation characteristics of these lines with perturbation has been explained by (Yin, et al., 2015), (Bandler, Johns, & Rizk, 1977) and (Wageeh, El-Sabban, & Khalil, 2022).

This work synthesises the common mode perturbation of the coupled line to design a modified Schiffman phase shifter with highly improved phase error and bandwidth performance. This proposed novel design is given in Fig. 5 below. The main line employs three coupled lines. The first set of coupled lines (θ_1, ρ_1, and θ_2,, ρ_2,) uses a multi-section technique to improve the bandwidth and phase performance at the lower frequency (Sun, Chen, Han, & Lu, 2019) and (Quirarte & Starski, 1993). The second coupled line ($\theta_3, \rho_3,$) employs the common mode signal (even mode excitation) with twice the matching impedance (100 Ω) which also improves the value of ρ. For instance, using a 50ω impedance gives a ρ value of two, whereas this approach can give a ρ value greater than 3 with a minimum odd mode impedance of not less than 25 Ω.

The third coupled line (θ, ρ) is based on the conventional Schiffman technique. The reference line employs a coupled line with weak coupling. This approach helps reduce the bulkiness of the structure if transmission lines are employed. The chosen structure is based on the interdependence of several physical parameters of the coupled line and the phase error, bandwidth and impedance matching. For instance, the effective impedance of a coupled line was found to be expressed as:

$$Z_{eff} = Z_o \frac{Z_{even}\cosh(\gamma d)+Z_{odd}\sinh(\gamma d)}{Z_{even}\sinh(\gamma d)+Z_{odd}\cosh(\gamma d)} \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Where $Z_o,$ is the characteristic impedance of each line, Z_{odd} is the odd mode impedance when the coupled line is excited with a differential signal, Zeven is the even mode impedance when the coupled line is excited with a common mode signal, γ is the complex propagation constant of the lines, and d is the separation between the lines. Equation (2) considers the effects of the even and odd mode impedance, the coupling between the lines given by the distance between the line, d and the complex propagation constant of the line, γ. This equation directly relates to (1).

In both the original Schiffman (Schiffman, 1958) and the novel approaches to Schiffman phase shifter designs proposed by (Quirarte & Starski, 1993) and (Guo, Zhang, & Ong, Improved wide-band Schiffman phase shifter. , 2006), the value of ρ in Equation (1) directly influences the phase error and bandwidth performance. Thus, an increasing value results in a large bandwidth but with a significant phase error. This is because a large ρ value means less coupling and vice-versa. With the even mode excitation in θ3, ρ3, (1) the odd mode impedance is made constant while at the same time increasing the even mode impedance due to coupling capacitance and inductance of the coupled line as given in Figure. 6 and (2) the characteristic impedance of the coupled line is twice the matching impedance thereby doubling the ratio of the even/odd mode impedance. This approach results in a larger value of ρ while at the same time maintaining the effective coupling that exists between the coupled lines.

$$Z_c = -20\log\left(\frac{\rho-1}{\rho+1}\right) \ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

$$\Delta\emptyset = K\theta - \cos\frac{\rho-tan^2\theta}{\rho+tan^2\theta} \ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

$$Z_{eff\_even} = Z_o + Z_{even} = Z_{oe} + \sqrt{\frac{L_{11}+L_{12}}{C_{11}+C_{12}}} \ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

$$\rho_{eff} = \frac{Z_{eff\_even}}{Z_{oo}} = \frac{Z_{oe}+\sqrt{\frac{L_{11}+L_{12}}{C_{11}+C_{12}}}}{Z_{oo}} \ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

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Here, L_{11}, L_{12}, $C_{11}$and C_{11} are the parasitic effects due to even mode excitation. This approach can overcome the design constraints discussed in Section 1 above based on this analysis. The proposed phase shifter was then designed and simulated in ADS using an FR4 substrate with Er=4.5, Mur=1, B=1.5 mm, T=35 um, and TanD=0.02.

