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A K-Band Ultra-Wideband Binary Phase Shifter for Phase Modulating Applications in Radar

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***Abstract*— In this letter, a 180° rat-race coupler-based binary phase shifter is investigated for use in modern radar applications, such as phase-modulated continuous-wave (PMCW) and encoded radars. This phase shifter utilizes a two-section rat-race coupler, along with fast switching p-i-n diodes and microstrip RF chokes, to create a wideband system that includes two active states with a near-180° phase difference between them, equal power usage, and less than 10 dB of insertion loss. The performance of this design is directly compared to a single-section rat-race coupler-based binary phase shifter that employs the same reflective loading structure. For this design, the operating bandwidth is 10.37 GHz, across which the binary state phase error between active states is less than ±10°, making it suitable for full-band radar applications.**

***Index Terms*— Binary phase shift keying (BPSK), *K*-band, phase shifter, planar technology.**

I. INTRODUCTION

As MODERN communication and radar systems continue to become more advanced, new applications and designs for critical components are being explored. Among these components, phase shifter designs have expanded to meet a wide range of design criteria. Of these designs, diode-based phase shifters have been around for decades and come in many forms [1], [2], [3], [4]. Utilizing the reflection loading, biasing, and switching properties of p-i-n diodes, these phase shifters are straightforward to design and integrate into high-frequency systems. For hybrid coupler-based designs, the operating bandwidth, defined here as the frequency range where the desired phase difference between states is within 10°, is directly tied to the coupler bandwidth. Improving the coupler bandwidth while minimizing insertion loss and maintaining a simplified design is key for more advanced signal modulation.

One of many uses for a phase shifter in modern radar is encoding the phase of the carrier frequency, such as in phase-modulated continuous-wave (PMCW) radars, as outlined in Fig. 1. This modulation spreads the carrier signal over the frequency spectrum and allows for multiple radars to operate in the same area and frequency band with low interference. To utilize this shifting, such as in high-resolution target detection, encoding, or joint-radar communication systems, a wide bandwidth is needed. This has led to PMCW radars operating at higher frequency bands where the modulation frequency can better fit in the allocated bandwidth [5]. An encoding scheme that offers a high signal-to-noise ratio (SNR) is binary phase shift keying (BPSK), which uses binary phase states where the phase angle between states is ideally 180° [6]. The encoded message or string of values is then mapped to these two binary states, which when downconverted with the carrier signal frequency are recovered as distinct voltage levels. For PMCW radars using BPSK encoding, the range resolution is dependent on the symbol width, while the maximum range is tied to the number of symbols used. Access to increasing clock speeds of modern field-programmable gate arrays (FPGAs) allows for faster binary encoding and signal processing, but for the best performance, the phase shifter needs to also isolate the oscillator and the modulated signal while providing a consistent near-180° phase shift over a wide bandwidth.

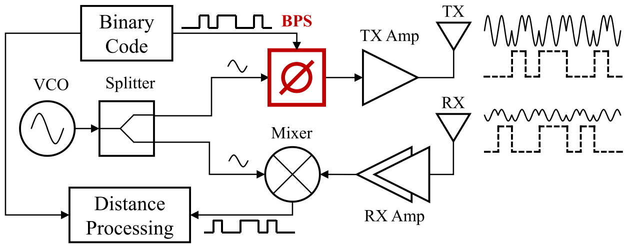

Fig. 1. PMCW radar block diagram.

With the demand to increase the capabilities of microwave systems, component footprints are critical in both designing around the shorter wavelengths of higher frequency systems as well as saving space. While CMOS technology can fill this need due to the ability to make low-cost and highly integrable chips, this work focuses on the bandwidth dependence of coupler-based reflective load phase shifters through the advantage of fast prototyping through planar board-level designs. To this end, a reflection-based binary phase shifter was implemented with fast-switching p-i-n diodes and a two-section rat-race coupler, which offers good matching and isolation while having a wider operational bandwidth than a single-section coupler [7].

In this work, the design principles in [8] are further explored by quantitatively analyzing the impact of the rat-race coupler bandwidth in diode-based binary phase shifters with the goal of achieving a greater than 40% operational bandwidth to suit present and future demands for phase shifter applications in radar. The influence on the operational bandwidth of the reflection-based rat-race phase shifter due to the bandwidth of the coupler is analyzed, and the performance of the two-section coupler-based phase shifter far outperforms a single-section coupler design in bandwidth and stability, albeit with the

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increased insertion loss. Both phase shifters are realized using printed circuit board (PCB) manufacturing techniques on a two-layer Rogers RO3003 laminate and use the same passive and active components to induce the phase shift while isolating the dc voltage biasing and RF signals.

