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독립 제어 가능 마이크로파  
이중 대역 가변 위상 변환기

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전자정보공학부

Sandy Saron

# 독립 제어 가능 마이크로파 이중 대역 가변 위상 변환기

Dual-Band Microwave Variable Phase Shifter With  
Individual Controls

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## List of Acronyms

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CL1	Coupled line at lower band circuit
CL2	Coupled line at higher band circuit
C <sub>v</sub>	Varactor diode
DPS	Dual-band phase shifter
ITPS	Independent tunable phase shifter
PDE	Phase deviation error
PSR	Phase shift range
MMIC	Concurrent dual-band monolithic microwave integrated circuit
TL	Transmission line



## ABSTRACT

### Dual-Band Microwave Variable Phase Shifter with Individual Controls

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This dissertation presents a design of reflection-type dual-band phase shifter (PSR) which allows to tune relative phase shift at two operating frequency bands independently. The proposed phase shifter consists of a 3-dB hybrid coupler where through and couple ports are terminated with reflection loads. Each reflection load comprises of couple line (CL), a transmission line (TL) and a varactor diode. The CL can achieve independent phase tuning at each operating frequency, while TL terminated with varactor diode is used to high relative PSR. To prove the validity of the proposed method, the dual-band phase shifter operating at center frequencies of 1.88 GHz and 2.44 GHz is designed and fabricated. The measured relative PSR is  $149.33^\circ$  at 1.88 GHz with phase derivation error (PDE) of  $\pm 8.45^\circ$  within 300 MHz bandwidth. Similarly, the PSR at 2.44 GHz is  $125.25^\circ$  with PDE of  $\pm 8.36^\circ$  within 300 MHz bandwidth. Likewise, the minimum return loss of around 17.36 dB, and the maximum insertion loss of 1.81 dB are measured at both operating bands.

**Keywords:** Coupled line, dual-band tunable phase shifter independent phase control, varactor diode.

## Chapter 1 Introduction

---

A tunable phase shifter typically modifies the phase of an input signal by changing the electrical path length or the propagation velocity of the signal within the device. This is often achieved using variable reactance components like varactor diodes or using mechanical means in some cases.

The tuning or control of the phase shift can be achieved through various methods. In electronic tunable phase shifters, this is often done by varying the voltage applied to a reactive component like a varactor diode, which changes its capacitance and thus alters the phase shift. Other methods might include mechanical adjustment of the phase shifter physical structure or using magnetic or ferroelectric materials whose properties can be changed with an external magnetic field or electric field.

Tunable phase shifter is used to control a phase of a signal which has been found wide range of various applications including beamforming [1], phased array antenna [2], self-interference cancellation [3]. To support multi-band wireless communications, it is necessary to design tunable phase shifter that operates over multiple frequency bands simultaneously. However, previously reported tunable phase shifters are mainly designed for single frequency band operations, which fail to provide independently controllable transmission phase shift over multi-band frequency operation. [4], [5], [6], [7].

Recently, a dual-band 90-degree SiGe HBT active phase shifter is presented in [8] using bandpass and bandstop filters in load circuit. In [9], dual-band phase shifter (DPS) is designed by using two stub-loaded

transmission lines (TLs) and two delay lines. Similarly, dual-band differential phase shifter is presented in [10] that utilized slope alignment of coupled line resonators.

However, these DPSs cannot provide independent tunable phase shift (ITPS) at two operating bands. Concurrent dual-band monolithic microwave integrated circuit (MMIC) tunable phase shifter is reported in [11] utilizing two-stage dual-branch phase tuning network topology. A reflection-type DPS with ITPS is presented in [12] using  $\lambda/4$  series and shunt TLs. However, this work requires compensation shunt elements at each operating band to compensate parasitic effect of  $\lambda/4$  shunt TL for achieving ITPS and high relative phase shift tuning range (PSR).

In this work, reflection-type dual-band tunable phase shifter is proposed using coupled lines terminated with TLs and varactor diodes, which does not require any compensation elements. The coupled lines have been utilized for achieving independent phase control at each operating band as well as improving PSR. The proposed DPS can provide independent tunable phase at each operating band as well as simultaneous tunable phase shift at both bands.

## Chapter 2 3-dB Hybrid Coupler

---

In the field of RF engineering, a reflective phase shifter typically comprises a  $90^\circ$  hybrid coupler combined with reflection loads. This setup is designed such that when an input is applied to port 1 of the hybrid coupler, it ensures an equal power distribution (3 dB) to the output port 3 and 4. A notable characteristic of this system is that the outputs at these ports have a  $90^\circ$  phase difference. When identical reflection loads, possessing only reactance, are connected to these output ports, they exploit the phase shifts resulting from the reflections load. This configuration is adept at adjusting the phase between port 1 and 2 while keeping the signal amplitude changes to a minimum. The phase shift range between these ports is effectively the same as that of a single reflection load. This phenomenon and its implications are validated through the port reduction method, a technique that derives the scattering matrix of a network by reducing the number of active ports. Interestingly, this method reveals that in this setup, the reflected signals at port 1 from both loads exhibit a  $180^\circ$  phase difference, effectively cancelling each other out and leading to superior reflection loss characteristics. The reverse application of this method is utilized to deduce the two-port scattering matrix of the reflective phase shifter from the four-port  $90^\circ$  hybrid coupler, thus enabling a detailed analysis of its phase characteristics. This approach underlines the efficiency and precision of the reflective phase shifter in managing phase shifts, crucial for various applications in RF system. Fig.2.1. shows the structure of reflection-type tunable phase shifter.

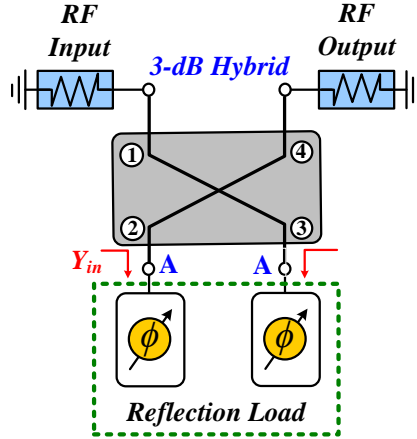


Fig. 2.1. Structure of reflection-type tunable phase shift

The scattering matrix of four-port networks can be expressed in equation 2.1.

$$S_{4\text{-ports}} = \begin{bmatrix} 0 & 0 & -1 & j \\ 0 & 0 & j & -1 \\ -1 & j & 0 & 0 \\ j & -1 & 0 & 0 \end{bmatrix} \quad (2.1)$$

This four-port circuit can be considered as divided into two parts: ports 1 to 2 and ports 3 to 4. This network is conceptually divided into two distinct sections: one comprising ports 1 and 2, and the other encompassing ports 3 and 4. Such a division allows for a more manageable analysis of the circuit's characteristics. In this scenario, the  $S$ -parameters, which are crucial for understanding how RF signals behave within the network, are expressed separately for each two-port section. These parameters, likely detailed in equation (2.2), are instrumental in determining how much signal is transmitted, reflected, or lost in each part of the circuit.

$$S_{11} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, S_{21} = -\frac{1}{\sqrt{2}} \begin{bmatrix} -1 & j \\ j & -1 \end{bmatrix}, S_{12} = -\frac{1}{\sqrt{2}} \begin{bmatrix} -1 & j \\ j & -1 \end{bmatrix}, S_{22} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (2.2)$$

Additionally, the determinant of the  $S$ -parameter matrix, referenced as equation (2.3), plays a significant role in providing insights into the overall behavior of the network. The terms 'a' and 'b' are used to denote the incident and reflected waves, respectively.

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \quad (2.3)$$

Let's consider a two-port circuit with reflection loads terminated to ports 3 and 4, having the same input admittance  $Y_{in}$ . If the reflection coefficient at ports 3 and 4 is denoted as  $\Gamma_{in}$ , then the  $S$ -parameter matrix and its determinant for the reflection load are as given in equations (2.4) and (2.5), respectively.

$$S_{in} = \begin{bmatrix} \Gamma_{in} & 0 \\ 0 & \Gamma_{in} \end{bmatrix} \quad (2.4)$$

$$b' = S_{in}a' \quad (2.5)$$

From the relationship between the incident and reflected waves between the connected coupler and the reflective load, the following equation can be derived.

$$a_2 = S_{in}b_2 \quad (2.6)$$

By substituting the relationship of Equation (2.6) into Equation (2.3) and using this to rearrange Equation (2.3) in terms of  $a_1$  and  $b_1$ , we obtained the following.

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \quad (2.7)$$

$$\frac{b_1}{a_1} = S_{11} + S_{12}S_{in} (U - S_{22}S_{in})^{-1} S_{21} \quad (2.8)$$

By substituting Equations (2.4) and (2.2) for the parameters corresponding to Equation (2.8), the  $S$ -parameter matrix of the new two-port network with the reflection load can be obtained as Equation (2.9).

$$S_{2-port} = \begin{bmatrix} 0 & -j\Gamma_{in} \\ -j\Gamma_{in} & 0 \end{bmatrix} \quad (2.9)$$

The reflection coefficient  $\Gamma_{in}$  of the reflection load, the phase shift ( $\phi$ ), and the maximum phase shift range ( $\Delta\phi$ ), are presented in Equation (2.10).

$$\begin{aligned} \Gamma_{in} &= \frac{jY_{in} - Y_0}{jY_{in} + Y_0} \\ \phi_{in} &= \pi - \tan^{-1}\left(\frac{Y_{in}}{Y_0}\right) - \tan^{-1}\left(\frac{Y_{in}}{Y_0}\right) = \pi - 2 \tan^{-1}\left(\frac{Y_{in}}{Y_0}\right) \\ \Delta\phi_{in} &= \phi_{in}|_{\max} - \phi_{in}|_{\min} \end{aligned} \quad (2.10)$$

where  $Y_0 = 1/Z_0$  is a port termination admittance.  $Y_{in}$  is the total input admittance of the reflection load in the note A of Fig. 2.1.

As can be seen from equations (2.10), it is apparent that the overall phase shift range ( $\Delta\phi$ ) of the reflection load. Therefore, by designing the reflection load, the desired phase shift range characteristic of the entire phase shifter can be obtained. If the reflection load only has a capacitive component in its reactance, it can be considered to be determined by the frequency ( $f$ ) and the variable capacitance  $C_v$  of the varactor diode. Consequently, the phase shift ( $\phi$ ) can be represented as a function of  $f$  and  $C_v$ .

$$\phi_{in}(f, C_v) = \pi - 2 \tan^{-1}\left(\frac{Y_{in}(f, C_v)}{Y_0}\right) \quad (2.11)$$

From equation (2.11), the phase shift range at the operating frequency due to the variation of the variable capacitance  $C_V$  from its minimum capacitance  $C_{V\_min}$  to its maximum capacitance  $C_{V\_max}$  can be calculated as shown in equation (2.12).

$$\Delta\phi(C_V)\Big|_{f_c} = \phi(C_V)\Big|_{f_c} - \phi(C_V)_{\min}\Big|_{f_c}, \text{ when } \phi(C_V)_{\min}\Big|_{f_c} < \phi(C_V)_{\max}\Big|_{f_c} \quad (2.12a)$$

$$\Delta\phi(C_V)\Big|_{f_c} = \phi(C_V)\Big|_{f_c} - \phi(C_V)_{\max}\Big|_{f_c}, \text{ when } \phi(C_V)_{\max}\Big|_{f_c} < \phi(C_V)_{\min}\Big|_{f_c} \quad (2.12b)$$

Additionally, in-band phase deviation error (PDE) within the operating bandwidth can be expressed as shown in equation (2.13).

$$\text{PDE}(C_V) = \frac{\max(\Delta\phi(C_V))\Big|_{BW} - \min(\Delta\phi(C_V))\Big|_{BW}}{2} \quad (2.13)$$



3.1. Reflection load

Fig. 3.1 shows the reflection load which consists of coupled lines terminated TL and varactor diode operating at lower and higher band frequencies. The tunable phase operation at high or low band can affect to other low or high band, and these interferences must be prevented to achieve independent phase shift at each operating band. Therefore, it is necessary to cancel the interference effect so that the proposed DPS can provide independent tunable phase at each operating band as well as simultaneous tunable phase shift at both bands operation. For the purpose of achieving independent phase control at each band, coupled lines are used. The total input admittance looking at point A in Fig. 3.1 is given as (1) where  $f$ ,  $f_L$ , and  $f_H$  are operating frequency, lower band center frequency, and higher band center frequency, respectively.

$$Y_{in} = Y_{inL} + Y_{inH} \tag{3.1}$$

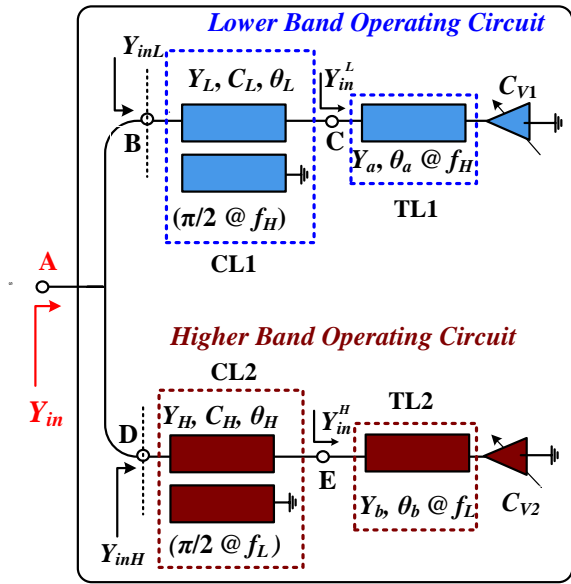


Fig. 3.1. Circuit implementation of tunable reflection load

### 3.2. Varactor Diode

Varactor diodes are preferred in these applications due to their low power loss caused by noise. These diodes are a type of P-N junction diode that can control the width of the depletion region when a reverse bias is applied. This control allows for adjustments in capacitance, which is crucial for managing the reactance in the reflection load of the phase shifter. By doing so, the phase characteristics can be controlled by using the bias voltage. The parasitic elements of varactor diode can lead to capacitance or inductance components that vary with frequency. This variation may cause an increase in phase deviation within the bandwidth operation. To investigate this issue, an Advanced Design System (ADS) simulation, provided by Keysight, was used. The simulation involved tweaking the parameters of the diode model to closely match the actual measurement results of the varactor diode, in this case, the SMV-1231 from Skyworks. This approach allowed for the construction of an equivalent circuit model that demonstrates similar characteristics to the real diode. The ADS simulation was used to confirm the frequency nonlinearity of the varactor diode as a function of voltage. The specific varactor diode studied, the SMV-1231, was chosen for its minimum capacitance value, which is the smallest in its product line. This characteristic enables a wider phase shift range in the reflection load due to reactance. The operating frequencies for the tests were 1.88 GHz at  $f_L$  and 2.44 GHz at  $f_H$ , and the capacitance values were measured by using a Network analyzer by varying the bias voltage from 0 V to 16V. Fig. 3.2 shows the parameter equivalent circuit model of the SMV-1231 diode. Fig. 3.3 and 3.4 shows about comparison of the simulation and measurement results for the SMV-1231 at both operating frequencies.