The design centre frequency is 10 GHz, and an uneven Wilkinson power divider was used to split/combine the power at ports 2, 3 and 1, depending on the application. The physical parameters for each coupled line were chosen based on the theoretical analysis as follows: S1= 0.250 mm, L1=1.39 mm, W1=0.33 mm, S2= 0.250 mm, L2= 0.97 mm, W2= 0.38 mm, S3= 0.28 mm, L3= 2.29 mm, W3= 0.29 mm, S4= 0.2 mm, L4= 3 mm and W4= 0.71 mm respectively for the main line. The physical parameters of the coupled line used in the reference line were obtained as S= 1 mm, L= 8.57 mm and W= 0.55 mm. The layout design which, was carried out in momentum, is given in Fig. 7 below. The Wilkinson power divider is also given in the layout at input/output port 1. All physical parameters were obtained using linecalc in ADS.

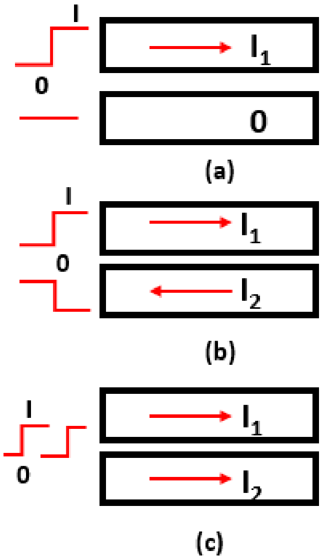

Figure 3: Coupled line excitations (a) standard, (b) odd mode and (c) Even mode excitations

