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RESEARCH ARTICLE

In-band phase deviation minimization method for wideband tunable phase shifter

Girdhari Chaudhary | **Boram An** | **Yongchae Jeong**

Division of Electronics and Information Engineering, IT Convergence Research Center, Chonbuk National University, Jeonju, Republic of Korea

Correspondence
Yongchae Jeong, Division of Electronics and Information Engineering, IT Convergence Research Center, Chonbuk National University, Jeonju, Republic of Korea.
Email: ycjeong@jbnu.ac.kr

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Abstract
This article provides a novel approach to analyze and design wideband tunable reflection-type phase shifter (RTPS) with low in-band phase deviation (IBPD) error. The proposed RTPS consists of coupled lines where through and coupled ports are terminated with varactor diodes. The coupled lines can minimize the parasitic elements of varactor diode to achieve high phase shift range (PSR). In addition, the measured frequency-dependent capacitance of varactor diode was used in the analytical analysis to obtain minimum IBPD error and high PSR. For experimental demonstration, phase shifter was fabricated at the center frequency of 2.5 GHz. The measured results show that the fabricated circuit achieved 126.85° PSR with ±6.48° IBPD error for 500 MHz bandwidth (BW). In addition, the measured maximum insertion loss variation and input/output return losses are within ±0.34 dB and higher than 16.85 dB within 500 MHz BW, respectively.

KEYWORDS
coupled line, low in-band phase deviation error, varactor diode, wideband tunable reflection-type phase shifter

1 | INTRODUCTION

The tunable phase shifter is one of the important components in a modern wireless communication system. Tunable phase shifter with minimum in-band phase deviation (IBFD) error over wide bandwidth (BW) is highly desirable in practical applications such as beamforming network and self-interference cancellation circuits.[1,2] The phase shifters can be practically realized using different concepts including vector modulator, switched or reflection-type phase shifter (RTPS).[3–8] Because the switched-type phase shifters provide discrete phase steps, this type of phase shifter requires multiple stages to obtain small phase steps. Therefore, the RTPS is the most common type of tunable phase shifter because of high return loss (RL) and simple design.

In References 4 and 5, a high phase shift range (PSR) has been achieved by modifying a hybrid coupler arm and reflection load; however, IBPD error is high. Similarly, the tunable phase shifter is designed by controlling coupling coefficient of coupled with varactor diode.[6] This structure is limited in PSR (<45°) and RL (<6 dB). In Reference [7], the coupled line where varactor was connected at the center point achieved 360° PSR; however, IBPD error is higher than ±20°. From the literature reviews, it can be concluded that conventional RTPS has drawbacks such as limited BW in terms of IBPD error and insertion loss (IL) variations.[4–8]

In this article, a novel RTPS design method is demonstrated to achieve minimum IBPD error with high PSR over wideband operating BW by using coupled line and varactor diode. Because the frequency dependence of varactor diode has a strong influence in IBPD error in overall BW, the proposed method uses the measured frequency-dependent capacitance of varactor diode in the analysis to obtain circuit parameters for minimum IBPD error and high PSR. For experimental demonstration, the RTPS is designed and fabricated at the center frequency of 2.5 GHz.

2 | DESIGN THEORY

Figure 1 depicts the proposed structure of tunable RTPS which consists of 3-dB hybrid and reflection termination load. The reflection load is composed of the coupled lines where coupled and through ports are terminated with a varactor diode. Assuming $Z_c = \sqrt{Z_{0e}Z_{0o}}$, even-mode and odd-mode impedances (Z_{0e}, and Z_{0o}) of coupled lined are expressed as Equations (1a) and (1b)

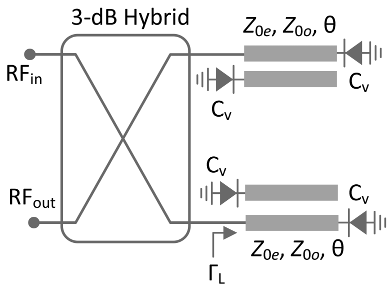

FIGURE 1 Proposed structure of tunable reflection-type phase shifter with low in-band deviation error

$$Z_{0e} = Z_c\sqrt{\frac{1+C_{\mathrm{eff}}}{1-C_{\mathrm{eff}}}} \tag{1a}$$

$$Z_{0o} = Z_c\sqrt{\frac{1-C_{\mathrm{eff}}}{1+C_{\mathrm{eff}}}}, \tag{1b}$$

where C_{eff} represents coupling coefficient. Denoting the reflection coefficient of termination load as Γ_L, the S-matrix of the proposed RTPS shown in Figure 1 can be expressed as Equation (2).

