Wideband Tunable Phase Shifter With Low In-Band Phase Deviation Using Coupled Line

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***Abstract*— This letter presents a design for a wideband reflection-type tunable phase shifter (RTPS) with a low in-band phase deviation error. The proposed RTPS consists of a 3-dB hybrid where a through port and a coupled port are terminated with coupled lines, varactor diodes, and a capacitor. The measured capacitance of the varactor diodes was used in the analysis to take into account the in-band phase deviation error caused by the parasitics of the varactor diode. The analysis shows that the desired phase shifting range (PSR) and a low in-band phase deviation error can be obtained by properly selecting the characteristic impedance and coupling coefficient of the coupled line and load capacitance. The experimental results show that the fabricated RTPS provides a PSR of 146.93° at 2.5 GHz and an in-band phase deviation error of ±5.79° within 500 MHz. Moreover, the input–output return losses are higher than 15.76 dB, and the insertion loss is smaller than 1.29 dB within the operating frequency band.**

***Index Terms*— Coupled lines, high phase shifting range (PSR), low in-band phase deviation, wideband tunable phase shifter (PS).**

I. Introduction

TUNABLE phase shifter (PS) is a basic building circuit that can control the phase of a signal in RF/microwave circuits and systems. A wideband PS with a high phase shifting range (PSR) and a low in-band phase derivation (PD) error is highly desirable. The tunable PS can be classified into transmission and reflection types; however, a reflection-type PS has been widely used due to its excellent return loss (RL) characteristics. In [1] and [2], the reflection-type PSs consisted of a transmission line and varactor diodes that provide a high PSR at the center frequency (f_0). However, the in-band PD errors were also very large due to the frequency-dependent transmission line. Similarly, several methods to achieve a high PSR were shown in [3] and [4] by modifying the hybrid coupler arm and reflective load. Although a high PSR was achieved in [4], the in-band PD error was still high.

Manuscript received May 10, 2018; accepted May 29, 2018. Date of publication July 19, 2018; date of current version August 7, 2018. This work was supported in part by the Korean Research Fellowship Program through the National Research Foundation of Korea funded by the Ministry of Science and ICT under Grant 2016H1D3A1938065, in part by the Basic Science Research Program through the National Research Foundation of Korea funded by Ministry of Education, Science, and Technology under Grant 2016R1D1A1B03931400, and in part by Research Base Construction Fund Support Program funded by Chonbuk National University in 2017. *(Corresponding author: Yongchae Jeong).*

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Digital Object Identifier 10.1109/LMWC.2018.2847025

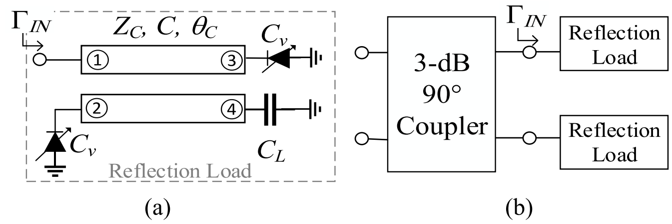


Fig. 1. Structures of proposed PS. (a) One-port reflection load. (b) Overall two-port circuit using hybrid and reflection loads.

A transmission-type PS using an arbitrary length coupled line and a varactor diode was presented in [5], and it provided a PSR of 360° with an in-band PD error of ±20°. In addition, this structure required a very tight coupling to obtain a high PSR and a low in-band PD error. Abbosh [6] presented a tunable PS that was obtained by varying the coupling coefficient of the coupled line with the varactor diode connected to the gap of the coupled line. However, the PSR at f_0 was limited to 45°, with an in-band maximum RL of 6 dB only. A practical tunable PS is difficult to design satisfying all ideal requirements, including a high PSR, low in-band PD error, high RL, and low insertion loss (IL), and the tradeoff occurs among these. Consequently, conventional tunable PS designs focus mainly on achieving a high PSR at f_0 and a high RL bandwidth (BW) around f_0 instead of an in-band PD error [7].

In this letter, a wideband tunable reflection-type PS considering a low in-band PD error is proposed based on a coupled line. The coupled line can minimize parasitic elements of varactors to achieve high PSR, low in-band PD error, and IL variation within wide operating BW without modification on the hybrid coupler.