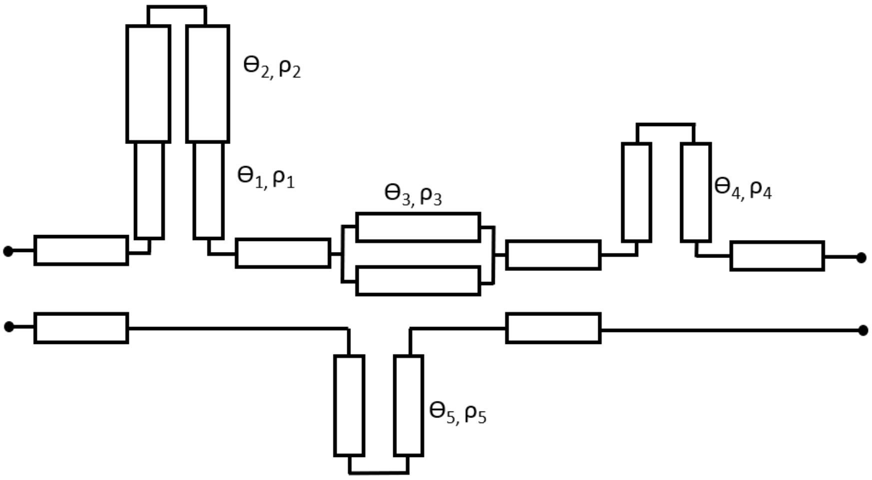

Figure 4: Block diagram of the proposed phase shifter

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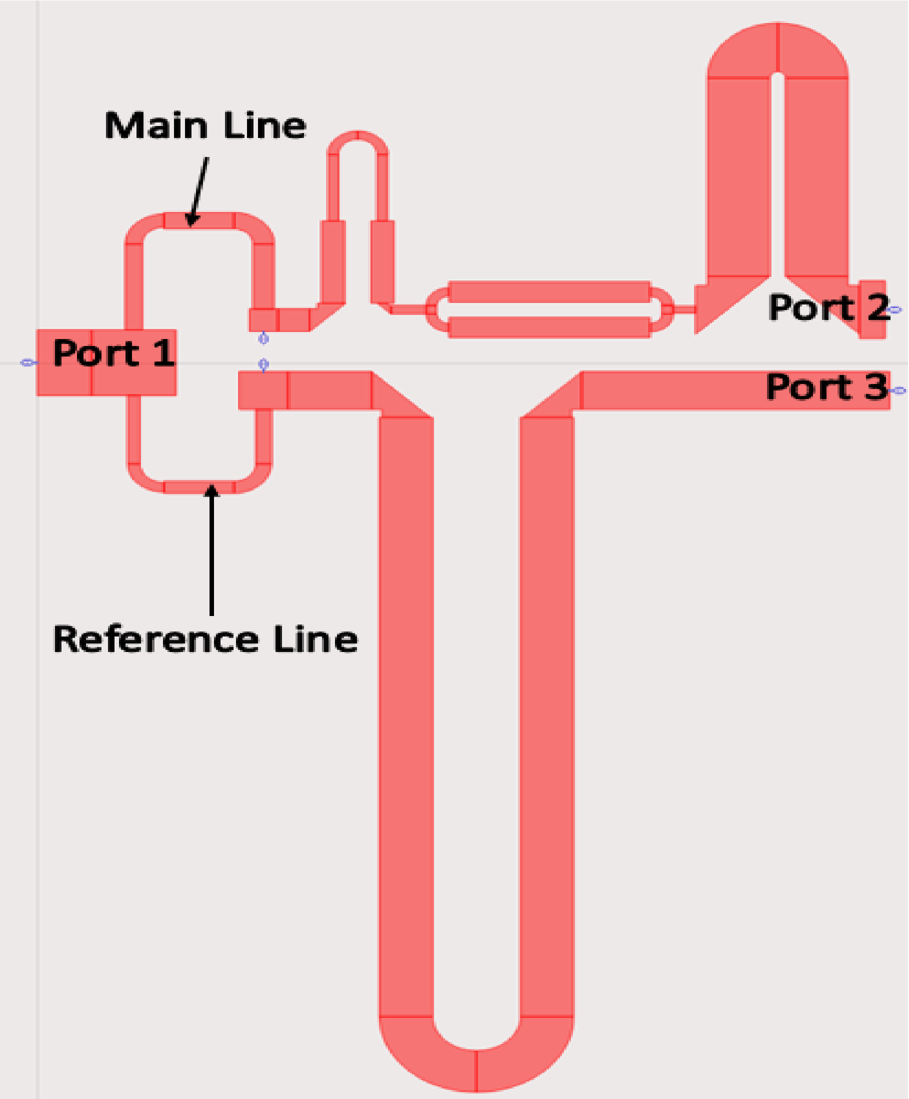

Figure 5: Photograph of a layout view of the proposed phase shifter

Six-Port Network Design Approach

The block diagram of the proposed six-port network is shown in Figure 6. The architecture uses four Wilkinson power dividers and two multiphase phase shifters, as mentioned in the preceding section. The Wilkinson power dividers (WP1 and WP2) give equal power splits at ports 5 and 6. WP1 sends half of its power to port 1 with no phase change and the other half to WP3. Also, PW2 power is split into port 4 with zero phase, and half is sent to WP4. The phase shifter then combines the outputs of WPs 3 and 4 to provide the 90° phase shift between the different ports.