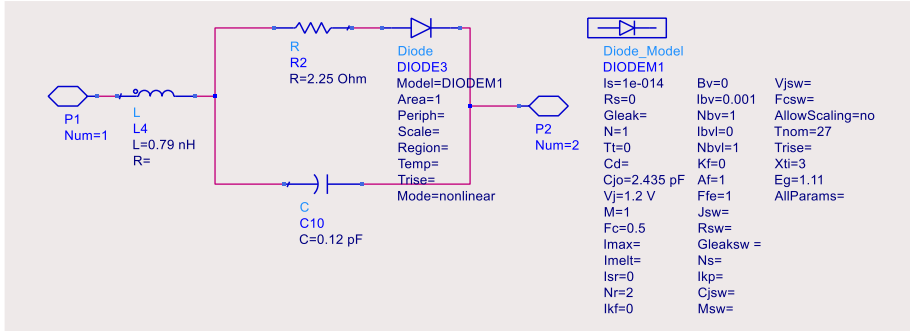


Fig. 3.2. Equivalent circuit of SMV-1231 varactor diode

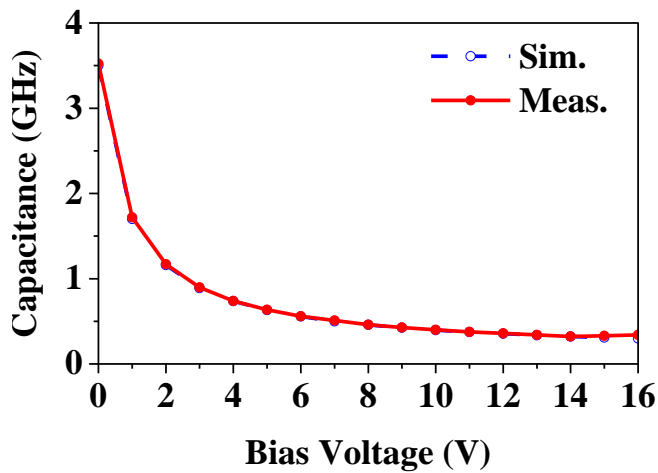


Fig. 3.3. Capacitance variation according to bias voltage at  $f_L$

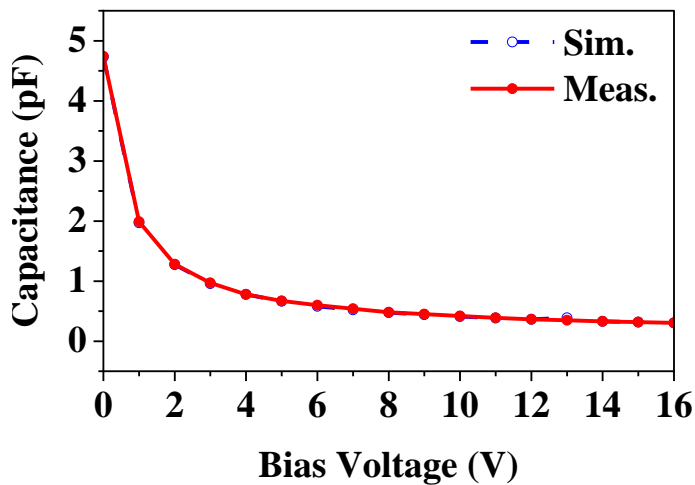


Fig. 3.4. Capacitance variation according to bias voltage at  $f_H$

### 3.3. Lower Band Operation Circuit

A quarter-wavelength of the coupled line (CL1) is used to achieve independent phase shift control at  $f_L$ . The equation 3.1 should be noted that the CL1 can provides an open condition at node B when  $f = f_H$ , while the CL1 acts as a capacitance at  $f_L$  is shown in Fig. 3.5(a). As the results, no phase shift occurs at  $f_H$  while tuning phase shift occurs at  $f_L$  is illustrated in Fig. 3.5(b). The input admittance at the lower band operation is given as

$$Y_{inL} = j \frac{Y_A - Y_B - 2Y_C + 2Y_D}{Y_E} \quad (3.2)$$

Where

$$Y_A = j^4 \left[ (Y_{11}^L)^2 - (Y_{12}^L)^2 \right] \left[ (Y_{in}^L)^2 + (Y_{11}^L)^2 \right] \quad (3.3a)$$

$$Y_B = j^4 \left[ (Y_{14}^L)^2 + (Y_{24}^L)^2 \right] \left[ (Y_{11}^L)^2 + Y_{11}^L Y_{in}^L \right] \quad (3.3b)$$

$$Y_C = j^4 Y_{in}^L Y_{12}^L (Y_{12}^L Y_{44}^L - Y_{42}^L Y_{14}^L) \quad (3.3c)$$

$$Y_D = 2j^4 \left[ (Y_{11}^L)^3 Y_{in}^L + Y_{44}^L Y_{12}^L Y_{42}^L Y_{14}^L \right] \quad (3.3d)$$

$$Y_E = j^4 \left[ (Y_{14}^L)^2 + (Y_{24}^L)^2 \right] \left[ (Y_{11}^L)^2 + Y_{11}^L Y_{in}^L \right] \quad (3.3e)$$

$$Y_{11}^L = -j \frac{Y_L}{\sqrt{1 - C_L^2}} \cot \theta_L \quad (3.3f)$$

$$Y_{12}^L = -j \frac{C_L Y_L}{\sqrt{1 - C_L^2}} \cot \theta_L \quad (3.3g)$$

$$\theta_L = \frac{\pi f}{2f_H} \quad , \quad C_L = 10^{[-C_L(dB)/20]} \quad (3.3h)$$

$$Y_{in}^L = -j \frac{2\pi f Y_a C_{V1} + Y_a^2 \tan \frac{\theta_a f}{f_H}}{Y_a - 2\pi f C_{V1} \tan \frac{\theta_a f}{f_H}} \quad (3.3i)$$

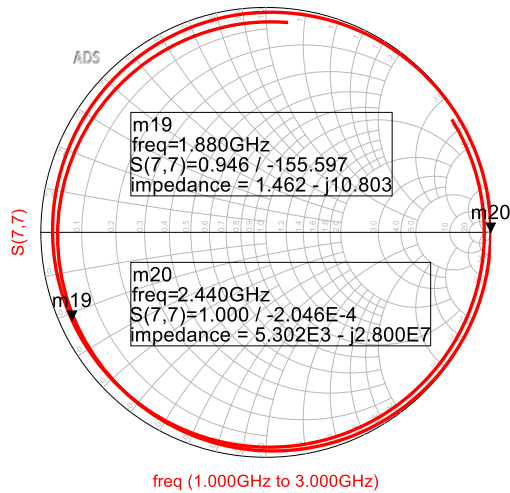
$Y_a$ ,  $\theta_a$ , and  $C_{V1}$  are characteristic admittances, electrical lengths of TL, and capacitance of varactor diode, respectively. Likewise,  $Y_L = 1/Z_L$  and  $C_L$  are characteristic admittances and coupling coefficients of coupled line, which are expressed terms of even and odd-mode admittances as depicted in (3).

$$Y_{0eL} = Y_L \sqrt{\frac{1+C_L}{1-C_L}}, \quad Y_{0oL} = Y_L \sqrt{\frac{1-C_L}{1+C_L}} \quad (3.4)$$

Using (3.1), (3.2), and (3.3), phase of the proposed DPS can be written as (4)

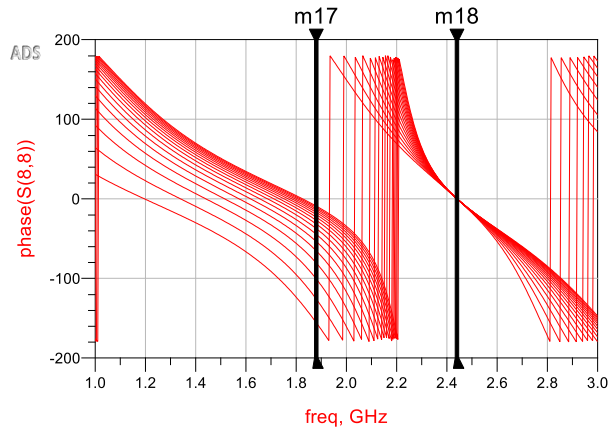
$$\varphi = \pi - 2 \tan^{-1} \left( \frac{Y_{inL} + Y_{inH}}{Y_0} \right), \quad (3.5)$$

where  $Y_0 = 1/Z_0$  is a port termination admittance.



(a)

m17	freq=1.880GHz	m18	freq=2.440GHz
phase(S(8,8))[0, :]	:-155.754	phase(S(8,8))[0, :]	:=0.000
phase(S(8,8))[1, :]	:-126.061	phase(S(8,8))[1, :]	:=0.000
phase(S(8,8))[2, :]	:-100.752	phase(S(8,8))[2, :]	:=0.000
phase(S(8,8))[3, :]	:-80.775	phase(S(8,8))[3, :]	:=0.000
phase(S(8,8))[4, :]	:-65.473	phase(S(8,8))[4, :]	:=0.000
phase(S(8,8))[5, :]	:-53.764	phase(S(8,8))[5, :]	:=0.000
phase(S(8,8))[6, :]	:-44.691	phase(S(8,8))[6, :]	:=0.000
phase(S(8,8))[7, :]	:-37.536	phase(S(8,8))[7, :]	:=0.000
phase(S(8,8))[8, :]	:-31.792	phase(S(8,8))[8, :]	:=0.000
phase(S(8,8))[9, :]	:-27.100	phase(S(8,8))[9, :]	:=0.000
phase(S(8,8))[10, :]	:-23.208	phase(S(8,8))[10, :]	:=0.000
phase(S(8,8))[11, :]	:-19.934	phase(S(8,8))[11, :]	:=0.000
phase(S(8,8))[12, :]	:-17.146	phase(S(8,8))[12, :]	:=0.000
phase(S(8,8))[13, :]	:-14.746	phase(S(8,8))[13, :]	:=0.000
phase(S(8,8))[14, :]	:-12.660	phase(S(8,8))[14, :]	:=0.000
phase(S(8,8))[15, :]	:-10.832	phase(S(8,8))[15, :]	:=0.000
phase(S(8,8))[16, :]	:-9.217	phase(S(8,8))[16, :]	:=0.000



(b)

Fig. 3.5. (a) Smith chart response according to bias voltage and (b) independent tunable phase shift (ITPS) by using the coupled line

### 3.4. Higher Band Operation Circuit

A quarter-wavelength of the coupled line (CL2) is used to achieve independent phase shift control at  $f_H$ . The equation 3.1 should be noted that the CL2 can provides an open condition at node D when  $f = f_L$ , while the CL2 acts as an inductance at  $f_H$  is shown in Fig. 3.6(a). As the results, no phase shift occurs at  $f_L$  while tuning phase shift occurs at  $f_H$ , as illustrated in Fig. 3.6(b). The input admittance at the higher band operation is given in equation (3.5).

$$Y_{inH} = j \frac{Y_F - Y_G - 2Y_H + 2Y_I}{Y_J} \quad (3.5)$$

Where

$$Y_F = j^4 \left[ (Y_{11}^H)^2 - (Y_{12}^H)^2 \right] \left[ (Y_{in}^H)^2 + (Y_{11}^H)^2 \right] \quad (3.6a)$$

$$Y_G = j^4 \left[ (Y_{14}^H)^2 + (Y_{24}^H)^2 \right] \left[ (Y_{11}^H)^2 + Y_{11}^H Y_{in}^H \right] \quad (3.6b)$$

$$Y_H = j^4 Y_{in}^H Y_{12}^H (Y_{12}^H Y_{44}^H - Y_{42}^H Y_{14}^H) \quad (3.6c)$$

$$Y_I = 2j^4 \left[ (Y_{11}^H)^3 Y_{in}^H + Y_{44}^H Y_{12}^H Y_{42}^H Y_{14}^H \right] \quad (3.6d)$$

$$Y_J = j^4 \left[ (Y_{14}^H)^2 + (Y_{24}^H)^2 \right] \left[ (Y_{11}^H)^2 + Y_{11}^H Y_{in}^H \right] \quad (3.6e)$$

$$Y_{11}^H = -j \frac{Y_H}{\sqrt{1 - C_H^2}} \cot \theta_H \quad (3.6f)$$

$$Y_{12}^H = -j \frac{C_H Y_H}{\sqrt{1 - C_H^2}} \cot \theta_H \quad (3.6g)$$

$$\theta_H = \frac{\pi f}{2f_L}, \quad C_H = 10^{[-C_H (dB)/20]} \quad (3.6h)$$

$$Y_{in}^H = -j \frac{2\pi f Y_b C_{V2} + Y_b^2 \tan \frac{\theta_b f}{f_L}}{Y_b - 2\pi f C_{V2} \tan \frac{\theta_b f}{f_L}} \quad (3.6i)$$