$$[S] = \begin{bmatrix} \left(S_{21}^{H}\right)^2\Gamma_L + \left(S_{31}^{H}\right)^2\Gamma_L & 2S_{21}^{H}S_{31}^{H}\Gamma_L \\ 2S_{21}^{H}S_{31}^{H}\Gamma_L & \left(S_{21}^{H}\right)^2\Gamma_L + \left(S_{31}^{H}\right)^2\Gamma_L \end{bmatrix}, \tag{2}$$

$$\varphi_L(f)|_V = \begin{cases} 2\tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_V - 2\tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_{V_{\min}} & \text{if } \tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_{V_{\min}} < \tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_{V_{\max}} \\ 2\tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_V - 2\tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_{V_{\max}} & \text{if } \tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_{V_{\min}} > \tan^{-1}\left(\frac{Z_{in}}{Z_0}\right)\Big|_{V_{\max}} \end{cases} \tag{5}$$

where S_{21}^{H} and S_{31}^{H} are the S-parameters of hybrid.[9] The RTPS exhibits perfect matching ($S_{11} = 0$) and transmission ($S_{21} = 1$), respectively, only if the hybrid coupler exhibits the S-parameter characteristics such that $\left|\left(S_{21}^{H}\right)^2 + \left(S_{31}^{H}\right)^2\right| = 0$ and $\left|2S_{21}^{H}S_{31}^{H}\right| = 1$. Because these requirements are practically limited in BW, any hybrid coupler implementation will affect magnitude responses of the overall circuit.

Because relative phase difference is important in tunable RTPS and mainly depends on the phase of Γ_L, the absolute phase of hybrid is of no interest. Therefore, the value of Γ_L of the tunable RTPS is expressed as Equation (3).

$$\Gamma_L = \frac{jZ_{in} - Z_0}{jZ_{in} + Z_0}, \tag{3}$$

where

$$Z_{in} = \frac{\frac{2Z_c C_{\mathrm{eff}}^2}{\sqrt{1-C_{\mathrm{eff}}^2}}\cot\theta\csc^2\theta + \left(\frac{1}{\omega C_v} - \frac{Z_c\cot\theta}{\sqrt{1-C_{\mathrm{eff}}^2}}\right)\left(C_{\mathrm{eff}}^2\cot^2\theta + \csc^2\theta\right)}{C_{\mathrm{eff}}^2\csc^2\theta_c - \left(\frac{\sqrt{1-C_{\mathrm{eff}}^2}}{\omega Z_c C_v} - \cot\theta\right)^2} - \frac{Z_c\cot\theta}{\sqrt{1-C_{\mathrm{eff}}^2}}, \tag{4}$$

and θ is the electrical length of the coupled line. Similarly, C_v is frequency-dependent capacitance of varactor diode. Using Equation (3), the PSR (Δϕ) of RTPS can be expressed as Equation (5) where subscript V represents the bias voltage that changes the C_v of the varactor diode.

Finally, IBPD error (ϕ_{err}) at particular bias voltage within the operating BW can be defined as Equation (6)

$$\phi_{err}(V) = \pm\frac{\left(\Delta\phi|_V\right)_{\max} - \left(\Delta\phi|_V\right)_{\min}}{2}. \tag{6}$$

When the RTPS is designed for wide operating BW, the frequency-dependent behavior of varactor diode C_v has great influence in IBFD error. To minimize the IBFD error within the wideband operating BW, the frequency-dependent varactor diode C_v should be used to calculate the optimum circuit parameters (Z_c, C_{eff}, θ) of the RTPS. In this work, the measured C_v of the varactor diode SMV-1231 from Skyworks as shown in Figure 2 is used. The design steps to obtain the values of Z_c, C_{eff}, and θ are summarized in Figure 3.

Based on above design equations, the calculated circuit parameters of RTPS are shown in Figure 4 according to different ϕ_{err}. As seen from these graphs, if Z_c increases and θ decreases, ϕ_{err} will be high. Similarly, Δϕ can be enhanced if the operating BW is decreased as shown in Figure 4B.