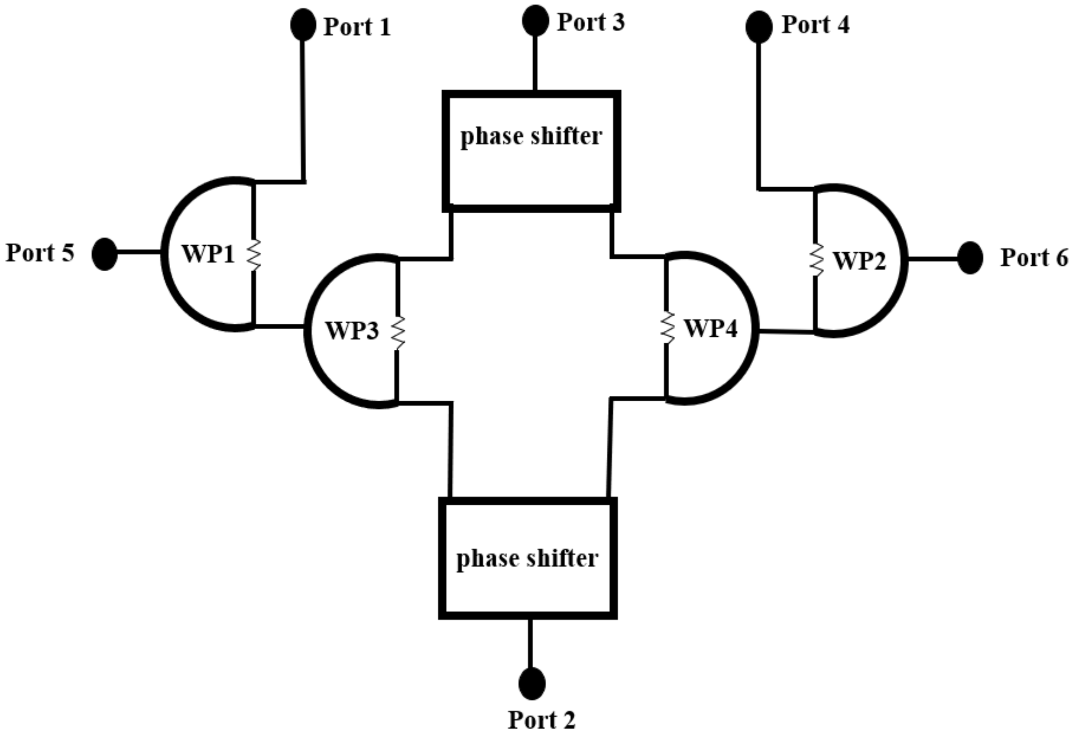

Figure 6: Photograph of the proposed six-port network

The proposed design was carried out in ADS, and both schematic and layout simulations were performed. The substrate material used was an FR4 with Er of 4.5, Mur=1, B=1.5625 mm, T=0.035mm and TanD=0.02. All ports were terminated with 50 Ω impedances. Similarly, Fig. 7 gives the layout view of the proposed six-port structure and the test bench for the EM co-simulation.