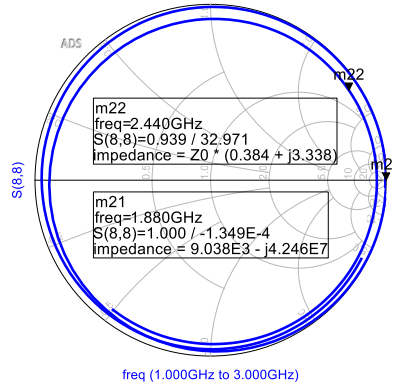
$Y_b$ ,  $\theta_b$ , and  $C_{V2}$  are characteristic admittances, electrical lengths of TL, and capacitance of varactor diode, respectively. Likewise,  $Y_H = 1/Z_H$  and  $C_H$  are characteristic admittances and coupling coefficients of coupled line, which are expressed terms of even and odd-mode admittances as depicted in (3.7).

$$Y_{0eL} = Y_L \sqrt{\frac{1 + C_L}{1 - C_L}}, \quad Y_{0oL} = Y_{L,H} \sqrt{\frac{1 - C_L}{1 + C_L}} \quad (3.7)$$

Using (3.1), (3.2) and (3.6), phase of the proposed DPS can be written as  
(3.8)

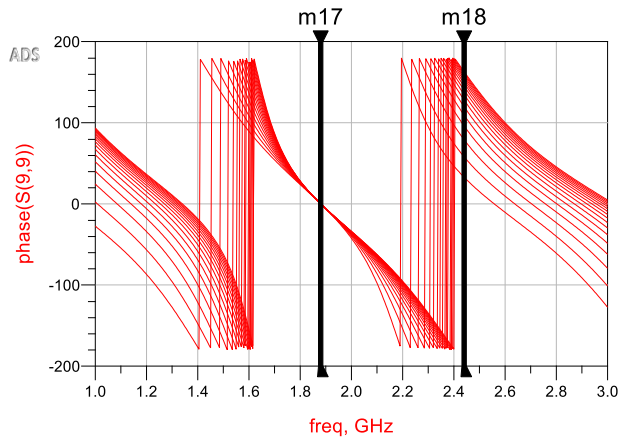
$$\varphi = \pi - 2 \tan^{-1} \left( \frac{Y_{inL} + Y_{inH}}{Y_0} \right), \quad (3.8)$$

where  $Y_0 = 1/Z_0$  is a port termination admittance.



(a)

m17	m18
freq=1.880GHz	freq=2.440GHz
phase(S(9,9))0, :::=0.000	phase(S(9,9))0, :::=32.737
phase(S(9,9))1, :::=0.000	phase(S(9,9))1, :::=57.872
phase(S(9,9))2, :::=0.000	phase(S(9,9))2, :::=78.987
phase(S(9,9))3, :::=0.000	phase(S(9,9))3, :::=95.891
phase(S(9,9))4, :::=0.000	phase(S(9,9))4, :::=109.190
phase(S(9,9))5, :::=0.000	phase(S(9,9))5, :::=119.663
phase(S(9,9))6, :::=0.000	phase(S(9,9))6, :::=127.997
phase(S(9,9))7, :::=0.000	phase(S(9,9))7, :::=134.719
phase(S(9,9))8, :::=0.000	phase(S(9,9))8, :::=140.221
phase(S(9,9))9, :::=0.000	phase(S(9,9))9, :::=144.787
phase(S(9,9))10, :::=0.000	phase(S(9,9))10, :::=148.627
phase(S(9,9))11, :::=0.000	phase(S(9,9))11, :::=151.893
phase(S(9,9))12, :::=0.000	phase(S(9,9))12, :::=154.702
phase(S(9,9))13, :::=0.000	phase(S(9,9))13, :::=157.140
phase(S(9,9))14, :::=0.000	phase(S(9,9))14, :::=159.274
phase(S(9,9))15, :::=0.000	phase(S(9,9))15, :::=161.156
phase(S(9,9))16, :::=0.000	phase(S(9,9))16, :::=162.829



(b)

Fig. 3.6. (a) Smith chart response and (b) ITPS by using the coupled line



### 3.5. Flowchart of Optimization

Fig. 3.7 shows the flowchart of optimization for designing a dual-band tunable phase shifter using a particular method involving reflection load.

- ✓ Step 1: The process begins with the input of specific values including lower and higher frequencies ( $f_L, f_H$ ), bandwidth (BW), number of point (NP), minimum and maximum phase shifts at both frequency limits ( $\Delta\phi_{\min\_L}, \Delta\phi_{\min\_H}, \Delta\phi_{\max\_L}, \Delta\phi_{\max\_H}$ ), minimum and maximum magnitudes ( $\text{Mag}_{\min}, \text{Mag}_{\max}$ ), voltage limits ( $V_{\min}, V_{\max}$ , parasitic components of varactor diode ( $L_p, C_p, R_p, C_j$ ).
- ✓ Step 2: The flowchart then splits into two paths for lower band operation and higher band operation. For lower band operation, you adjust  $Z_L, C_L, Z_{Ls}$ , and  $\theta_{Ls}$ . For high band operation, you adjust  $Z_H, C_H, Z_{Hs}$ , and  $\theta_{Hs}$ .
- ✓ Step 3: After these adjustments, Calculate the phase shift range ( $\Delta\phi_L, \Delta\phi_H$ ) at the center frequency, the maximum phase deviation ( $\phi_{\text{err\_L}}, \phi_{\text{err\_H}}$ ) within 300 MHz operating BW, and the maximum return loss ( $\text{Mag}_L, \text{Mag}_H$ ) within 300 MHz operating BW at the both band operating frequencies by varied the bias voltage from 0 – 16 V.
- ✓ Step 4: The next step is another decision point where you compare the calculated phase shift and magnitude against reference or required values. For lower band: If  $\Delta\phi_L > \Delta\phi_{\text{ref\_L}}, \phi_{\text{err\_L}} < \phi_{\text{err\_ref\_L}}$ , and  $\text{Mag}_L < \text{Mag}_{\text{ref}}$ , then proceed. For high band: If  $\Delta\phi_H > \Delta\phi_{\text{ref\_H}}, \phi_{\text{err\_H}} < \phi_{\text{err\_ref\_H}}$ , and  $\text{Mag}_H < \text{Mag}_{\text{ref}}$ , then proceed.
- ✓ Step 5: If the conditions are met (Yes), then you check if the PDE is minimum and PSR is maximum for both low and high bands are

within acceptable limits, then go to next step.

- ✓ Step 6: The final decision point asks if the values of length, width, and gap are acceptable to fabricate. If yes, then the design is presumably finalized for fabrication. If no, then adjustments must be made.

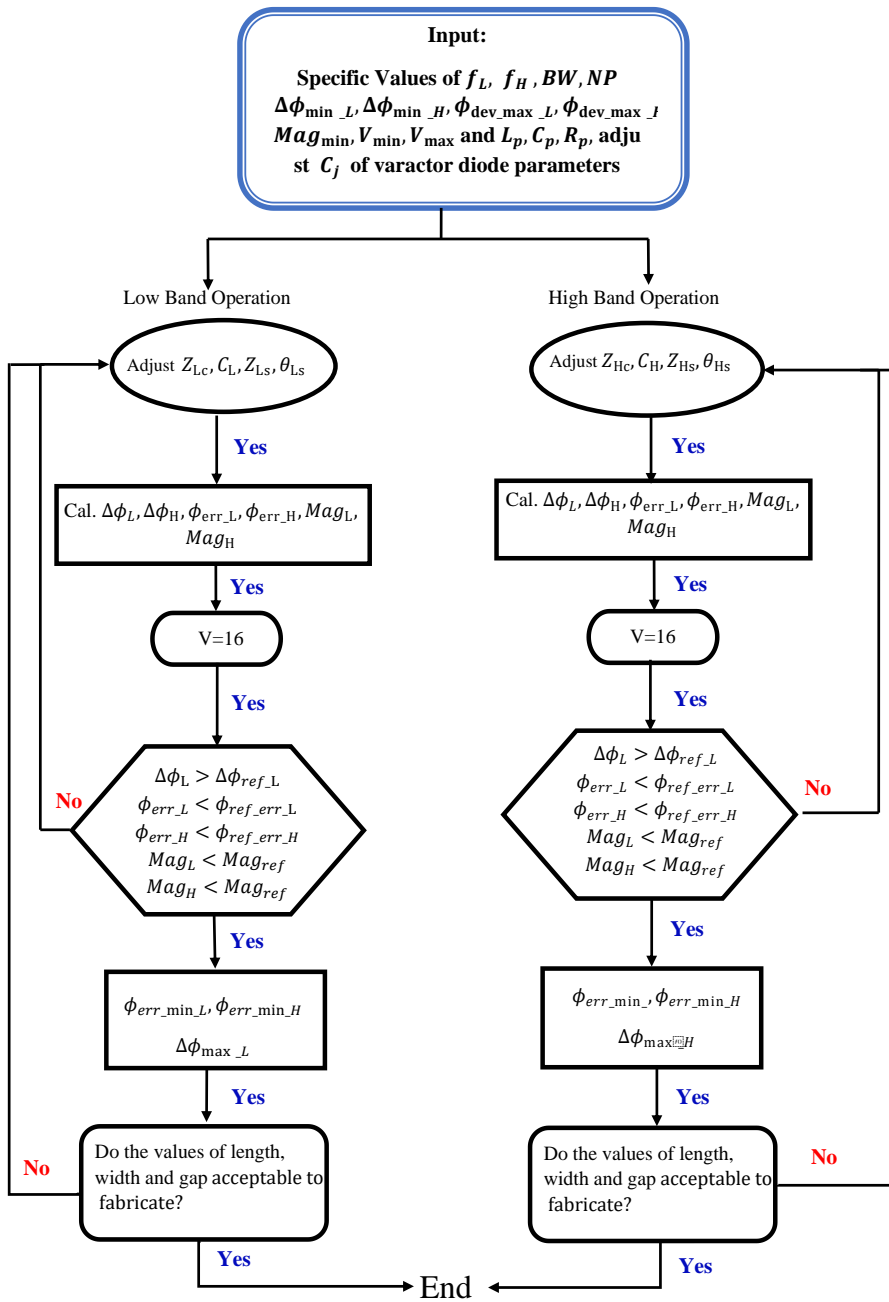


Fig. 3.7. Algorithm flowchart for designing a phase shifter

The circuit parameters of coupled lines and TLs are optimized for each operating center frequency by using MATLAB and results are shown in Tables I and II.

As seen from Table I, maximum relative PSR of  $146^\circ$  is achieved at lower operating center frequency  $f_L = 1.88$  GHz with PDE of  $\pm 6.72^\circ$  within bandwidth of 300 MHz, when circuit parameters are selected as  $Z_L = 1/Y_L = 81 \Omega$ ,  $C_L = -8.3$  dB,  $Z_a = 1/Y_a = 120 \Omega$ , and  $\theta_a = 110^\circ$ . Fig. 3.8 shows independent tunable phase shifter (ITPS) characteristics at lower and higher operating bands. As seen in the figure, the transmission phase shift is independently tuned at lower operating frequency band (1.73 ~ 2.03 GHz) when  $C_{V1}$  is varied and  $C_{V2}$  is fixed.

TABLE I

Calculated PSR =  $\Delta\phi_{max}$  and PDE =  $\phi_{err}$  within bandwidth of 300 MHz at  $f_L = 1.88$  GHz for different circuit parameters

Varactor diode SMV-1231 with $C_V$ : 0.3 pF to 3.5 pF					
$Z_L (\Omega)$	$C_L$ (dB)	$Z_a (\Omega)$	$\theta_a (^\circ)$	$\Delta\phi_{max} (^\circ)$	$\phi_{err} (^\circ)$
70	-8	120	117	142.16	$\pm 9.76$
70	-8.5		123	134.83	$\pm 8.97$
80	-8		110	151.34	$\pm 8.84$
81	-8.3		110	146.15	$\pm 6.72$
85	-8.5		117	143.65	$\pm 9.89$

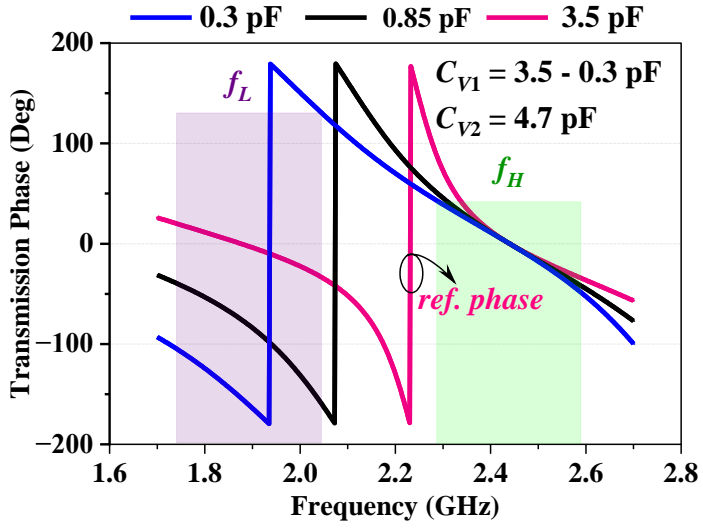


Fig. 3.8 ITPS characteristics at  $f_L$  according to  $C_{V1}$  is varied from 0.3 pF to 3.5 pF while  $C_{V2}$  is fixed at 4.7 pF.

As seen from Table II, the maximum relative PSR of  $130.6^\circ$  is achieved at  $f_H$  with PDE of  $\pm 8.64^\circ$  within bandwidth of 300 MHz, when circuit parameters are selected as  $Z_H = 1/Y_H = 70 \Omega$ ,  $C_H = -7 \text{ dB}$ ,  $Z_b = 1/Y_b = 120 \Omega$ , and  $\theta_b = 123^\circ$ . Fig. 3.9 depicts the phase shift is also independently controlled at higher operating frequency band (2.29 ~ 2.59 GHz) while tuning  $C_{V2}$  and fixing  $C_{V1}$ . This independent phase shift control is achieved due to coupled lines.