II. PHASE SHIFTER DESIGN

To better meet the increasing data rate, range resolution, and operating bandwidth demands in modern radar, the phase shifter needs to have a stable phase shift and insertion loss over a large bandwidth. In addition, constant active power was also desired. With these goals in mind, the following design concepts were implemented.

A. Inducing the Phase Shift

Typically, rat-race couplers are used to split a signal into two 180° out of phase signals at ports b and d by loading the normally isolated port c with a matched load, but these roles can be reversed to generate different phase delays from port a to port c. The ideal rat-race four-port S-parameters

$$\begin{bmatrix} V_a^- \\ V_b^- \\ V_c^- \\ V_d^- \end{bmatrix} = \frac{-j}{\sqrt{2}} \begin{bmatrix} 0 & -1 & 0 & 1 \\ -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_a^+ \\ V_b^+ \\ V_c^+ \\ V_d^+ \end{bmatrix} \tag{1}$$

can be broken down to a two-port structure dependent on the reflection coefficients of the loads on ports b and d. Using the definition for a multiport S-parameter matrix

$$S_{ij} = \frac{b_i}{a_j} = \left.\frac{V_i^-}{V_j^+}\right|_{V_k^+=0 \text{ for } k\neq j} \tag{2}$$

and assuming that ports b and d have reflective loads $\Gamma_b = V_b^+/V_b^-$ and $\Gamma_d = V_d^+/V_d^-$, the simplified two-port structure can be defined as a function of the reflective loads as

$$S_{RR\_PS} = \begin{bmatrix} S'_{11} & S'_{12} \\ S'_{21} & S'_{22} \end{bmatrix} = \frac{-1}{2} \begin{bmatrix} \Gamma_b + \Gamma_d & -\Gamma_b + \Gamma_d \\ -\Gamma_b + \Gamma_d & \Gamma_b + \Gamma_d \end{bmatrix}. \tag{3}$$

This equation holds for the two-section rat-race coupler design, as coupler maintains equal power splitting between matched ports, while the phase delay constant $-j/\sqrt{2}$ in (1) is increased by a quarter wavelength from the additional section.

From (3), the four load states of interest for a binary phase shifter are those that use the combinations of ideal RF open ($\Gamma = 1$) and RF short ($\Gamma = -1$) loads on ports b and d (Γ_b and Γ_d). When the states are equal, the system will present as the inverse of the state at the input and output ports and have high insertion loss. Conversely, when the states are opposing open and short circuits, the input and output ports will be matched, and the insertion loss will be low. It is important to recognize that this performance is defined at the center frequency of the coupler, and as the frequency drifts away from the center frequency, the S-parameters become less ideal. Therefore, the bandwidth of the coupler is a major factor in the final bandwidth of the phase shifter.

The method used to implement the RF open and short loads, shown in Fig. 2, is a pair of p-i-n diodes with cathodes connected to the ports, anodes connected to an RF short stub, and a dc bias circuit to control their states. When the diode is 0 V biased, the port is loaded as an RF open, and when forward biased, the signal passes through the diode to the RF short stub. While this method results in RF opens and shorts that are not perfect, from (3), it can be shown that, with the use of the complex expansion of the reflection coefficients of the loads, the absolute angle difference between the two loaded S_{21} responses comes out to 180° when the alternate states use the same "open" and "short" loads. The magnitude of the S_{11} and S_{21} responses also becomes more lossy with the nonideal loads.

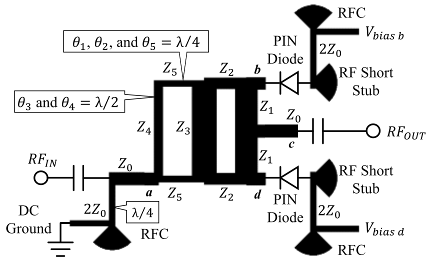

Fig. 2. Two-section rat-race coupler phase shifter schematic.

B. Wideband Rat-Race Coupler

The phase shifter design utilizes the additional bandwidth gained from using a two-section rat-race coupler. The coupler, which is based on the design in [7], was optimized for a 10-GHz bandwidth in high-frequency RF circuit simulators. Based on even–odd mode analysis independent of the center frequency, fractional bandwidths of more than 40% should be achievable with the two-section coupler design [9].