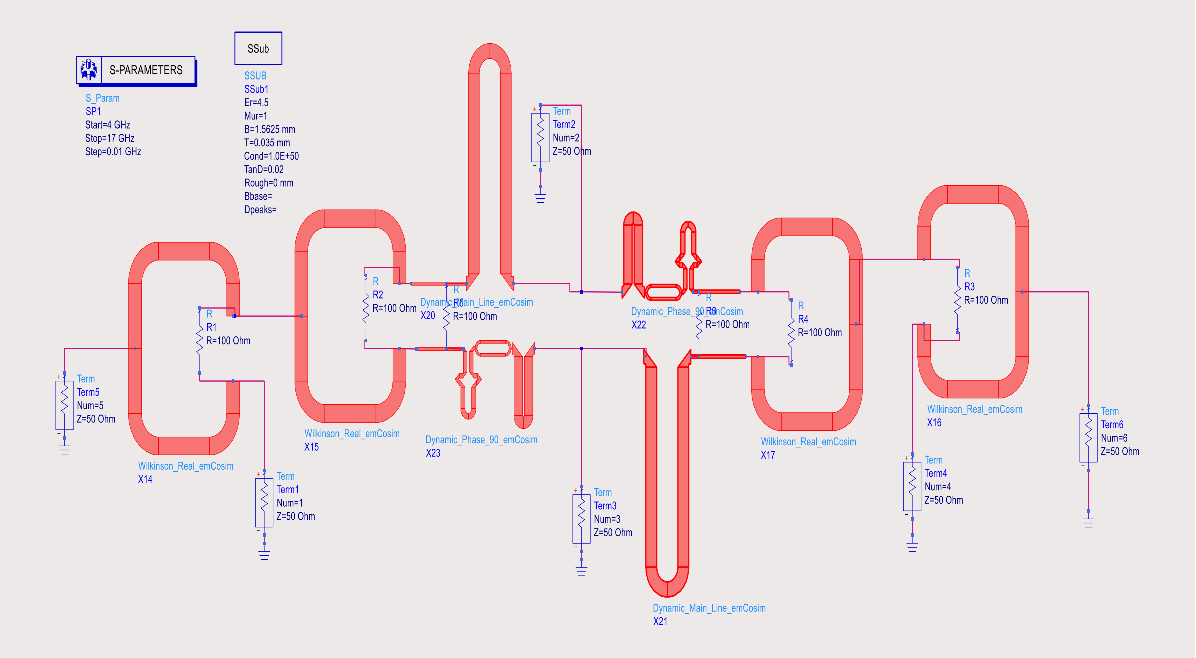

Figure 7: Layout view of the proposed six-port network for the 90° phase shift

RESULTS AND DISCUSSION

The schematic and layout simulation results showed a strong correlation with the theoretical analysis given in (1) to (6). The schematic results gave a phase error of ±1.8° within a frequency range of 5.52 -12.21 GHz, representing an FBW of 75.47% and a good match at all ports, below -10 dB. This phase and impedance matching performance is given in Fig. 8 and that of Figure 9. Similarly, the layout results gave a phase error of ±2.0° within a frequency range of 5.52 - 12.21 GHz, representing an FBW of 75.47%. Also, a good match, below -10 dB was achieved for all the ports. It should be noted that a much larger bandwidth can be obtained; however, this will cost a more significant phase deviation. Furthermore, the EM co-simulation for the six-port network was equally carried out.

Figure. 10 shows the post-layout results' phase performance, showing a 90±2.1° across the proposed band. The results for ports one and four, which solely employ the Wilkinson power dividers, achieve a returned loss below -20 dB, insertion loss of 3.15 dB and a phase shift of 0°. The -20 dB from ports five and six to ports one and four provide excellent isolation for these ports. Fig. 11 depicts the impedance matching at six separate ports, all less than -10 dB. Ports one and four, which solely employ

Wilkinson power dividers, performed well, while ports five and six performed relatively well in impedance matching. Ports two and three performed the poorest in terms of impedance matching, resulting in a multiphase phase shifter network. The insertion loss of the intended six-port network is shown in Figure 12. As predicted, the insertion loss for ports one and three

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with input from ports five and six is around 3.15 dB due to the Wilkinson power divider. While from ports five and six to ports one and four, the insertion loss is less than -20 dB, providing excellent isolation for these ports. Finally, the observed insertion loss for ports two and three was -12 dB. This result was compared with similar research works that have been carried out in recent years. Table 1 gives a details comparison of the proposed design and other works in literature.