TABLE II

Calculated PSR =  $\Delta\varphi_{max}$  and PDE =  $\varphi_{err}$  within bandwidth of 300 MHz at  $f_H$   
 = 2.44 GHz for different circuit parameters

Varactor diode SMV-1231 with $C_V$ : 0.3 pF to 4.7 pF					
$Z_H$ ( $\Omega$ )	$C_H$ (dB)	$Z_b$ ( $\Omega$ )	$\theta_b$ ( $^\circ$ )	$\Delta\varphi_{max}$ ( $^\circ$ )	$\varphi_{err}$ ( $^\circ$ )
61	-7	110	128	135.5	$\pm 8.82$
65	-7	120	125	127.14	$\pm 8.48$
70	-7		123	130.6	$\pm 8.64$
71	-6.9		123	133.23	$\pm 9.36$
72	-7.1		123	130.62	$\pm 9.48$

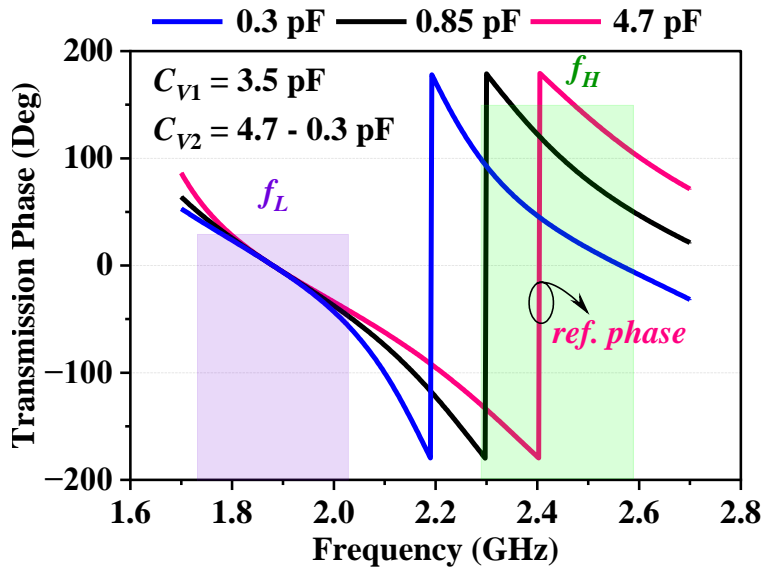


Fig. 3.9 ITPS characteristics at  $f_H$  according to  $C_{V1}$  is fixed at 3.5 pF while  $C_{V2}$  is varied from 0.3 pF to 4.7 pF.

## Chapter 4 Simulation Results

The dual-band tunable phase shifter proposed in our study. The circuit parameters are selected as  $Z_L = 1/Y_L = 81 \Omega$ ,  $C_L = -8.3 \text{ dB}$ ,  $Z_a = 1/Y_a = 120 \Omega$ , and  $\theta_a = 110^\circ$  at  $f_L$  and  $Z_H = 1/Y_H = 70 \Omega$ ,  $C_H = -7 \text{ dB}$ ,  $Z_b = 1/Y_b = 120 \Omega$ , and  $\theta_b = 123^\circ$  at  $f_H$ . The performance of overall circuit was simulated by using Advanced Design System (ADS) with an ideal simulation approach. Fig. 4.1. shows the schematic of overall circuit simulation of propose dual-band tunable phase shifter. This ideal simulation was conducted in three cases: lower band operation band, higher band operation, and both band operation.

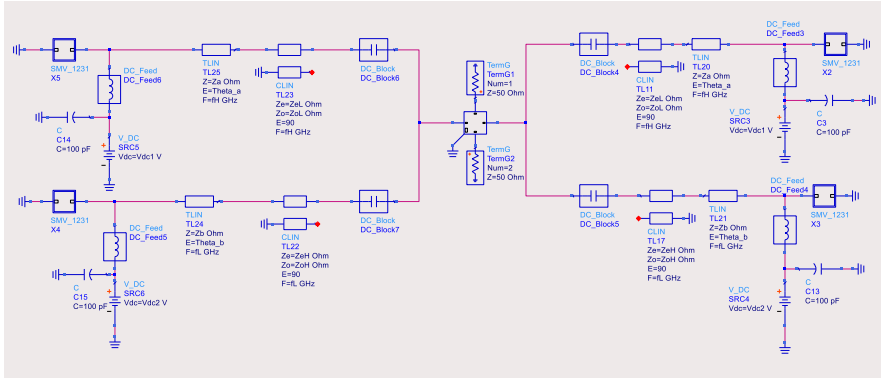


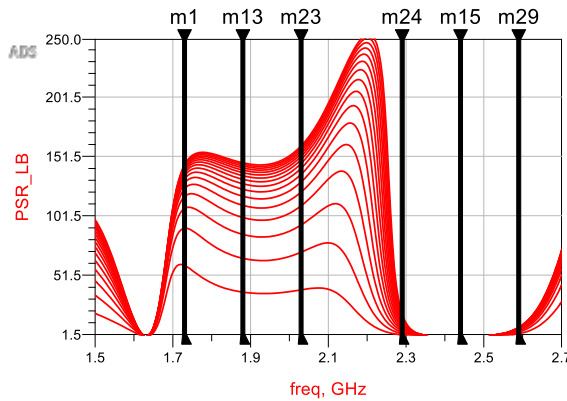
Fig. 4.1. Overall circuit simulation schematic

### 4.1. Lower Band Operation

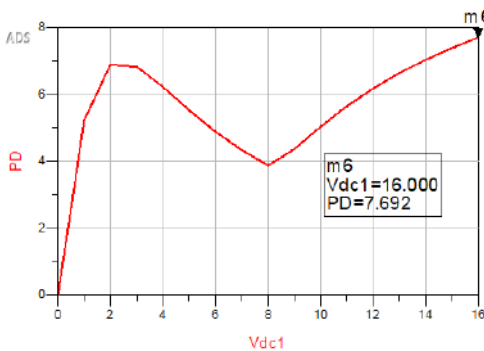
The bias voltage of varactor diode operating at  $f_L$  is varied from 0 to 16 V, while the bias voltage of varactor diode operating at  $f_H$  is fixed 0 V. In this case, the maximum PSR of  $146.26^\circ$  is obtained at  $f_L$ , while maintaining PSR of  $0^\circ$  at  $f_H$  is shown in Fig. 4.2(a). Furthermore, the maximum PDE is  $7.69^\circ$

at  $f_L$  and  $6.5^\circ$  at  $f_H$ , as shown in Figures 4.2(b) and (c). Additionally, the maximum insertion loss is depicted as 0.56 dB in Figure 4.3(a). Figure 4.3(b) illustrates the return loss according to the bias voltage of the varactor diode, with the maximum return loss is 17.48 dB at both bands.

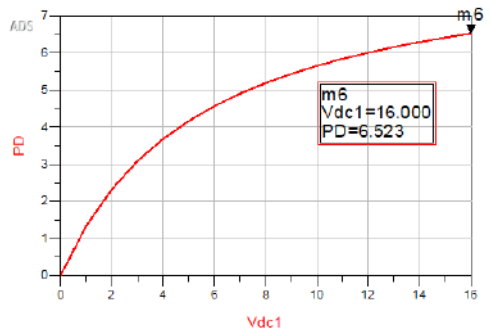
m1	m13	m23	m24	m15	m29
freq=1.730GHz	freq=1.880GHz	freq=2.030GHz	freq=2.290GHz	freq=2.440GHz	freq=2.590GHz
PSR_LB[0]::=0.000	PSR_LB[0]::=0.000	PSR_LB[0]::=0.000	PSR_LB[0]::=0.000	PSR_LB[0]::=0.000	PSR_LB[0]::=0.000
PSR_LB[1]::=59.734	PSR_LB[1]::=37.194	PSR_LB[1]::=39.097	PSR_LB[1]::=1.078	PSR_LB[1]::=0.000	PSR_LB[1]::=2.179
PSR_LB[2]::=90.982	PSR_LB[2]::=65.649	PSR_LB[2]::=70.832	PSR_LB[2]::=2.168	PSR_LB[2]::=0.000	PSR_LB[2]::=3.519
PSR_LB[3]::=107.702	PSR_LB[3]::=85.790	PSR_LB[3]::=93.762	PSR_LB[3]::=3.269	PSR_LB[3]::=0.000	PSR_LB[3]::=4.426
PSR_LB[4]::=117.701	PSR_LB[4]::=99.989	PSR_LB[4]::=109.899	PSR_LB[4]::=4.381	PSR_LB[4]::=0.000	PSR_LB[4]::=5.080
PSR_LB[5]::=124.261	PSR_LB[5]::=110.252	PSR_LB[5]::=121.447	PSR_LB[5]::=5.504	PSR_LB[5]::=0.000	PSR_LB[5]::=5.575
PSR_LB[6]::=128.867	PSR_LB[6]::=117.903	PSR_LB[6]::=129.961	PSR_LB[6]::=6.639	PSR_LB[6]::=0.000	PSR_LB[6]::=5.962
PSR_LB[7]::=132.289	PSR_LB[7]::=123.790	PSR_LB[7]::=136.431	PSR_LB[7]::=7.785	PSR_LB[7]::=0.000	PSR_LB[7]::=6.272
PSR_LB[8]::=134.880	PSR_LB[8]::=128.413	PSR_LB[8]::=141.485	PSR_LB[8]::=8.942	PSR_LB[8]::=0.000	PSR_LB[8]::=6.528
PSR_LB[9]::=136.946	PSR_LB[9]::=132.149	PSR_LB[9]::=145.527	PSR_LB[9]::=10.110	PSR_LB[9]::=0.000	PSR_LB[9]::=6.741
PSR_LB[10]::=138.620	PSR_LB[10]::=135.218	PSR_LB[10]::=148.826	PSR_LB[10]::=11.289	PSR_LB[10]::=0.000	PSR_LB[10]::=6.922
PSR_LB[11]::=140.003	PSR_LB[11]::=137.781	PSR_LB[11]::=151.566	PSR_LB[11]::=12.479	PSR_LB[11]::=0.000	PSR_LB[11]::=7.077
PSR_LB[12]::=141.165	PSR_LB[12]::=139.952	PSR_LB[12]::=153.874	PSR_LB[12]::=13.679	PSR_LB[12]::=0.000	PSR_LB[12]::=7.212
PSR_LB[13]::=142.155	PSR_LB[13]::=141.813	PSR_LB[13]::=155.845	PSR_LB[13]::=14.891	PSR_LB[13]::=0.000	PSR_LB[13]::=7.330
PSR_LB[14]::=143.008	PSR_LB[14]::=143.425	PSR_LB[14]::=157.546	PSR_LB[14]::=16.112	PSR_LB[14]::=0.000	PSR_LB[14]::=7.435
PSR_LB[15]::=143.751	PSR_LB[15]::=144.834	PSR_LB[15]::=159.028	PSR_LB[15]::=17.344	PSR_LB[15]::=0.000	PSR_LB[15]::=7.528
PSR_LB[16]::=144.403	PSR_LB[16]::=146.077	PSR_LB[16]::=160.330	PSR_LB[16]::=18.587	PSR_LB[16]::=0.000	PSR_LB[16]::=7.611



(a)



(b)

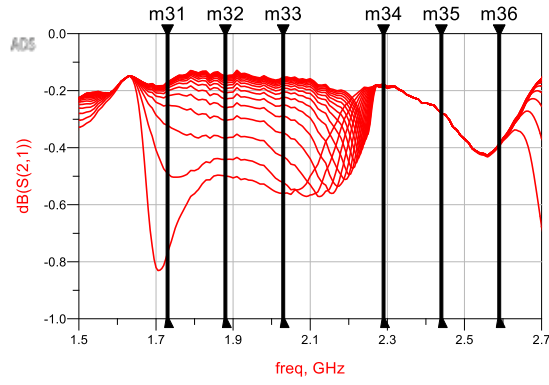


(c)

Fig. 4.2. PSR responses according to bias voltage of both bands, (b) PDE of  $f_L$ , and (c) PDE of  $f_H$ .