II. Mathematical Analysis

Fig. 1 shows the structure of the proposed reflection-type PS that consists of a 90° hybrid coupler where a coupled port and through port are terminated with two identical reflection loads. The one-port reflection load shown in Fig. 1(a) consists of a coupled line where the coupled port (port ②) and through port (port ③) are terminated with a varactor diode of capacitance C_V and isolated (port ④) with a lumped capacitor (C_L). From Fig. 1(a), the reflection coefficient of load (Γ_{IN}) with respect to reference port impedance Z_0 can be derived as follows:

$$\Gamma_{IN} = \frac{jX_{IN} - Z_0}{jX_{IN} + Z_0} \tag{1}$$

where

$$X_{\rm IN}(f) = X_1 - \frac{\omega C_L X_2^2}{\omega C_L X_1 - 1} \quad (2a)$$

$$X_1 = \frac{\frac{2m^2 p\cos\theta_c}{\sin^3\theta_c} + \left(\frac{1}{\omega C_V} - \frac{p}{\tan\theta_c}\right)\left(\frac{m^2}{\tan^2\theta_c} + \frac{p^2}{\sin^2\theta_c}\right)}{\frac{m^2}{\sin^2\theta_c} - \left(\frac{1}{\omega C_V} - \frac{p}{\tan\theta_c}\right)^2} - \frac{p}{\tan\theta_c} \quad (2b)$$

$$X_2 = \frac{\frac{m}{\sin\theta_c}\left(\frac{m^2}{\tan^2\theta_c} + \frac{p^2}{\sin^2\theta_c}\right) + \left(2mp\frac{\cos\theta_c}{\sin^2\theta_c}\right)\left(\frac{1}{\omega C_V} - \frac{p}{\tan\theta_c}\right)}{\frac{m^2}{\sin^2\theta_c} - \left(\frac{1}{\omega C_V} - \frac{p}{\tan\theta_c}\right)^2} - \frac{m}{\sin\theta_c} \quad (2c)$$

$$p = \frac{Z_C}{\sqrt{(1+C)(1-C)}}, \quad m = \frac{Z_C C}{\sqrt{(1+C)(1-C)}}. \quad (2d)$$

where Z_C, C, and θ_C are characteristics impedance, coupling coefficient, and electrical length of the coupled line, respectively. From (1), the phase of the reflection load can be expressed as follows:

$$\phi_{\rm IN}(f)|_V = -2\tan^{-1}(X_{\rm IN}(f)/Z_0) \quad (3)$$

where subscript V represents the bias voltage that changes the capacitance of the varactor diode. Subsequently, the PSR ($\Delta\phi_{\rm IN}$) of the proposed structure can be expressed in the following equation, where V is varied from $V_{\rm min}$ to $V_{\rm max}$:

$$\Delta\phi_{\rm IN}(f)|_V = \begin{cases} \phi_{\rm IN}(f)|_V - \phi_{\rm IN}(f)|_{V_{\rm min}} & \text{if } \phi_{\rm IN}(f)|_{V_{\rm min}} < \phi_{\rm IN}(f)|_{V_{\rm max}} \\ \phi_{\rm IN}(f)|_V - \phi_{\rm IN}(f)|_{V_{\rm max}} & \text{if } \phi_{\rm IN}(f)|_{V_{\rm min}} > \phi_{\rm IN}(f)|_{V_{\rm max}}. \end{cases} \quad (4)$$

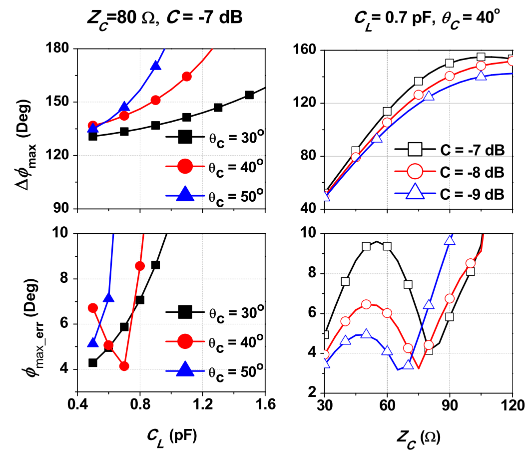
Finally, the in-band PD error ($\phi_{\rm err}$) within the operating BW can be defined as the difference between the maximum and minimum $\Delta\phi_{\rm IN}$ within the operating BW at the specific V, as shown in the following equation:

$$\phi_{\rm err}(V) = \pm\{\max(\Delta\phi_{\rm IN}|{\rm v}) - \min(\Delta\phi_{\rm IN}|{\rm v})\}/2. \quad (5)$$

Since the C_V of the varactor diode is frequency dependent, it can increase $\phi_{\rm err}$. Taking the frequency dependent C_V in $\phi_{\rm err}$ into account, the capacitance of the varactor diode should be extracted for the operating BW using an equivalent model provided by the manufacturer. After obtaining the frequency dependent C_V of the varactor diode for the entire operating BW, the electric parameters of the proposed PS with the given specifications (such as f_0, BW, $\Delta\phi_{\rm max}$, and $\phi_{\rm max\_err}$) can be calculated using (3)–(5) in MATLAB. In this letter, the varactor diode SMV-1231 from Skyworks is used which provides C_V from 0.5 to 2.5 pF at $f_0 = 2.5$ GHz when a V of 1–13 V is applied.