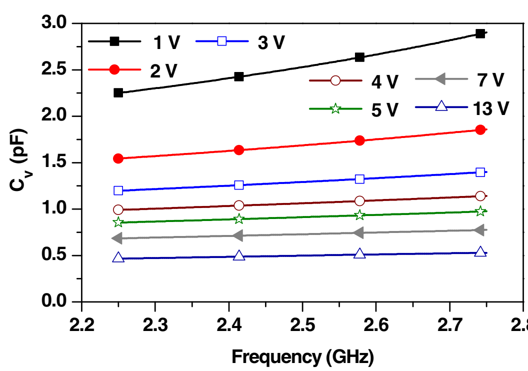

FIGURE 2 Measured frequency-dependent capacitance of varactor diode SMV-1231 from Skyworks [Color figure can be viewed at wileyonlinelibrary.com]

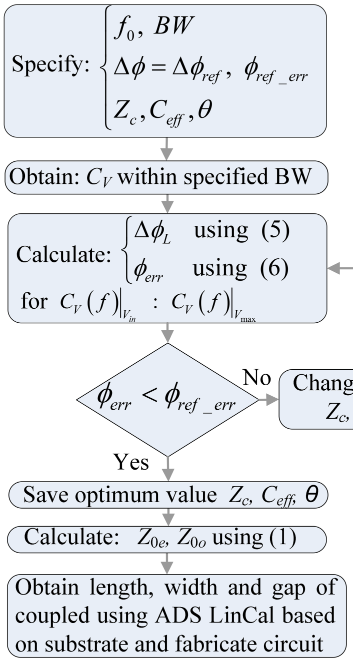

FIGURE 3 Flow chart to obtain optimum circuit parameters based on the specification [Color figure can be viewed at wileyonlinelibrary.com]

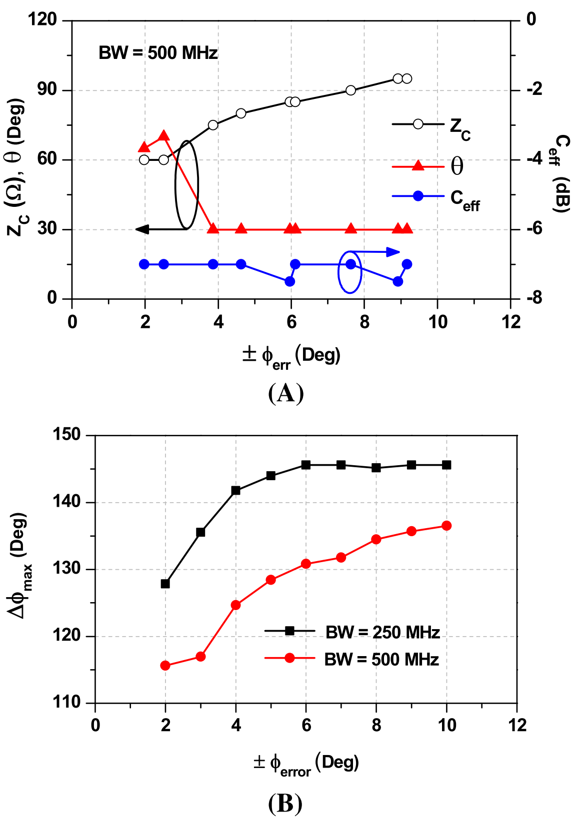

FIGURE 4 Calculated circuit parameters and phase shift range (PSR) using varactor diode SMV-1231 from Skyworks: (A) circuit parameters and (B) PSRs according to in-band phase deviation error [Color figure can be viewed at wileyonlinelibrary.com]

To demonstrate the validity of the proposed method, the simulated results are shown in Figure 5 for different operating BWs. In these results, ϕ_{err} is maintained less than 4° for