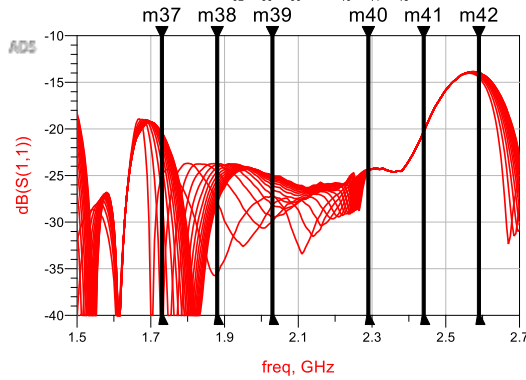


m31	m32	m33	m34	m35	m36
freq=1.730GHz	freq=1.880GHz	freq=2.030GHz	freq=2.290GHz	freq=2.440GHz	freq=2.590GHz
dB(S(2,1))0. :=-0.768	dB(S(2,1))0. :=-0.500	dB(S(2,1))0. :=-0.560	dB(S(2,1))0. :=-0.186	dB(S(2,1))0. :=-0.279	dB(S(2,1))0. :=-0.395
dB(S(2,1))1. :=-0.489	dB(S(2,1))1. :=-0.442	dB(S(2,1))1. :=-0.523	dB(S(2,1))1. :=-0.185	dB(S(2,1))1. :=-0.279	dB(S(2,1))1. :=-0.389
dB(S(2,1))2. :=-0.322	dB(S(2,1))2. :=-0.387	dB(S(2,1))2. :=-0.431	dB(S(2,1))2. :=-0.185	dB(S(2,1))2. :=-0.279	dB(S(2,1))2. :=-0.387
dB(S(2,1))3. :=-0.251	dB(S(2,1))3. :=-0.305	dB(S(2,1))3. :=-0.348	dB(S(2,1))3. :=-0.184	dB(S(2,1))3. :=-0.279	dB(S(2,1))3. :=-0.387
dB(S(2,1))4. :=-0.218	dB(S(2,1))4. :=-0.260	dB(S(2,1))4. :=-0.289	dB(S(2,1))4. :=-0.184	dB(S(2,1))4. :=-0.279	dB(S(2,1))4. :=-0.387
dB(S(2,1))5. :=-0.201	dB(S(2,1))5. :=-0.230	dB(S(2,1))5. :=-0.250	dB(S(2,1))5. :=-0.183	dB(S(2,1))5. :=-0.279	dB(S(2,1))5. :=-0.387
dB(S(2,1))6. :=-0.191	dB(S(2,1))6. :=-0.208	dB(S(2,1))6. :=-0.223	dB(S(2,1))6. :=-0.183	dB(S(2,1))6. :=-0.279	dB(S(2,1))6. :=-0.388
dB(S(2,1))7. :=-0.184	dB(S(2,1))7. :=-0.193	dB(S(2,1))7. :=-0.204	dB(S(2,1))7. :=-0.182	dB(S(2,1))7. :=-0.279	dB(S(2,1))7. :=-0.388
dB(S(2,1))8. :=-0.180	dB(S(2,1))8. :=-0.182	dB(S(2,1))8. :=-0.191	dB(S(2,1))8. :=-0.182	dB(S(2,1))8. :=-0.279	dB(S(2,1))8. :=-0.388
dB(S(2,1))9. :=-0.177	dB(S(2,1))9. :=-0.174	dB(S(2,1))9. :=-0.181	dB(S(2,1))9. :=-0.181	dB(S(2,1))9. :=-0.279	dB(S(2,1))9. :=-0.389
dB(S(2,1))10. :=-0.175	dB(S(2,1))10. :=-0.167	dB(S(2,1))10. :=-0.174	dB(S(2,1))10. :=-0.180	dB(S(2,1))10. :=-0.279	dB(S(2,1))10. :=-0.389
dB(S(2,1))11. :=-0.173	dB(S(2,1))11. :=-0.162	dB(S(2,1))11. :=-0.168	dB(S(2,1))11. :=-0.180	dB(S(2,1))11. :=-0.279	dB(S(2,1))11. :=-0.389
dB(S(2,1))12. :=-0.172	dB(S(2,1))12. :=-0.158	dB(S(2,1))12. :=-0.164	dB(S(2,1))12. :=-0.179	dB(S(2,1))12. :=-0.279	dB(S(2,1))12. :=-0.390
dB(S(2,1))13. :=-0.171	dB(S(2,1))13. :=-0.155	dB(S(2,1))13. :=-0.160	dB(S(2,1))13. :=-0.179	dB(S(2,1))13. :=-0.279	dB(S(2,1))13. :=-0.390
dB(S(2,1))14. :=-0.170	dB(S(2,1))14. :=-0.152	dB(S(2,1))14. :=-0.157	dB(S(2,1))14. :=-0.178	dB(S(2,1))14. :=-0.279	dB(S(2,1))14. :=-0.390
dB(S(2,1))15. :=-0.170	dB(S(2,1))15. :=-0.150	dB(S(2,1))15. :=-0.155	dB(S(2,1))15. :=-0.177	dB(S(2,1))15. :=-0.279	dB(S(2,1))15. :=-0.390
dB(S(2,1))16. :=-0.169	dB(S(2,1))16. :=-0.148	dB(S(2,1))16. :=-0.152	dB(S(2,1))16. :=-0.177	dB(S(2,1))16. :=-0.279	dB(S(2,1))16. :=-0.391



(a)

m37	m38	m39	m40	m41	m42
freq=1.730GHz	freq=1.880GHz	freq=2.030GHz	freq=2.290GHz	freq=2.440GHz	freq=2.590GHz
dB(S(1,1))0. :=25.125	dB(S(1,1))0. :=-35.594	dB(S(1,1))0. :=-27.123	dB(S(1,1))0. :=-24.364	dB(S(1,1))0. :=-20.313	dB(S(1,1))0. :=-14.434
dB(S(1,1))1. :=-47.043	dB(S(1,1))1. :=-27.906	dB(S(1,1))1. :=-28.120	dB(S(1,1))1. :=-24.365	dB(S(1,1))1. :=-20.313	dB(S(1,1))1. :=-14.267
dB(S(1,1))2. :=-27.338	dB(S(1,1))2. :=-24.630	dB(S(1,1))2. :=-23.885	dB(S(1,1))2. :=-24.366	dB(S(1,1))2. :=-20.313	dB(S(1,1))2. :=-14.172
dB(S(1,1))3. :=-23.824	dB(S(1,1))3. :=-23.789	dB(S(1,1))3. :=-23.509	dB(S(1,1))3. :=-24.370	dB(S(1,1))3. :=-20.313	dB(S(1,1))3. :=-14.110
dB(S(1,1))4. :=-22.430	dB(S(1,1))4. :=-23.809	dB(S(1,1))4. :=-23.240	dB(S(1,1))4. :=-24.375	dB(S(1,1))4. :=-20.313	dB(S(1,1))4. :=-14.067
dB(S(1,1))5. :=-21.718	dB(S(1,1))5. :=-24.143	dB(S(1,1))5. :=-27.233	dB(S(1,1))5. :=-24.381	dB(S(1,1))5. :=-20.313	dB(S(1,1))5. :=-14.035
dB(S(1,1))6. :=-21.300	dB(S(1,1))6. :=-24.581	dB(S(1,1))6. :=-26.558	dB(S(1,1))6. :=-24.389	dB(S(1,1))6. :=-20.313	dB(S(1,1))6. :=-14.011
dB(S(1,1))7. :=-21.031	dB(S(1,1))7. :=-25.038	dB(S(1,1))7. :=-26.109	dB(S(1,1))7. :=-24.399	dB(S(1,1))7. :=-20.313	dB(S(1,1))7. :=-13.991
dB(S(1,1))8. :=-20.846	dB(S(1,1))8. :=-25.481	dB(S(1,1))8. :=-25.802	dB(S(1,1))8. :=-24.411	dB(S(1,1))8. :=-20.313	dB(S(1,1))8. :=-13.976
dB(S(1,1))9. :=-20.713	dB(S(1,1))9. :=-25.895	dB(S(1,1))9. :=-25.587	dB(S(1,1))9. :=-24.424	dB(S(1,1))9. :=-20.313	dB(S(1,1))9. :=-13.963
dB(S(1,1))10. :=-20.614	dB(S(1,1))10. :=-26.278	dB(S(1,1))10. :=-25.432	dB(S(1,1))10. :=-24.440	dB(S(1,1))10. :=-20.313	dB(S(1,1))10. :=-13.952
dB(S(1,1))11. :=-20.536	dB(S(1,1))11. :=-26.629	dB(S(1,1))11. :=-25.318	dB(S(1,1))11. :=-24.457	dB(S(1,1))11. :=-20.313	dB(S(1,1))11. :=-13.943
dB(S(1,1))12. :=-20.475	dB(S(1,1))12. :=-26.951	dB(S(1,1))12. :=-25.232	dB(S(1,1))12. :=-24.477	dB(S(1,1))12. :=-20.313	dB(S(1,1))12. :=-13.938
dB(S(1,1))13. :=-20.428	dB(S(1,1))13. :=-27.246	dB(S(1,1))13. :=-25.168	dB(S(1,1))13. :=-24.498	dB(S(1,1))13. :=-20.313	dB(S(1,1))13. :=-13.928
dB(S(1,1))14. :=-20.388	dB(S(1,1))14. :=-27.517	dB(S(1,1))14. :=-25.115	dB(S(1,1))14. :=-24.522	dB(S(1,1))14. :=-20.313	dB(S(1,1))14. :=-13.921
dB(S(1,1))15. :=-20.352	dB(S(1,1))15. :=-27.765	dB(S(1,1))15. :=-25.074	dB(S(1,1))15. :=-24.549	dB(S(1,1))15. :=-20.313	dB(S(1,1))15. :=-13.916
dB(S(1,1))16. :=-20.323	dB(S(1,1))16. :=-27.994	dB(S(1,1))16. :=-25.049	dB(S(1,1))16. :=-24.577	dB(S(1,1))16. :=-20.313	dB(S(1,1))16. :=-13.911



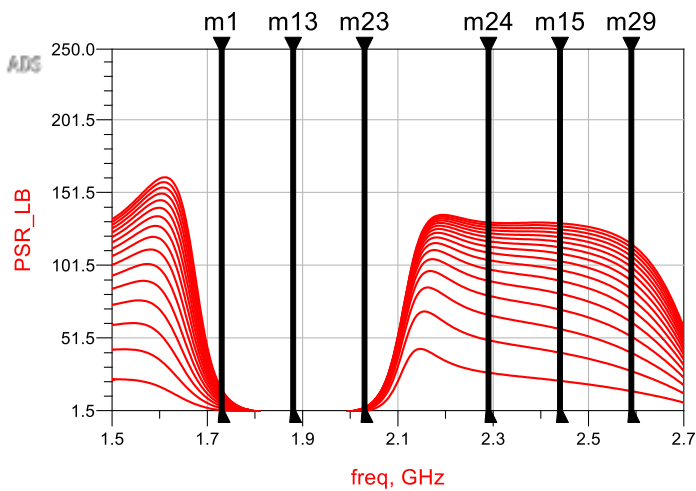
(b)

Fig. 4.3 (a) Insertion loss responses according to bias voltages of both bands, and (b) return loss responses according to bias voltages of both bands.

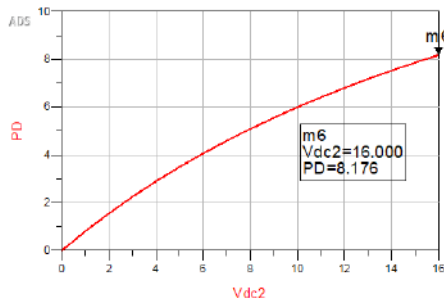
## 4.2. Higher Band Operation

Likewise to the lower band operation, the bias the bias voltage of varactor diode operating at  $f_L$  is fixed to 0 V, while the bias voltage of varactor diode operating at  $f_H$  is varied 0 to 16 V. The PSR at  $f_L$  is maintained to  $0^\circ$ , while the maximum PSR of  $130.2^\circ$  is obtained as shown in Fig. 4.4(a). Fig. 4.4(b) shows that the maximum PDE at  $f_L$  is  $\pm 8.2^\circ$ , and Fig. 4.4(c) shows that the maximum PDE at  $f_H$  is  $\pm 9^\circ$ . Additionally, the maximum insertion loss is 0.5 dB, as shown in Fig. 4.5(a). Fig. 4.5(b) demonstrates the return loss according to the bias voltage, with the minimum return loss is 17.48 dB at both bands.

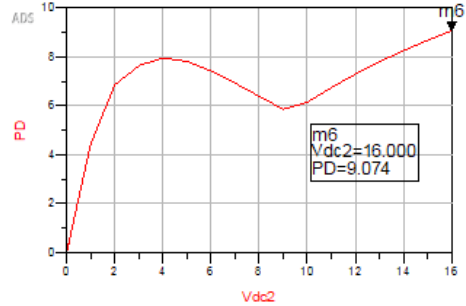
m1 freq=1.730GHz PSR_LB[0, ..]=0.000 PSR_LB[1, ..]=1.586 PSR_LB[2, ..]=3.056 PSR_LB[3, ..]=4.422 PSR_LB[4, ..]=6.694 PSR_LB[5, ..]=6.882 PSR_LB[6, ..]=7.993 PSR_LB[7, ..]=9.034 PSR_LB[8, ..]=10.012 PSR_LB[9, ..]=10.932 PSR_LB[10, ..]=11.799 PSR_LB[11, ..]=12.617 PSR_LB[12, ..]=13.390 PSR_LB[13, ..]=14.122 PSR_LB[14, ..]=14.816 PSR_LB[15, ..]=15.474 PSR_LB[16, ..]=16.100	m13 freq=1.880GHz PSR_LB[0, ..]=0.000 PSR_LB[1, ..]=0.000 PSR_LB[2, ..]=0.000 PSR_LB[3, ..]=0.000 PSR_LB[4, ..]=0.000 PSR_LB[5, ..]=0.000 PSR_LB[6, ..]=0.000 PSR_LB[7, ..]=0.000 PSR_LB[8, ..]=0.000 PSR_LB[9, ..]=0.000 PSR_LB[10, ..]=0.000 PSR_LB[11, ..]=0.000 PSR_LB[12, ..]=0.000 PSR_LB[13, ..]=0.000 PSR_LB[14, ..]=0.000 PSR_LB[15, ..]=0.000 PSR_LB[16, ..]=0.000	m23 freq=2.030GHz PSR_LB[0, ..]=0.000 PSR_LB[1, ..]=1.074 PSR_LB[2, ..]=1.717 PSR_LB[3, ..]=2.145 PSR_LB[4, ..]=2.450 PSR_LB[5, ..]=2.679 PSR_LB[6, ..]=2.857 PSR_LB[7, ..]=2.999 PSR_LB[8, ..]=3.115 PSR_LB[9, ..]=3.212 PSR_LB[10, ..]=3.294 PSR_LB[11, ..]=3.364 PSR_LB[12, ..]=3.425 PSR_LB[13, ..]=3.478 PSR_LB[14, ..]=3.525 PSR_LB[15, ..]=3.567 PSR_LB[16, ..]=3.604	m24 freq=2.290GHz PSR_LB[0, ..]=0.000 PSR_LB[1, ..]=27.550 PSR_LB[2, ..]=49.951 PSR_LB[3, ..]=67.276 PSR_LB[4, ..]=80.509 PSR_LB[5, ..]=90.693 PSR_LB[6, ..]=98.656 PSR_LB[7, ..]=104.996 PSR_LB[8, ..]=110.134 PSR_LB[9, ..]=114.367 PSR_LB[10, ..]=117.904 PSR_LB[11, ..]=120.900 PSR_LB[12, ..]=123.466 PSR_LB[13, ..]=125.686 PSR_LB[14, ..]=127.626 PSR_LB[15, ..]=129.333 PSR_LB[16, ..]=130.846	m15 freq=2.440GHz PSR_LB[0, ..]=0.000 PSR_LB[1, ..]=21.987 PSR_LB[2, ..]=41.333 PSR_LB[3, ..]=57.602 PSR_LB[4, ..]=70.971 PSR_LB[5, ..]=81.881 PSR_LB[6, ..]=90.806 PSR_LB[7, ..]=98.161 PSR_LB[8, ..]=104.281 PSR_LB[9, ..]=109.427 PSR_LB[10, ..]=113.796 PSR_LB[11, ..]=117.543 PSR_LB[12, ..]=120.786 PSR_LB[13, ..]=123.614 PSR_LB[14, ..]=126.101 PSR_LB[15, ..]=128.302 PSR_LB[16, ..]=130.262	m29 freq=2.590GHz PSR_LB[0, ..]=0.000 PSR_LB[1, ..]=14.844 PSR_LB[2, ..]=28.657 PSR_LB[3, ..]=41.200 PSR_LB[4, ..]=52.386 PSR_LB[5, ..]=62.240 PSR_LB[6, ..]=70.863 PSR_LB[7, ..]=78.386 PSR_LB[8, ..]=84.950 PSR_LB[9, ..]=90.691 PSR_LB[10, ..]=95.728 PSR_LB[11, ..]=100.166 PSR_LB[12, ..]=104.094 PSR_LB[13, ..]=107.587 PSR_LB[14, ..]=110.708 PSR_LB[15, ..]=113.509 PSR_LB[16, ..]=116.033
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(a)