Fig. 2 shows the calculated $\Delta\phi_{\rm max}$ and $\phi_{\rm err}$ according to the circuit parameters (Z_C, C, θ_C, C_L) at $f_0 = 2.5$ GHz. As seen from Fig. 2(a), $\Delta\phi_{\rm max}$ increased when θ_C increases. However, $\phi_{\rm max\_err}$ is also increased. Similarly, $\phi_{\rm max\_err}$ is increased as C_L increases. $\Delta\phi_{\rm max}$ increases with higher values of Z_C and C. However, $\phi_{\rm max\_err}$ is high for a low and high Z_C, as shown in Fig. 2(b).

To investigate the effect of BW in $\Delta\phi_{\rm max}$, Table I shows the calculated parameters at $f_0 = 2.5$ GHz. As seen from Table I, $\Delta\phi_{\rm max}$ and $\phi_{\rm max\_err}$ are increased with an increase in BW. Therefore, a tradeoff occurs between $\Delta\phi_{\rm max}$, $\phi_{\rm max\_err}$, and BW.



(a) (b)

Fig. 2. Calculated PSRs at f_0 and in-band PD errors with $f_0 = 2.5$ GHz, BW = 500 MHz, and C_v = 0.5–2.5 pF. (a) Fixed Z_C and C. (b) Fixed C_L and θ_C.

TABLE I

CALCULATED CIRCUIT PARAMETERS, $\Delta\phi_{\rm max}$ AND $\phi_{\rm err}$, WITH SMV-1231 VARACTOR DIODE FROM SKYWORKS (C_V = 0.5–2.5 pF AT 2.5 GHz)

BW (MHz)	$\phi_{\rm ref\_err}$ (°)	Z_C (Ω)	C (dB)	θ_C (°)	C_L (pF)	$\phi_{\rm max\_err}$ (°)	$\Delta\phi_{\rm max}$ (°)
200	±2.5	80	-7	40	0.7	±1.9	142.24
	±5	105	-7	35	0.9	±3.6	170.81
	±10	115	-7	30	1.1	±9.3	188.87
500	±2.5	70	-8.5	50	0.5	±2.3	123.48
	±5	80	-7	40	0.7	±4.1	142.24
	±10	120	-7	30	0.9	±8.1	176.57
1000	±2.5	30	-9.5	30	0.3	±2.5	54.34
	±5	60	-10	50	0.3	±4.9	105.69
	±10	95	-7	30	0.7	±9.6	149.66

III. SIMULATION AND MEASUREMENT RESULTS

For experimental demonstration, the PS was designed and fabricated at $f_0 = 2.5$ GHz with an operating BW of 500 MHz. Based on the above specifications, the circuit parameters are calculated using MATLAB as $Z_C = 80$ Ω, $C = -7$ dB, $\theta_C = 40°$, and $C_L = 0.7$ pF based on design method described in Section II. In this calculation, $\Delta\phi_{\rm min}$ and $\phi_{\rm ref\_err}$ were selected as 88° and ±4.4°, respectively. Similarly, the C_V of varactor diode SMV-1231 ($C_v = 0.5$ to 2.5 pF) was used. Using the calculated circuit parameters, $\Delta\phi_{\rm max}$ and $\phi_{\rm max\_err}$ over 500 MHz were estimated as 142.24° and ±4.14°, respectively. The circuit was fabricated on a substrate RT/Duroid-5880 with a dielectric constant (ε_r) of 2.2 and thickness (h) of 62 mil. One-port network is converted to two-port network shown in Fig. 1(b) using a 90° hybrid coupler S03A2500N1 from ANAREN due to its wideband characteristics [8].

The simulation and measured results of the designed PS are shown in Figs. 3 and 4. Within the 500 MHz BW centered

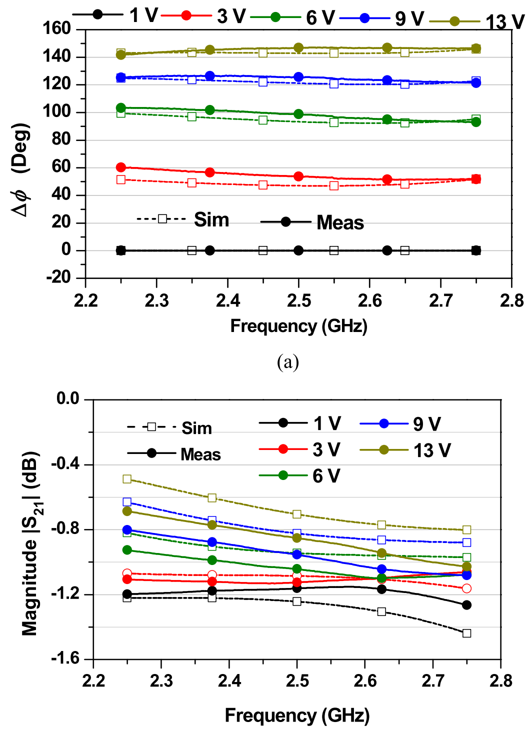


Fig. 3. Simulation and measured results of fabricated circuit. (a) PSR. (b) IL within 500 MHz BW at $f_0 = 2.5$ GHz.