The characteristic impedances of the microstrip lines were optimized as in [7]. After optimizing the microstrip widths for bandwidth and matching to $Z_0 = 50\ \Omega$, the impedances used in this design are $Z_1 = 33.5\ \Omega$, $Z_2 = 52.8\ \Omega$, $Z_3 = 31.3\ \Omega$, $Z_4 = 59.6\ \Omega$, and $Z_5 = 72.5\ \Omega$. The electrical line lengths used are θ_1, θ_2, and $\theta_5 = \lambda/4$, as well as the RF choke line, while θ_3 and $\theta_4 = \lambda/2$. Using these values, with Z_1 being almost half of other two-section designs, additional zeros in the S_{11} response are introduced at 3.94 GHz above and below the center design frequency of 24 GHz. These zeros help keep the input isolation response below –20 dB over a 10-GHz bandwidth. The original 66.1 Ω value for Z_1 still gives a less than –16.4-dB S_{11} response across the bandwidth, but the simulated performance is lowered. The lower impedance line also results in a wider microstrip trace, which is less prone to fabrication errors.

III. MEASUREMENT RESULTS

The two-section coupler-based binary phase shifter shown in Fig. 3(a) was fabricated on a 250-μm-thick Rogers RO3003 substrate and designed to have a center operating frequency of 24 GHz using the same process as the single-section design in Fig. 3(b) [8]. The characteristic impedances of the RF signal lines are 50 Ω, and the radial stubs are tuned to be RF shorts at 24 GHz. RF chokes used in the design consist of 100-Ω quarter-wavelength lines terminated with radial short stubs. The p-i-n diodes used are MACOM MADP-000907-14020P diodes, which have modeled reflection

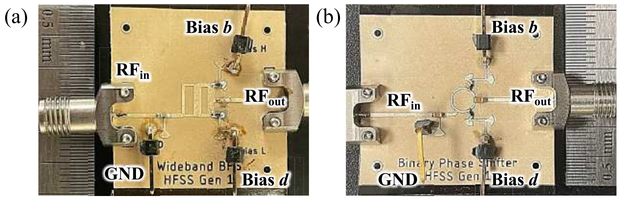

Fig. 3. (a) Fabricated two-section rat-race coupler phase shifter. (b) Single–section rat-race coupler phase shifter [8].

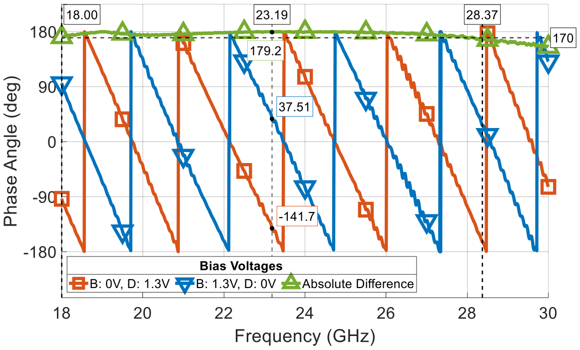

Fig. 4. Measured absolute phase shift between active bias states for two-section coupler design.

coefficients of $0.8977e^{-j0.9908}$ and $0.06612e^{-j1.764}$ at the measured center frequency of 23.19 GHz when 0 V biased and forward biased at 1.3 V and 10 mA, respectively. The low reflection of the forward biased state allows a radial short stub and RF choke in parallel to become the RF short load and limit signal leakage to the bias source. The signal ports of the phase shifter have 330-pF coupling capacitors to reduce the dc bias introduced to the signal, while the input also employs an RF choke to provide the dc ground.

While the diode is safely biased along the forward bias region of its I–V curve, it provides an RF path to the short stub. Therefore, lower power forward bias states can be used while maintaining the high absolute phase difference, but at the cost of higher loss to the short stub as well as higher system loss due to the less ideal reflection coefficients in (3). For instance, when driving the diodes with a digital logic signal, a resistive voltage divider can be used to control the bias voltage and current instead. In addition, the transient time of the phase shifter is dependent on the switching speed of the loaded ports. For these p-i-n diodes, their transient switching time is about 2 ns and their active power consumption is 13 mW when forward biased.

The shifter's performance was measured using two power supplies to directly control the bias voltage and current. The first dataset was measured with port *b* biased with 0 V and port *d* forward biased, while the second was taken with the supplies reversed. The S_{21} phase from 18 to 30 GHz with these bias states is shown in Fig. 4, along with their absolute phase difference. With this biasing setup, the phase shifter has an operating bandwidth of more than 10.37 GHz, across which there is a minimum absolute phase difference of 170° or a ±10° phase error. At the measured center frequency of 23.19 GHz, there is a 179.2° phase difference between the two bias states.

Two additional bias states were tested to measure the S_{21} isolation of the inactive modes of the phase shifter, in which both supplies were set to 0 or 1.3 V. The insertion loss of the phase shifter across all four test states is shown in Fig. 5. Across the operating bandwidth, the alternately biased states attenuate the input signal between 4.4 and 9.2 dB. The equally based states attenuate the signal by more than 15.5 dB when both ports are 0 V biased and more than 24.1 dB when forward biased.