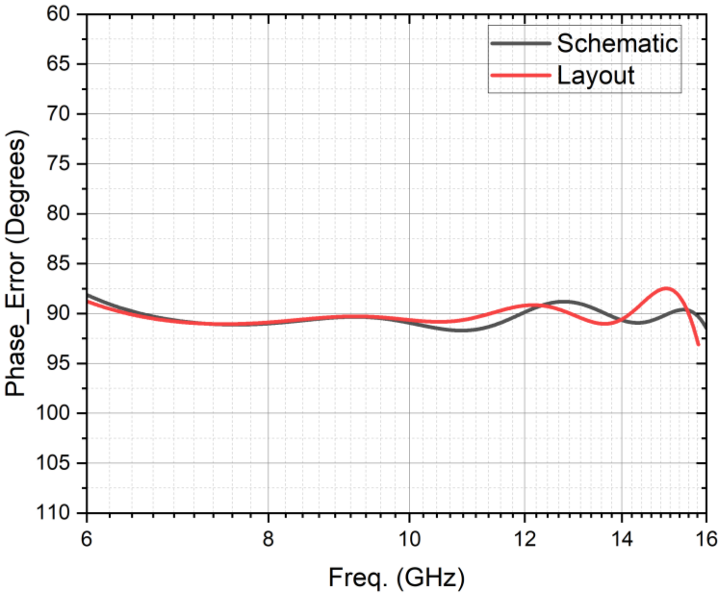

Figure 8: Phase shift performance results of the proposed phase shifter

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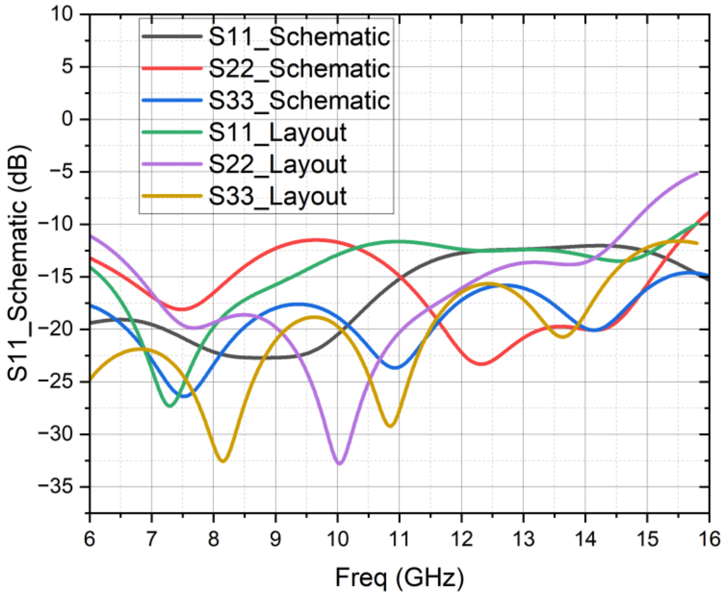