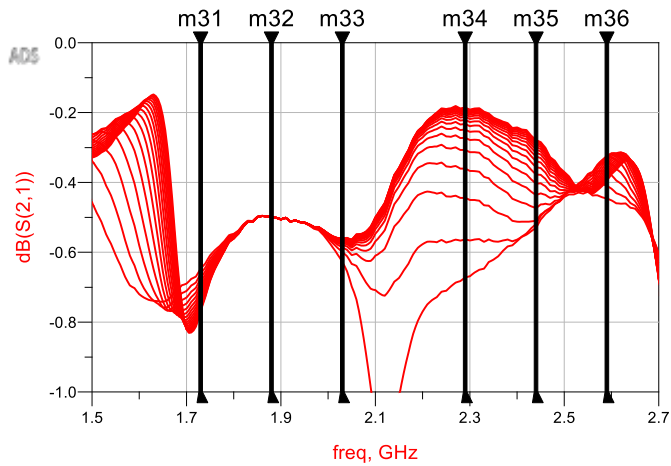
(b)



(c)

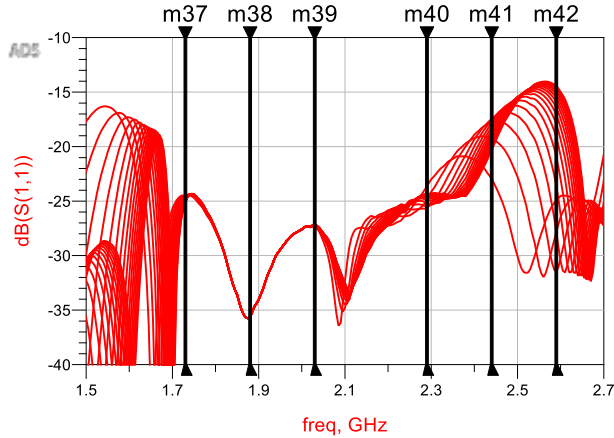
Fig. 4.4. (a) PSR responses according to bias voltage of both bands, (b) PDE of  $f_L$  and (c) PDE of  $f_H$ .

m31 freq=1.730GHz dB(S(2,1))0. : :-0.647 dB(S(2,1))1. : :-0.661 dB(S(2,1))2. : :-0.674 dB(S(2,1))3. : :-0.686 dB(S(2,1))4. : :-0.696 dB(S(2,1))5. : :-0.705 dB(S(2,1))6. : :-0.714 dB(S(2,1))7. : :-0.721 dB(S(2,1))8. : :-0.728 dB(S(2,1))9. : :-0.733 dB(S(2,1))10. : :-0.741 dB(S(2,1))11. : :-0.746 dB(S(2,1))12. : :-0.751 dB(S(2,1))13. : :-0.756 dB(S(2,1))14. : :-0.760 dB(S(2,1))15. : :-0.764 dB(S(2,1))16. : :-0.768	m32 freq=1.880GHz dB(S(2,1))0. : :-0.500 dB(S(2,1))1. : :-0.500 dB(S(2,1))2. : :-0.500 dB(S(2,1))3. : :-0.500 dB(S(2,1))4. : :-0.500 dB(S(2,1))5. : :-0.500 dB(S(2,1))6. : :-0.500 dB(S(2,1))7. : :-0.500 dB(S(2,1))8. : :-0.500 dB(S(2,1))9. : :-0.500 dB(S(2,1))10. : :-0.500 dB(S(2,1))11. : :-0.500 dB(S(2,1))12. : :-0.500 dB(S(2,1))13. : :-0.500 dB(S(2,1))14. : :-0.500 dB(S(2,1))15. : :-0.500 dB(S(2,1))16. : :-0.500	m33 freq=2.030GHz dB(S(2,1))0. : :-0.628 dB(S(2,1))1. : :-0.599 dB(S(2,1))2. : :-0.586 dB(S(2,1))3. : :-0.579 dB(S(2,1))4. : :-0.574 dB(S(2,1))5. : :-0.571 dB(S(2,1))6. : :-0.569 dB(S(2,1))7. : :-0.567 dB(S(2,1))8. : :-0.566 dB(S(2,1))9. : :-0.564 dB(S(2,1))10. : :-0.564 dB(S(2,1))11. : :-0.563 dB(S(2,1))12. : :-0.562 dB(S(2,1))13. : :-0.562 dB(S(2,1))14. : :-0.561 dB(S(2,1))15. : :-0.561 dB(S(2,1))16. : :-0.560	m34 freq=2.290GHz dB(S(2,1))0. : :-0.672 dB(S(2,1))1. : :-0.563 dB(S(2,1))2. : :-0.444 dB(S(2,1))3. : :-0.360 dB(S(2,1))4. : :-0.307 dB(S(2,1))5. : :-0.272 dB(S(2,1))6. : :-0.249 dB(S(2,1))7. : :-0.233 dB(S(2,1))8. : :-0.221 dB(S(2,1))9. : :-0.212 dB(S(2,1))10. : :-0.206 dB(S(2,1))11. : :-0.200 dB(S(2,1))12. : :-0.196 dB(S(2,1))13. : :-0.193 dB(S(2,1))14. : :-0.190 dB(S(2,1))15. : :-0.188 dB(S(2,1))16. : :-0.186	m35 freq=2.440GHz dB(S(2,1))0. : :-0.520 dB(S(2,1))1. : :-0.530 dB(S(2,1))2. : :-0.510 dB(S(2,1))3. : :-0.473 dB(S(2,1))4. : :-0.436 dB(S(2,1))5. : :-0.403 dB(S(2,1))6. : :-0.377 dB(S(2,1))7. : :-0.356 dB(S(2,1))8. : :-0.339 dB(S(2,1))9. : :-0.326 dB(S(2,1))10. : :-0.315 dB(S(2,1))11. : :-0.306 dB(S(2,1))12. : :-0.299 dB(S(2,1))13. : :-0.293 dB(S(2,1))14. : :-0.287 dB(S(2,1))15. : :-0.283 dB(S(2,1))16. : :-0.279	m36 freq=2.590GHz dB(S(2,1))0. : :-0.446 dB(S(2,1))1. : :-0.410 dB(S(2,1))2. : :-0.371 dB(S(2,1))3. : :-0.343 dB(S(2,1))4. : :-0.328 dB(S(2,1))5. : :-0.324 dB(S(2,1))6. : :-0.327 dB(S(2,1))7. : :-0.333 dB(S(2,1))8. : :-0.342 dB(S(2,1))9. : :-0.350 dB(S(2,1))10. : :-0.358 dB(S(2,1))11. : :-0.366 dB(S(2,1))12. : :-0.373 dB(S(2,1))13. : :-0.379 dB(S(2,1))14. : :-0.385 dB(S(2,1))15. : :-0.390 dB(S(2,1))16. : :-0.395
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(a)

m37	m38	m39	m40	m41	m42
freq=1.730GHz	freq=1.880GHz	freq=2.030GHz	freq=2.290GHz	freq=2.440GHz	freq=2.590GHz
dB(S(1,1))0. :-24.522	dB(S(1,1))0. :-35.594	dB(S(1,1))0. :-27.282	dB(S(1,1))0. :-23.657	dB(S(1,1))0. :-22.962	dB(S(1,1))0. :-24.965
dB(S(1,1))1. :-24.523	dB(S(1,1))1. :-35.594	dB(S(1,1))1. :-27.214	dB(S(1,1))1. :-24.951	dB(S(1,1))1. :-19.257	dB(S(1,1))1. :-27.871
dB(S(1,1))2. :-24.537	dB(S(1,1))2. :-35.594	dB(S(1,1))2. :-27.184	dB(S(1,1))2. :-25.659	dB(S(1,1))2. :-17.836	dB(S(1,1))2. :-31.458
dB(S(1,1))3. :-24.563	dB(S(1,1))3. :-35.594	dB(S(1,1))3. :-27.167	dB(S(1,1))3. :-25.540	dB(S(1,1))3. :-17.473	dB(S(1,1))3. :-27.812
dB(S(1,1))4. :-24.596	dB(S(1,1))4. :-35.594	dB(S(1,1))4. :-27.156	dB(S(1,1))4. :-25.224	dB(S(1,1))4. :-17.563	dB(S(1,1))4. :-23.611
dB(S(1,1))5. :-24.634	dB(S(1,1))5. :-35.594	dB(S(1,1))5. :-27.148	dB(S(1,1))5. :-24.957	dB(S(1,1))5. :-17.830	dB(S(1,1))5. :-20.928
dB(S(1,1))6. :-24.676	dB(S(1,1))6. :-35.594	dB(S(1,1))6. :-27.143	dB(S(1,1))6. :-24.766	dB(S(1,1))6. :-18.150	dB(S(1,1))6. :-19.164
dB(S(1,1))7. :-24.720	dB(S(1,1))7. :-35.594	dB(S(1,1))7. :-27.139	dB(S(1,1))7. :-24.636	dB(S(1,1))7. :-18.472	dB(S(1,1))7. :-17.946
dB(S(1,1))8. :-24.765	dB(S(1,1))8. :-35.594	dB(S(1,1))8. :-27.135	dB(S(1,1))8. :-24.548	dB(S(1,1))8. :-18.773	dB(S(1,1))8. :-17.068
dB(S(1,1))9. :-24.811	dB(S(1,1))9. :-35.594	dB(S(1,1))9. :-27.133	dB(S(1,1))9. :-24.487	dB(S(1,1))9. :-19.048	dB(S(1,1))9. :-16.416
dB(S(1,1))10. :-24.858	dB(S(1,1))10. :-35.594	dB(S(1,1))10. :-27.131	dB(S(1,1))10. :-24.446	dB(S(1,1))10. :-19.294	dB(S(1,1))10. :-15.916
dB(S(1,1))11. :-24.904	dB(S(1,1))11. :-35.594	dB(S(1,1))11. :-27.129	dB(S(1,1))11. :-24.417	dB(S(1,1))11. :-19.515	dB(S(1,1))11. :-15.526
dB(S(1,1))12. :-24.950	dB(S(1,1))12. :-35.594	dB(S(1,1))12. :-27.127	dB(S(1,1))12. :-24.397	dB(S(1,1))12. :-19.711	dB(S(1,1))12. :-15.214
dB(S(1,1))13. :-24.995	dB(S(1,1))13. :-35.594	dB(S(1,1))13. :-27.126	dB(S(1,1))13. :-24.383	dB(S(1,1))13. :-19.887	dB(S(1,1))13. :-14.982
dB(S(1,1))14. :-25.038	dB(S(1,1))14. :-35.594	dB(S(1,1))14. :-27.125	dB(S(1,1))14. :-24.374	dB(S(1,1))14. :-20.044	dB(S(1,1))14. :-14.754
dB(S(1,1))15. :-25.083	dB(S(1,1))15. :-35.594	dB(S(1,1))15. :-27.124	dB(S(1,1))15. :-24.368	dB(S(1,1))15. :-20.186	dB(S(1,1))15. :-14.580
dB(S(1,1))16. :-25.125	dB(S(1,1))16. :-35.594	dB(S(1,1))16. :-27.123	dB(S(1,1))16. :-24.364	dB(S(1,1))16. :-20.313	dB(S(1,1))16. :-14.434



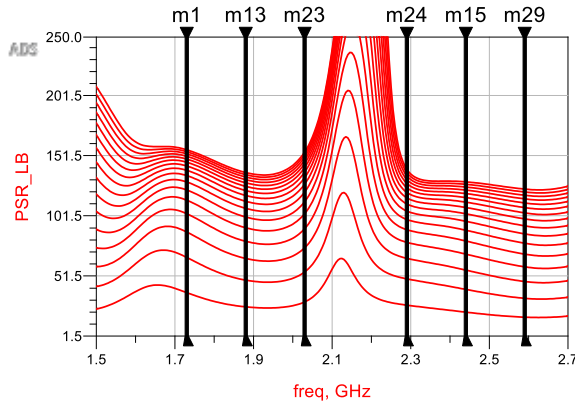
(b)

Fig. 4.5 (a) insertion loss responses according to bias voltages of both bands and (b) return loss responses according to bias voltages of both bands.

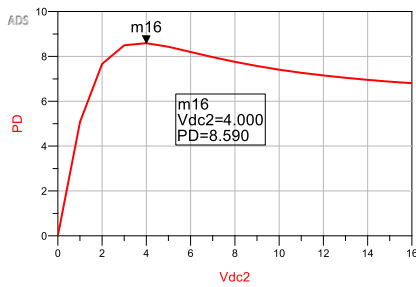
### 4.3. Both Bands Operation

The bias voltages of varactor diodes varying from 0 to 16 V at the both operating band. The maximum PSRs are  $146^\circ$  at  $f_L$  and  $130.2^\circ$  at  $f_H$ , as shown in Fig. 4.6(a). Furthermore, the maximum PDE within a 300 MHz range are  $8.6^\circ$  at  $f_L$  and  $9.4^\circ$  at  $f_H$ , as illustrated in Fig. 4.6(b) and 4.6(c). Additionally, the maximum insertion loss is 0.5 dB and the minimum return loss is 16.78 dB at both bands, as depicted in Fig. 4.7(a) and 4.7(b).