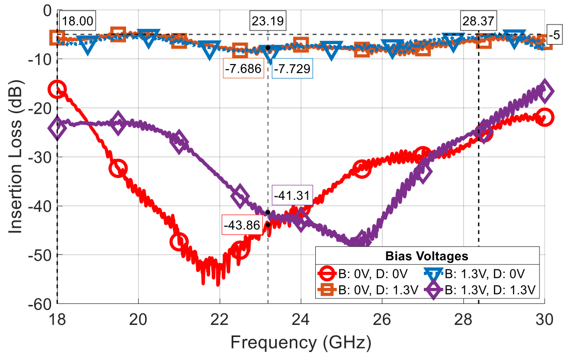

Fig. 5. Measured insertion loss at main bias state combinations for two-section coupler design.

TABLE I

PERFORMANCE COMPARISON OF PHASE SHIFTER DESIGNS

	Bias (V)	Single-Section [8]	Two-Section
Active State Insertion Loss (dB)	0/1.3	-3.891 ± 1.036	-6.810 ± 2.350
	1.3/0	-4.082 ± 1.121	-7.006 ± 2.156
Min. Inactive State Attenuation (dB)	0/0	-14.133	-16.059
	1.3/1.3	-14.25	-22.455
Center Frequency f_0 (GHz)		24.74	23.19
Operational Bandwidth (GHz)		5.72	10.37
Absolute Phase Offset at f_0 (deg)		175.7	179.2

Table I compares the key performance attributes of the single and two-section coupler phase shifter designs. The use of the two-section rat-race coupler improves the operating bandwidth by 4.65 GHz while reducing the upper end of the phase error from 4.3° to 0.8° and exhibiting less phase fluctuation over the bandwidth, but at the cost of more attenuation of the signal when the ports are alternately biased.

IV. CONCLUSION

The design and measurements of a two-section rat-race coupler-based ultra-wideband *K*-band binary phase shifter designed for modern radar are presented in this letter. This design employs the properties of p-i-n diodes and radial stubs to steer the signal's path through the coupler. The two paths have a net 180° phase difference, and the signal path is controlled using alternating reflection coefficients on bias ports. The design utilizes the bandwidth dependence of reflective load binary phase shifters to improve the operational bandwidth, allowing for wideband isolation, stable binary states, and high SNR between them across the 10.37-GHz active bandwidth. With these advantages, this binary phase shifter is suited for a wide range of phase modulation applications in modern radars.

REFERENCES

[1] J. F. White, “Diode phase shifters for array antennas,” *IEEE Trans. Microw. Theory Techn.*, vol. MTT-22, no. 6, pp. 658–674, Jun. 1974.

[2] D. Kim, Y. Choi, M. G. Allen, J. S. Kenney, and D. Kiesling, “A wideband reflection-type phase shifter at S-band using BST coated substrate,” *IEEE Trans. Microw. Theory Techn.*, vol. 50, no. 12, pp. 2903–2909, Dec. 2002.

[3] G. Monti, F. Congedo, and L. Tarricone, “On the use of a rat-race coupler in the design of a 180° phase shifter,” *J. Electromagn. Waves Appl.*, vol. 23, nos. 8–9, pp. 1201–1210, Jan. 2009.

[4] N. Fourikis, *Advanced Array Systems, Applications and RF Technologies*. New York, NY, USA: Academic, 2000.

[5] D. Guermandi et al., “A 79-GHz 2×2 MIMO PMCW radar SoC in 28-nm CMOS,” *IEEE J. Solid-State Circuits*, vol. 52, pp. 2613–2626, Oct. 2017.

[6] J. Wang, D. Rodriguez, A. Mishra, P. R. Nallabolu, T. Karp, and C. Li, “24-GHz impedance-modulated BPSK tags for range tracking and vital signs sensing of multiple targets using an FSK radar,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 3, pp. 1817–1828, Mar. 2021.

[7] M. Caillet, M. Clenet, A. Sharaiha, and Y. M. M. Antar, “A compact wide-band rat-race hybrid using microstrip lines,” *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 4, pp. 191–193, Apr. 2009.

[8] M. Brown and C. Li, “A K-band broadband binary phase shifter,” in *Proc. IEEE Radio Wireless Symp. (RWS)*, Jan. 2022, pp. 16–18.

[9] Y. Kim, “Analysis method for a multi-section rat-race hybrid coupler using microstrip lines,” *J. Electromagn. Eng. Sci.*, vol. 22, no. 2, pp. 95–102, Mar. 2022.