Figure 9: Simulation results of the return loss

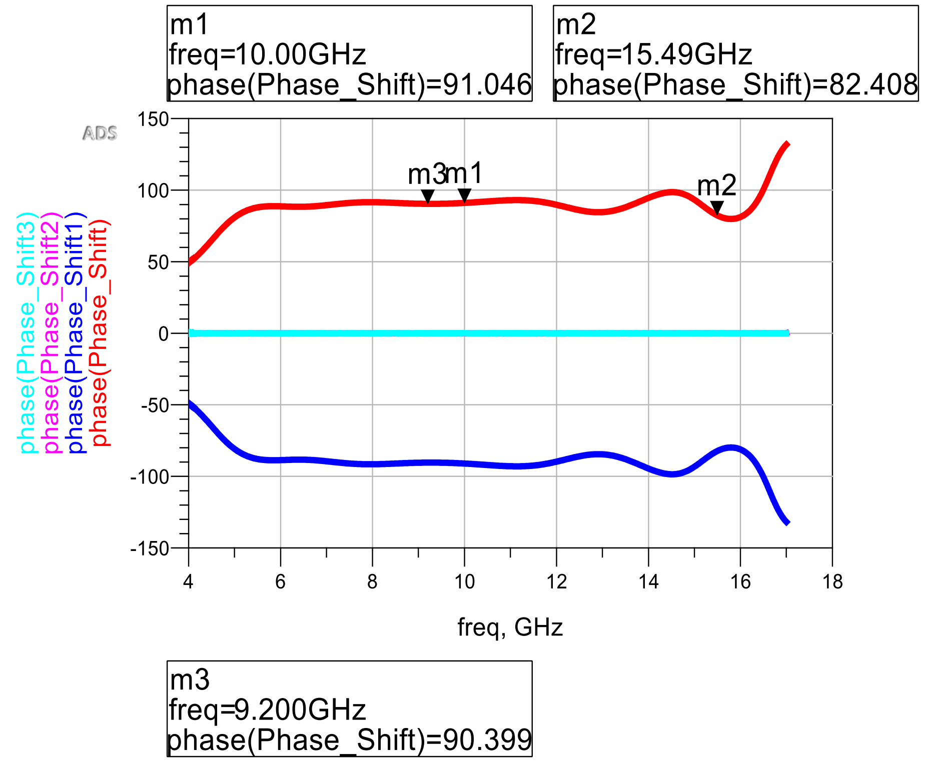

Figure 10: EM co-simulation of the phase performance

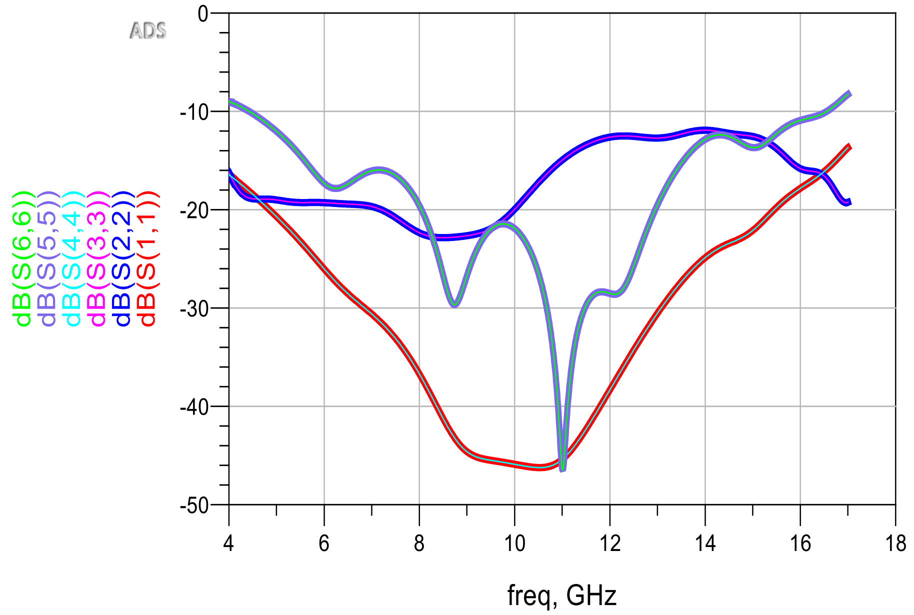

Figure 11: EM co-simulation of the impedance matching

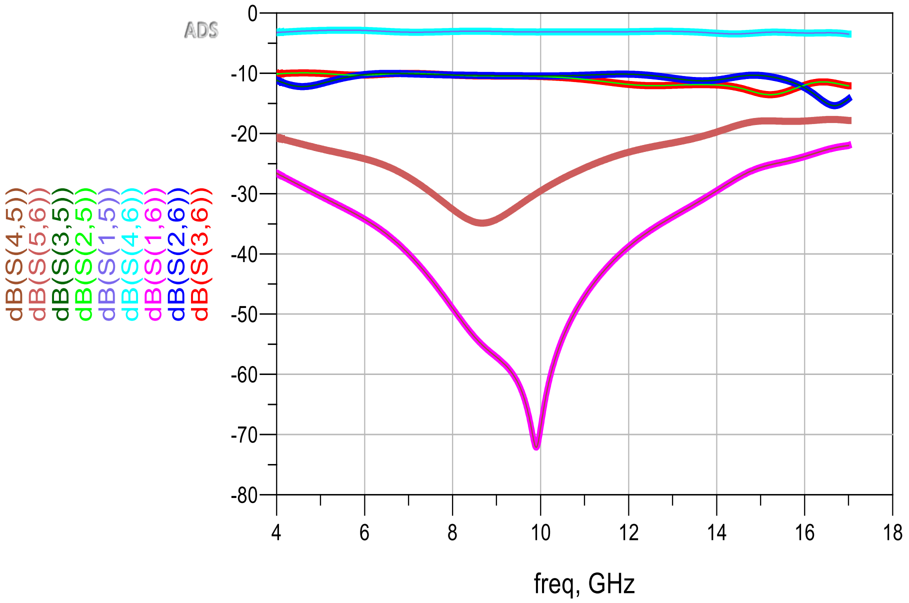

Figure 12: EM co-simulation of the insertion loss

Table 1: Phase shifter performance comparison with previous works

Ref	Approach Used	Phase error (°)	FBW (%)
(An, et al., 2022)	High-pass network	±2	125
(Hussain, Rashid, & Ullah, 2013)	Deep neural networks	±1.86 for 40% and 4.1 for 60%	40 and 60
(Huang & Lu, 2015)	multi-sectioned coupled line	±1	20.4
(Geyikoglu, Koc Polat, & Cavusoglu, 2020)	Modified Schiffman	±3	33.6 and 36.7 at 90◦ and 150◦ phase shifts
(Qiu, Zhu, & Lyu, 2019)	Hybrid Schiffman	±5	143
This work	**Even mode-coupled line excitation**	**±1.8 and ±5**	**75.47 for the ±1.8 and 91.5 for the ±5**

CONCLUSION

In conclusion, this work presented a novel design of a six-port network based on a modified Schiffman phase shifter operating at a 90° phase shift. The design utilises three distinct techniques to achieve the desired performance. Theoretical analysis with equations was formulated to show the relationships of the various techniques with the phase error and bandwidth performance, which were backed up by the simulation results. The schematic results showed an operational bandwidth from 5.52 GHz to 12.21 GHz, translating to a fractional bandwidth of 75.47% with a maximum phase error of ±1.8° for the 90° phase shift. Also, the post-layout simulation results from momentum demonstrated outstanding performance with an operation frequency band spanning from 5.52 GHz to 12.21 GHz, representing a factional bandwidth of 75.47% and ±2.1° phase error across the entire band. In addition, good impedance matching was achieved at all the ports well below -10 dB.

Also, the recorded insertion loss for ports two and three was -12 dB. The proposed phase shifter was integrated into a six-port network to implement a 90° at ports two and three. The simulation results for ports one and four, which solely employ Wilkinson power dividers, achieve a returned loss below -20 dB, insertion loss of -3.15 dB and a phase shift of 0 dB. The -20 dB from ports five and six to ports one and four provide excellent isolation for these ports.