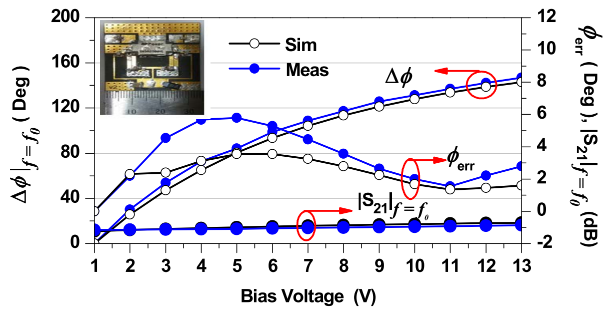


Fig. 4. Simulated and measured PSR, ϕ_{err}, and IL variation at f_0 according to bias voltage.

at 2.5 GHz, the measured $\Delta\phi_{\max}$, $\phi_{\max\_\mathrm{err}}$, and IL variation are determined to be 146.93°, ±5.79°, and ±0.308 dB, respectively. The measured $\phi_{\max\_\mathrm{err}}$ is slightly higher than the simulation results due to a fabrication error and a tolerance between the simulated and measured varactor diode C_{v}. Similarly, the measured IL variation and input–output RLs are within ±0.14 dB, and higher than 15.76 dB at $f_0 = 2.5$ GHz, respectively. A photograph of fabricated circuit is shown in Fig. 4.

In [3], the figure of merit (FoM) is defined only considering $\Delta\phi_{\max}$ and IL at f_0. In fact, a tunable PS should provide low IL, high $\Delta\phi$, low ϕ_{err}, and high RL within wide operating BW. Therefore, a new FoM is defined as (6) in this letter to evaluate the performance of tunable PSs by considering all requirements.

$$\mathrm{FoM}=\frac{\mathrm{BW(GHz)}\times\Delta\phi_{\max}(\mathrm{rad})}{f_0(\mathrm{GHz})\times\phi_{\max\_\mathrm{err}}(\mathrm{rad})}\times\frac{10^{\left(-\frac{\mathrm{IL_{max}(dB)}}{20}\right)}}{10^{\left(-\frac{\mathrm{RL_{min}(dB)}}{20}\right)}}. \quad (6)$$

TABLE II

PERFORMANCE COMPARISON WITH STATE OF THE ARTS

	f_0 (GHz)	BW (GHz)	FBW (%)	$\Delta\phi_{\max}$ (°)	$\phi_{\max\_\mathrm{err}}$ (°)	$\mathrm{IL_{max}}$ (dB)	$\mathrm{IL_v}$ (dB)	$\mathrm{RL_{min}}$ (dB)	FoM
[3]	2	0.2	10	385	±55	1	±0.58	11	2.21
[4]	2	0.2	10	234	±45	4.6	±0.60	13	1.37
[5]	2.2	0.9	40.9	372.5	±21	4.1	±0.85	7.8	11.11
[6]	2.25	0.5	22.2	45	±4.5	4.5	±0.70	6	2.64
[7]	1.5	1	66.7	350	±100	5.8	±2.70	14	5.99
This work	**2.5**	**0.5**	**20**	**146.9**	**±5.79**	**1.28**	**±0.31**	**15.76**	**26.87**

$\mathrm{IL_v}$: Maximum insertion loss variation in overall frequency bandwidth.

Using (6), the performance comparison of the proposed circuit with state of the arts is shown in Table II. As seen from Table II, the proposed letter provides the highest FoM compared to state of the arts. In addition, the IL variation of the proposed PS is very small within BW of 500 MHz as compared to state of arts.

IV. CONCLUSION

This letter presents a method to design a reflection-type wideband tunable PS with a low in-band PD error using coupled lines terminated with varactor diodes and a fixed load capacitor. The theoretical analysis demonstrated that the desired high PSR at the center frequency and low in-band phase deviation error over the operating BW can be obtained by properly selecting the characteristic impedance, coupling coefficient, and electrical length of the coupled line. The fabricated circuit shows excellent performance and FoM compared to conventional structures. Therefore, the proposed tunable PS is expected to be applicable in a wideband phased-array antenna, wideband signal cancellation circuit, and broadband signal processing system for next generation wireless communication systems.

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