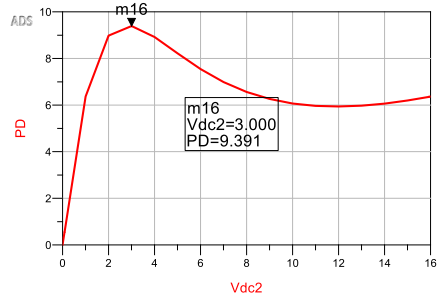
m1	m13	m23	m24	m15	m29
freq=1.730GHz	freq=1.880GHz	freq=2.030GHz	freq=2.290GHz	freq=2.440GHz	freq=2.590GHz
PSR_LB[0, ..]=0.000	PSR_LB[0, ..]=0.000	PSR_LB[0, ..]=0.000	PSR_LB[0, ..]=0.000	PSR_LB[0, ..]=0.000	PSR_LB[0, ..]=0.000
PSR_LB[1, ..]=37.599	PSR_LB[1, ..]=25.774	PSR_LB[1, ..]=29.866	PSR_LB[1, ..]=27.162	PSR_LB[1, ..]=21.369	PSR_LB[1, ..]=17.170
PSR_LB[2, ..]=68.884	PSR_LB[2, ..]=47.968	PSR_LB[2, ..]=54.775	PSR_LB[2, ..]=49.029	PSR_LB[2, ..]=40.294	PSR_LB[2, ..]=32.881
PSR_LB[3, ..]=88.028	PSR_LB[3, ..]=65.986	PSR_LB[3, ..]=74.841	PSR_LB[3, ..]=66.075	PSR_LB[3, ..]=56.333	PSR_LB[3, ..]=46.835
PSR_LB[4, ..]=103.249	PSR_LB[4, ..]=80.249	PSR_LB[4, ..]=90.711	PSR_LB[4, ..]=79.358	PSR_LB[4, ..]=69.614	PSR_LB[4, ..]=59.045
PSR_LB[5, ..]=114.451	PSR_LB[5, ..]=91.496	PSR_LB[5, ..]=103.234	PSR_LB[5, ..]=89.869	PSR_LB[5, ..]=80.523	PSR_LB[5, ..]=69.593
PSR_LB[6, ..]=122.949	PSR_LB[6, ..]=100.436	PSR_LB[6, ..]=113.196	PSR_LB[6, ..]=98.365	PSR_LB[6, ..]=89.496	PSR_LB[6, ..]=78.653
PSR_LB[7, ..]=129.585	PSR_LB[7, ..]=107.632	PSR_LB[7, ..]=121.219	PSR_LB[7, ..]=105.386	PSR_LB[7, ..]=96.922	PSR_LB[7, ..]=86.430
PSR_LB[8, ..]=134.904	PSR_LB[8, ..]=113.506	PSR_LB[8, ..]=127.772	PSR_LB[8, ..]=111.313	PSR_LB[8, ..]=103.123	PSR_LB[8, ..]=93.120
PSR_LB[9, ..]=139.280	PSR_LB[9, ..]=118.368	PSR_LB[9, ..]=133.198	PSR_LB[9, ..]=116.411	PSR_LB[9, ..]=108.351	PSR_LB[9, ..]=98.898
PSR_LB[10, ..]=142.895	PSR_LB[10, ..]=122.445	PSR_LB[10, ..]=137.750	PSR_LB[10, ..]=120.875	PSR_LB[10, ..]=112.800	PSR_LB[10, ..]=103.916
PSR_LB[11, ..]=145.976	PSR_LB[11, ..]=125.906	PSR_LB[11, ..]=141.614	PSR_LB[11, ..]=124.842	PSR_LB[11, ..]=116.622	PSR_LB[11, ..]=108.297
PSR_LB[12, ..]=148.624	PSR_LB[12, ..]=128.674	PSR_LB[12, ..]=144.930	PSR_LB[12, ..]=128.417	PSR_LB[12, ..]=119.935	PSR_LB[12, ..]=112.147
PSR_LB[13, ..]=150.925	PSR_LB[13, ..]=131.445	PSR_LB[13, ..]=147.804	PSR_LB[13, ..]=131.675	PSR_LB[13, ..]=122.828	PSR_LB[13, ..]=115.548
PSR_LB[14, ..]=152.945	PSR_LB[14, ..]=133.692	PSR_LB[14, ..]=150.319	PSR_LB[14, ..]=134.677	PSR_LB[14, ..]=125.374	PSR_LB[14, ..]=118.570
PSR_LB[15, ..]=154.734	PSR_LB[15, ..]=135.670	PSR_LB[15, ..]=152.527	PSR_LB[15, ..]=137.469	PSR_LB[15, ..]=127.629	PSR_LB[15, ..]=121.270
PSR_LB[16, ..]=156.330	PSR_LB[16, ..]=137.425	PSR_LB[16, ..]=154.469	PSR_LB[16, ..]=140.085	PSR_LB[16, ..]=129.640	PSR_LB[16, ..]=123.693



(a)



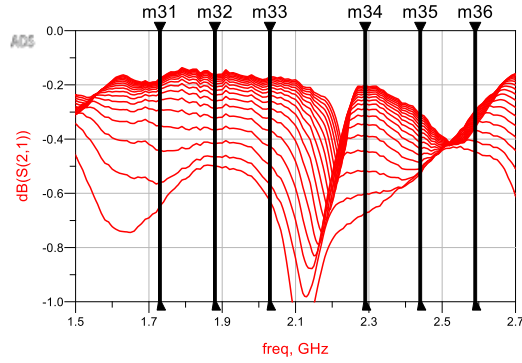
(b)



(c)

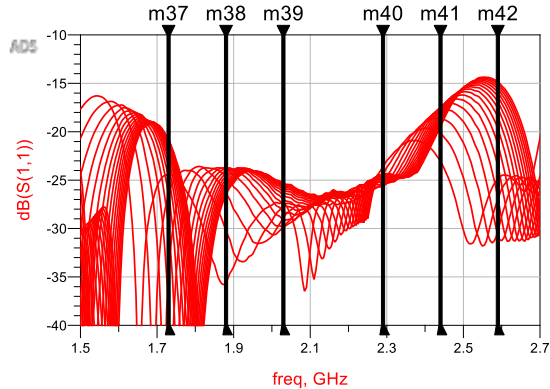
Fig. 4.6. (a) PSR responses according to bias voltage of both bands, (b) PDE of  $f_L$ , and (c) PDE of  $f_H$ .

m31	m32	m33	m34	m35	m36
freq=1.730GHz	freq=1.880GHz	freq=2.030GHz	freq=2.290GHz	freq=2.440GHz	freq=2.590GHz
dB(S(2,1))0. :=-0.647	dB(S(2,1))0. :=-0.500	dB(S(2,1))0. :=-0.628	dB(S(2,1))0. :=-0.673	dB(S(2,1))0. :=-0.519	dB(S(2,1))0. :=-0.447
dB(S(2,1))1. :=-0.560	dB(S(2,1))1. :=-0.466	dB(S(2,1))1. :=-0.568	dB(S(2,1))1. :=-0.601	dB(S(2,1))1. :=-0.530	dB(S(2,1))1. :=-0.408
dB(S(2,1))2. :=-0.441	dB(S(2,1))2. :=-0.417	dB(S(2,1))2. :=-0.496	dB(S(2,1))2. :=-0.517	dB(S(2,1))2. :=-0.526	dB(S(2,1))2. :=-0.368
dB(S(2,1))3. :=-0.351	dB(S(2,1))3. :=-0.367	dB(S(2,1))3. :=-0.429	dB(S(2,1))3. :=-0.443	dB(S(2,1))3. :=-0.509	dB(S(2,1))3. :=-0.336
dB(S(2,1))4. :=-0.292	dB(S(2,1))4. :=-0.323	dB(S(2,1))4. :=-0.368	dB(S(2,1))4. :=-0.387	dB(S(2,1))4. :=-0.486	dB(S(2,1))4. :=-0.312
dB(S(2,1))5. :=-0.256	dB(S(2,1))5. :=-0.288	dB(S(2,1))5. :=-0.322	dB(S(2,1))5. :=-0.344	dB(S(2,1))5. :=-0.460	dB(S(2,1))5. :=-0.300
dB(S(2,1))6. :=-0.232	dB(S(2,1))6. :=-0.260	dB(S(2,1))6. :=-0.287	dB(S(2,1))6. :=-0.312	dB(S(2,1))6. :=-0.435	dB(S(2,1))6. :=-0.296
dB(S(2,1))7. :=-0.216	dB(S(2,1))7. :=-0.238	dB(S(2,1))7. :=-0.260	dB(S(2,1))7. :=-0.288	dB(S(2,1))7. :=-0.413	dB(S(2,1))7. :=-0.296
dB(S(2,1))8. :=-0.205	dB(S(2,1))8. :=-0.221	dB(S(2,1))8. :=-0.239	dB(S(2,1))8. :=-0.269	dB(S(2,1))8. :=-0.393	dB(S(2,1))8. :=-0.301
dB(S(2,1))9. :=-0.197	dB(S(2,1))9. :=-0.208	dB(S(2,1))9. :=-0.223	dB(S(2,1))9. :=-0.255	dB(S(2,1))9. :=-0.377	dB(S(2,1))9. :=-0.307
dB(S(2,1))10. :=-0.191	dB(S(2,1))10. :=-0.197	dB(S(2,1))10. :=-0.211	dB(S(2,1))10. :=-0.243	dB(S(2,1))10. :=-0.362	dB(S(2,1))10. :=-0.314
dB(S(2,1))11. :=-0.187	dB(S(2,1))11. :=-0.189	dB(S(2,1))11. :=-0.200	dB(S(2,1))11. :=-0.233	dB(S(2,1))11. :=-0.350	dB(S(2,1))11. :=-0.322
dB(S(2,1))12. :=-0.184	dB(S(2,1))12. :=-0.182	dB(S(2,1))12. :=-0.192	dB(S(2,1))12. :=-0.225	dB(S(2,1))12. :=-0.338	dB(S(2,1))12. :=-0.330
dB(S(2,1))13. :=-0.181	dB(S(2,1))13. :=-0.176	dB(S(2,1))13. :=-0.185	dB(S(2,1))13. :=-0.218	dB(S(2,1))13. :=-0.330	dB(S(2,1))13. :=-0.337
dB(S(2,1))14. :=-0.179	dB(S(2,1))14. :=-0.171	dB(S(2,1))14. :=-0.179	dB(S(2,1))14. :=-0.212	dB(S(2,1))14. :=-0.322	dB(S(2,1))14. :=-0.344
dB(S(2,1))15. :=-0.177	dB(S(2,1))15. :=-0.167	dB(S(2,1))15. :=-0.175	dB(S(2,1))15. :=-0.206	dB(S(2,1))15. :=-0.315	dB(S(2,1))15. :=-0.351
dB(S(2,1))16. :=-0.175	dB(S(2,1))16. :=-0.163	dB(S(2,1))16. :=-0.171	dB(S(2,1))16. :=-0.202	dB(S(2,1))16. :=-0.309	dB(S(2,1))16. :=-0.357



(a)

m37	m38	m39	m40	m41	m42
freq=1.730GHz	freq=1.880GHz	freq=2.030GHz	freq=2.290GHz	freq=2.440GHz	freq=2.590GHz
dB(S(1,1))0. :=-24.528	dB(S(1,1))0. :=-35.588	dB(S(1,1))0. :=-27.294	dB(S(1,1))0. :=-23.645	dB(S(1,1))0. :=-23.037	dB(S(1,1))0. :=-24.935
dB(S(1,1))1. :=-26.573	dB(S(1,1))1. :=-30.259	dB(S(1,1))1. :=-27.512	dB(S(1,1))1. :=-24.490	dB(S(1,1))1. :=-20.187	dB(S(1,1))1. :=-27.006
dB(S(1,1))2. :=-34.803	dB(S(1,1))2. :=-26.368	dB(S(1,1))2. :=-28.816	dB(S(1,1))2. :=-25.301	dB(S(1,1))2. :=-18.622	dB(S(1,1))2. :=-30.336
dB(S(1,1))3. :=-38.528	dB(S(1,1))3. :=-24.632	dB(S(1,1))3. :=-29.864	dB(S(1,1))3. :=-25.655	dB(S(1,1))3. :=-17.941	dB(S(1,1))3. :=-30.657
dB(S(1,1))4. :=-39.818	dB(S(1,1))4. :=-23.928	dB(S(1,1))4. :=-29.848	dB(S(1,1))4. :=-25.630	dB(S(1,1))4. :=-17.524	dB(S(1,1))4. :=-26.797
dB(S(1,1))5. :=-26.469	dB(S(1,1))5. :=-23.738	dB(S(1,1))5. :=-29.136	dB(S(1,1))5. :=-25.441	dB(S(1,1))5. :=-17.471	dB(S(1,1))5. :=-23.541
dB(S(1,1))6. :=-24.666	dB(S(1,1))6. :=-23.811	dB(S(1,1))6. :=-28.314	dB(S(1,1))6. :=-25.220	dB(S(1,1))6. :=-17.563	dB(S(1,1))6. :=-21.271
dB(S(1,1))7. :=-23.550	dB(S(1,1))7. :=-24.017	dB(S(1,1))7. :=-27.810	dB(S(1,1))7. :=-25.019	dB(S(1,1))7. :=-17.731	dB(S(1,1))7. :=-19.659
dB(S(1,1))8. :=-22.800	dB(S(1,1))8. :=-24.288	dB(S(1,1))8. :=-27.057	dB(S(1,1))8. :=-24.853	dB(S(1,1))8. :=-17.935	dB(S(1,1))8. :=-18.476
dB(S(1,1))9. :=-22.269	dB(S(1,1))9. :=-24.587	dB(S(1,1))9. :=-26.631	dB(S(1,1))9. :=-24.722	dB(S(1,1))9. :=-18.152	dB(S(1,1))9. :=-17.583
dB(S(1,1))10. :=-21.876	dB(S(1,1))10. :=-24.894	dB(S(1,1))10. :=-26.302	dB(S(1,1))10. :=-24.620	dB(S(1,1))10. :=-18.368	dB(S(1,1))10. :=-16.893
dB(S(1,1))11. :=-21.676	dB(S(1,1))11. :=-25.196	dB(S(1,1))11. :=-26.047	dB(S(1,1))11. :=-24.543	dB(S(1,1))11. :=-18.578	dB(S(1,1))11. :=-16.349
dB(S(1,1))12. :=-21.342	dB(S(1,1))12. :=-25.489	dB(S(1,1))12. :=-25.847	dB(S(1,1))12. :=-24.485	dB(S(1,1))12. :=-18.778	dB(S(1,1))12. :=-15.913
dB(S(1,1))13. :=-21.154	dB(S(1,1))13. :=-25.770	dB(S(1,1))13. :=-25.688	dB(S(1,1))13. :=-24.445	dB(S(1,1))13. :=-18.963	dB(S(1,1))13. :=-15.558
dB(S(1,1))14. :=-21.002	dB(S(1,1))14. :=-26.038	dB(S(1,1))14. :=-25.560	dB(S(1,1))14. :=-24.417	dB(S(1,1))14. :=-19.137	dB(S(1,1))14. :=-15.264
dB(S(1,1))15. :=-20.876	dB(S(1,1))15. :=-26.288	dB(S(1,1))15. :=-25.456	dB(S(1,1))15. :=-24.402	dB(S(1,1))15. :=-19.298	dB(S(1,1))15. :=-15.020
dB(S(1,1))16. :=-20.771	dB(S(1,1))16. :=-26.526	dB(S(1,1))16. :=-25.372	dB(S(1,1))16. :=-24.395	dB(S(1,1))16. :=-19.448	dB(S(1,1))16. :=-14.813