Implications of the Study

The designed phase shifter and, by extension, the six-port network finds applications within the X-band and C-band for Radar Systems such as Phased Array Radar in both military and civilian applications to steer the radar beam electronically without moving the antenna and Synthetic SAR for high-resolution imaging to create detailed images of the ground. It also finds application in satellite communications for beamforming to enhance signal strength and quality by directing the signal towards specific locations on Earth as well as antenna arrays for satellite uplink and downlink antennas to adjust the beam direction and coverage area dynamically. It can also be used in wireless communication, particularly in 5G midband, 6G, 802.11a, and 802.11k. In 5G and beyond for phase shifters to enable adaptive beam steering in massive MIMO systems.

In addition, by enhancing the performance of the Six-Port Networks, the study paves the path for more dependable and effective communication systems, thereby improving access in distant and underprivileged places, bridging the digital gap and encouraging more inclusion. Furthermore, developments in telecommunications can spur economic growth by enabling new commercial possibilities and inventions. Finally, the research contributes to a more connected and egalitarian society in which access to information and communication is a fundamental right.

Recommendations

Despite the overwhelming performance of the proposed multiphase six-port network, such as the precise phase shifts and the wideband of operation. There are still significant investigations that can be considered to enhance further the device's performance and reliability, including the replacement of the Wilkinson power dividers with the multiphase phase shifters in a manner that can lead to phase error cancellation and conducting an in-depth sensitivity analysis of the newly designed six-port network to confirm the devices’ reliability and susceptibility to port mismatches.

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