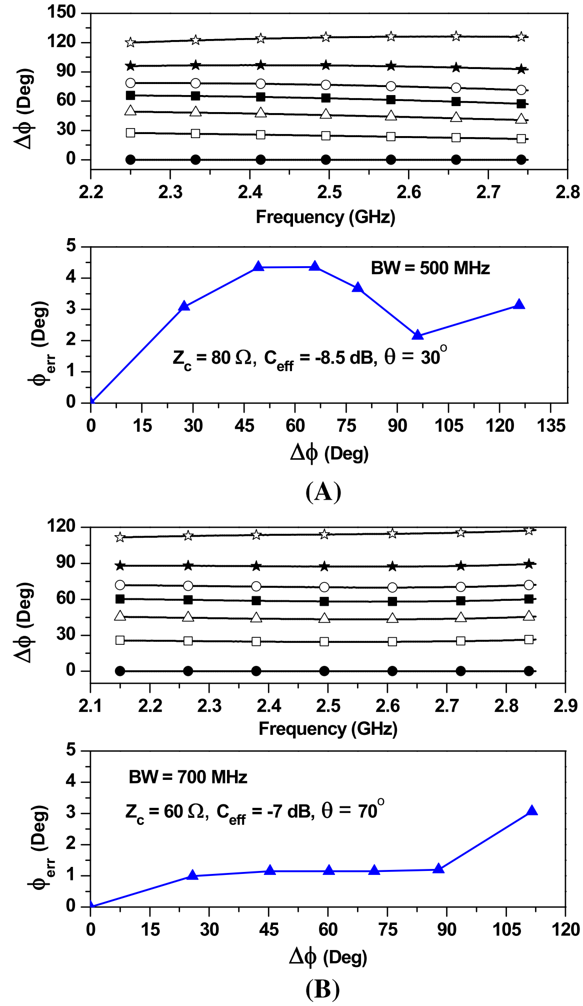

FIGURE 5 Simulation results of reflection-type phase shifter within (A) 500 MHz and (B) 700 MHz operating bandwidths [Color figure can be viewed at wileyonlinelibrary.com]

overall $\Delta\phi$. In addition, these results also confirmed that $\Delta\phi$ will be decreased if the operating BW is increased. Therefore, a trade-off occurs among ϕ_{err}, $\Delta\phi$, and operating BW.

3 | EXPERIMENTAL VERIFICATION

To verify the proposed analysis, the RTPS was designed and fabricated for $\phi_{err} < 5°$ within an operating BW of 500 MHz at $f_0 = 2.5$ GHz. Using the C_v of varactor diode SMV-1231 from Skyworks, the circuit parameters of RTPS were obtained as $Z_c = 80\ \Omega$, $C_{eff} = -8.4$ dB, and $\theta = 30°$. The circuit was fabricated on a substrate RT/Duroid-5880 with a dielectric constant (ε_r) of 2.2 and thickness (h) of 62 mils. Similarly, a 90° hybrid coupler S03A2500N1 from ANAREN was used because of wide-band characteristics.

The experimental results of fabricated RTPS are depicted in Figures 6 and 7. As seen from these graphs, the measured $\Delta\phi_{max}$, ϕ_{max_err}, and IL variation are estimated as 126.85°, ±6.48°, and ± 0.34 dB, respectively, within the BW of

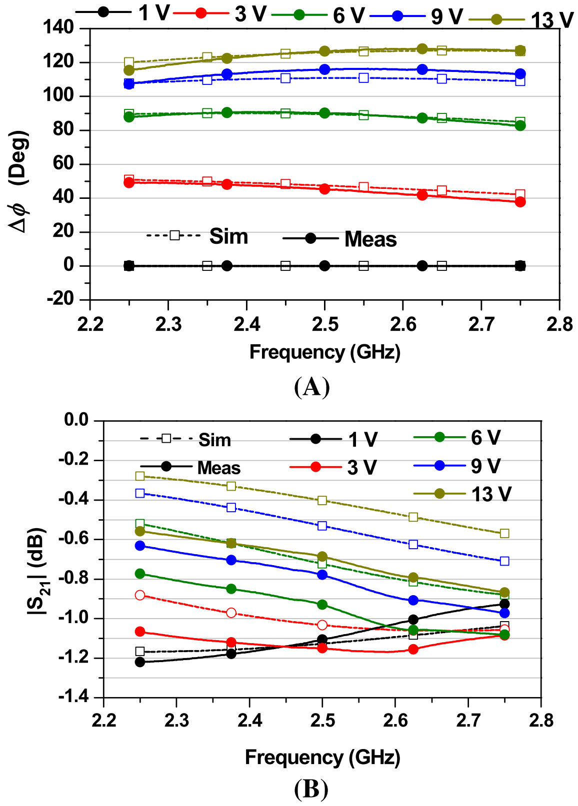

FIGURE 6 Experimental results: (A) phase shift range and (B) magnitude $|S_{21}|$ responses [Color figure can be viewed at wileyonlinelibrary.com]

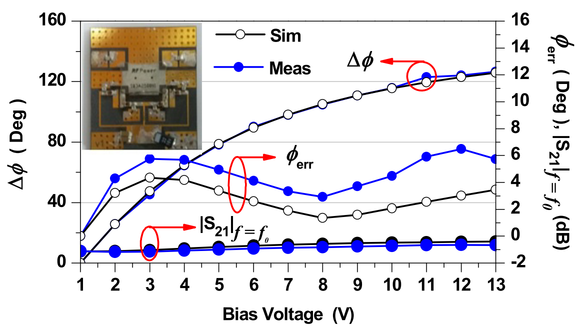

FIGURE 7 Simulated and measured phase shift range, φ_{err}, and insertion loss variations at f_0 according to bias voltage [Color figure can be viewed at wileyonlinelibrary.com]

500 MHz. The measured ϕ_{max_err} is slightly higher than the simulated results because of 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 ±0.26 dB and higher than 16.85 dB at f_0 = 2.5 GHz, respectively. A photograph of the fabricated circuit is shown in Figure 7.

In previous research, the performance of RTPS is investigated by only considering $\Delta\phi_{max}$ and IL at f_0.[4–8] In fact, ϕ_{err} and RL along with $\Delta\phi_{max}$ and IL within wide operating BW are also important characteristics to evaluate performances of tunable RTPS. The high RL is also desirable characteristics while the RTPS is integrated with other circuits. Therefore, a new figure of merit (FoM) is defined Equation (7) by considering these characteristics in this work.

$$\mathrm{FoM} = \frac{\mathrm{BW(GHz)} \times \Delta\phi_{max}(\mathrm{rad})}{f_0(\mathrm{GHz}) \times \phi_{max\_err}(\mathrm{rad})} \times \frac{10^{\left(-\frac{\mathrm{IL_{max}(dB)}}{20}\right)}}{10^{\left(-\frac{\mathrm{RL_{min}(dB)}}{20}\right)} \tag{7}$$

Using Equation (7), the performance of the proposed RTPS is compared with state-of-the-art as shown in Table 1. From this table, it can be confirmed that the proposed RTPS provides the highest FoM and small IL variation within the BW of 500 MHz as compared to previous research.

4 | CONCLUSION

In this article, a novel RTPS with minimized IBFD error within wide operating BW is demonstrated. The proposed tunable phase shifter uses the coupled line that can minimize the parasitic elements of varactor diode to achieve high PSR and low IBFD error within the wide BW. In addition, analytical analysis confirms that the PSR with low error can be enhanced if the operating BW is narrow. The proposed structure is verified by fabricating circuit at the center frequency of 2.5 GHz. The experiment results show that the proposed phase shifter provides the highest FoM as compared to the state of arts. Therefore, the proposed tunable phase shifter is expected to be applicable in a wideband-phased array antenna, wideband signal cancellation circuit,

TABLE 1 Performance comparison with state of arts

Reference	f_0 (GHz)	BW (GHz)	FBW (%)	$\Delta\varphi_{max}$ (°)	φ_{max_err} (°)	$\mathrm{IL_{max}}$ (dB)	$\mathrm{IL_v}$ (dB)	$\mathrm{RL_{min}}$ (dB)	FoM
4	2	0.2	10	385	±55	1	±0.58	11	2.21
5	2	0.2	10	234	±45	4.6	±0.60	13	1.37
6	2.2	0.9	40.9	372.5	±21	4.1	±0.85	7.8	11.11
7	2.25	0.5	22.2	45	±4.5	4.5	±0.70	6	2.64
8	1.5	1	66.7	350	±100	5.8	±2.70	14	5.99
This work	**2.5**	**0.5**	**20**	**126.6**	**±6.48**	**1.23**	**±0.34**	**16.85**	**23.64**

BW = bandwidth; FBW = BW/f_0x100; $\mathrm{IL_{max}}$ = maximum insertion loss; $\mathrm{RL_{min}}$ = minimum return loss; FoM = figure of merit; $\mathrm{IL_v}$ = maximum insertion loss variation in overall frequency bandwidth.

and broadband signal processing system for next-generation wireless communication systems.

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ORCID

Boram An https://orcid.org/0000-0002-7576-7017

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