(b)

Fig. 4.7 (a) Insertion loss responses according to bias voltages of both bands and (b) return loss responses according to bias voltages of both bands.

## Chapter 5 Experiment Results

For experimental validation, a prototype of tunable DPS operating at  $f_L = 1.88$  GHz and  $f_H = 2.44$  GHz is designed and fabricated using Taconic substrate with dielectric constant of 2.2 and thickness of 0.787 mm. Fig. 5.1 depicts the physical layout of fabricated circuit with dimensions. The photograph of fabricated circuit is shown in Fig. 5.2 and its size is  $85 \times 75$  mm. In this work, a 3-dB hybrid coupler S03A2500N1 from ANAREN is used. The measurement results are well agreed with EM simulations. The performances of the proposed phase shifter are investigated in three cases such as lower band operation, higher band operation, and both bands operation.

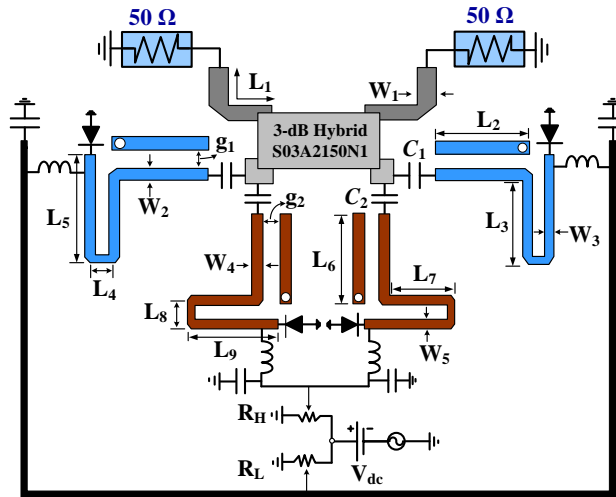


Fig. 5.1. Microstrip line implementation of proposed fully dual-band tunable phase shifter. Physical dimensions:  $W_1 = 2.35$ ,  $L_1 = 12.8$ ,  $W_2 = 0.8$ ,  $L_2 = 22.6$ ,  $g_1 = 0.15$ ,  $W_3 = 0.5$ ,  $L_3 = 15.75$ ,  $L_4 = 3$ ,  $L_5 = 17.55$ ,  $W_4 = 0.9$ ,  $L_6 = 30.7$ ,  $W_5 = 0.5$ ,  $L_7 = 15.75$ ,  $g_2 = 0.15$ ,  $L_8 = 2$ ,  $L_9 = 17.55$ . Unit: millimeter (mm). DC block:  $C_1 = 56.6$  pF,  $C_2 = 120$  pF. Varactor SMV: 1231 from Skyworks Inc. Variable resistor:  $R_{L,H} = 100 \Omega$ .

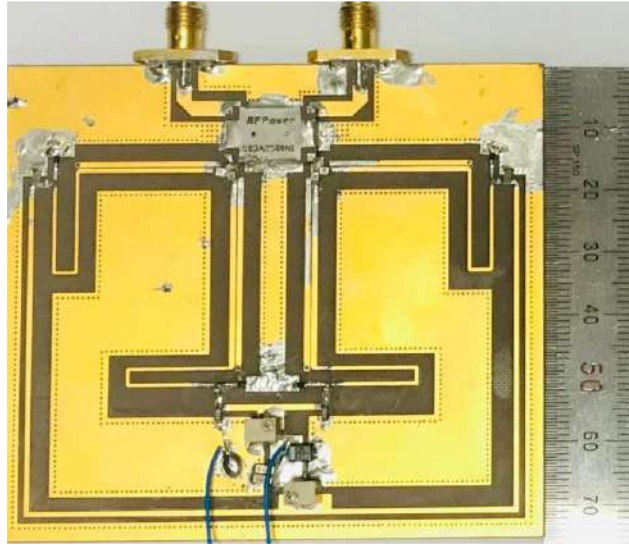
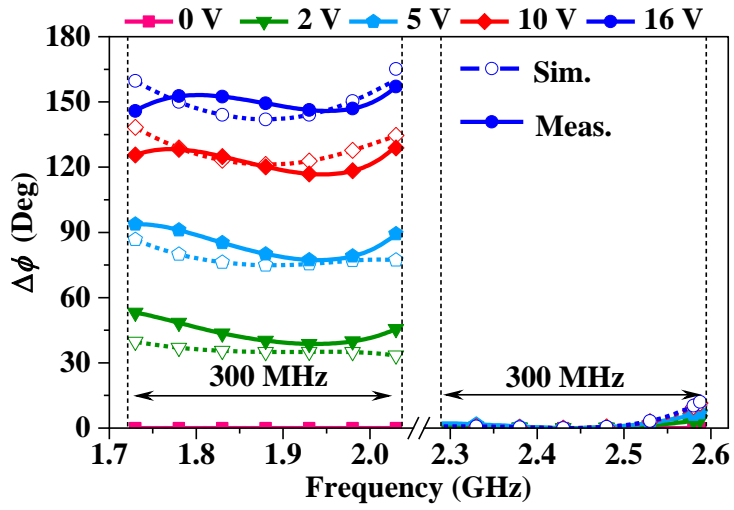


Fig. 5.2 Photograph of fabricated DPS.

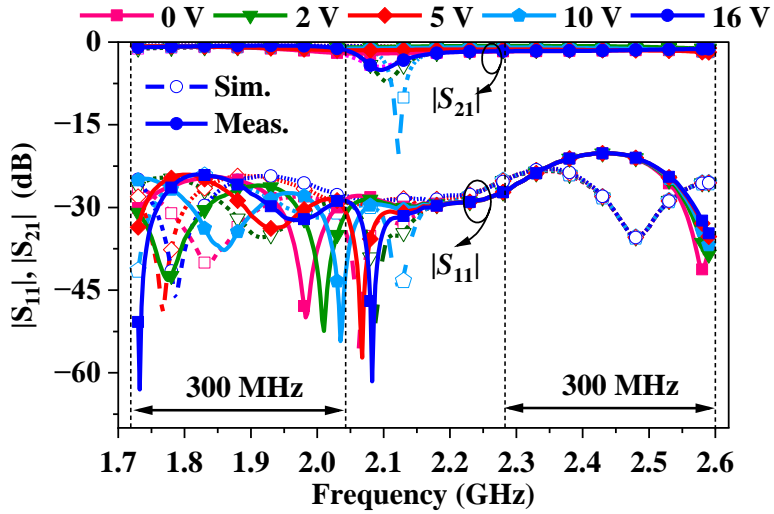
### 5.1. Lower Band Operation

The bias voltage of varactor diode operating at lower band  $f_L$  is varied from 0 to 16 V while the bias voltage of varactor diode operating at higher band  $f_H$  is fixed 0 V. In this case, measured maximum PSR of  $149.32^\circ$  with PDE of  $\pm 8.25^\circ$  are achieved within bandwidth of 300 MHz at  $f_L$ , while maintaining  $0^\circ$  phase shift at  $f_H$ , is shown in Fig. 5.3(a). Furthermore, insertion loss smaller than 1.96 dB and input/output return losses larger than 20.16 dB are measured at both operating bands is depicted in Fig. 5.3(b).





(a)

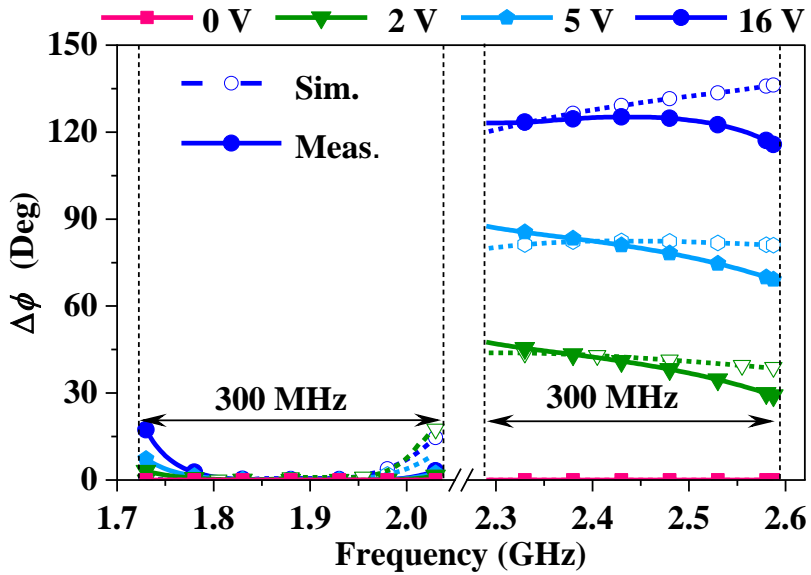


(b)

Fig. 5.3. Simulation and measurement results of the lower band operation: (a) PSR and (b)  $S$ -parameter responses.

## 5.2. Higher Band Operation

The bias voltage of varactor diode operating at  $f_L$  is fixed to 0 V, while the bias voltage of varactor diode operating at  $f_H$  is varied 0 to 16 V. The simulation and measured results of this case is shown in Fig. 5.4(a). From the measurement, maximum PSR of  $125.14^\circ$  and PDE of  $\pm 9.34^\circ$  are obtained within 300 MHz bandwidth of  $f_H$ . Moreover, insertion loss smaller than 1.86 dB and input/output return losses larger than 16.14 dB are measured at both operating bands is shown in Fig. 5.4(b).



(a)

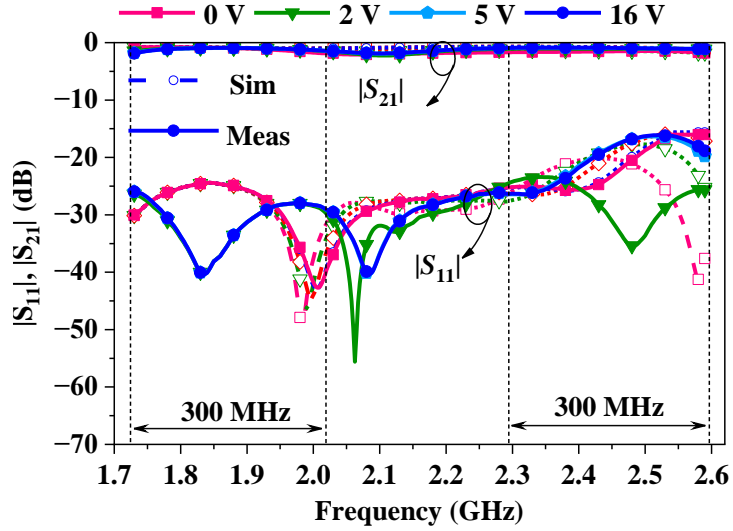
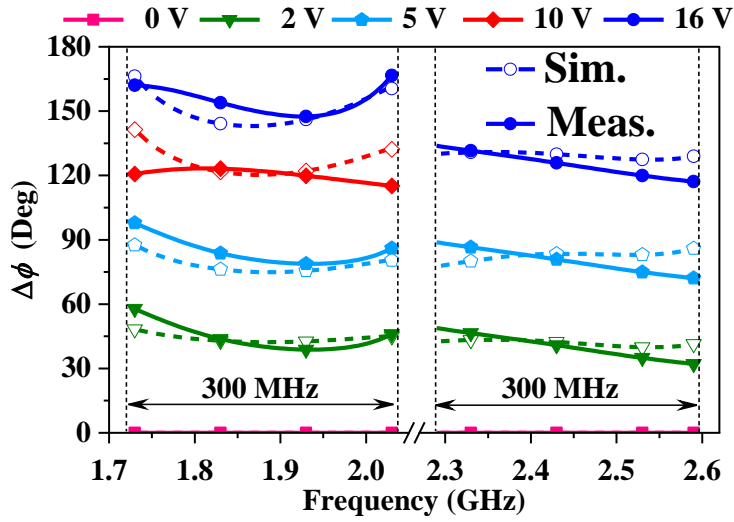


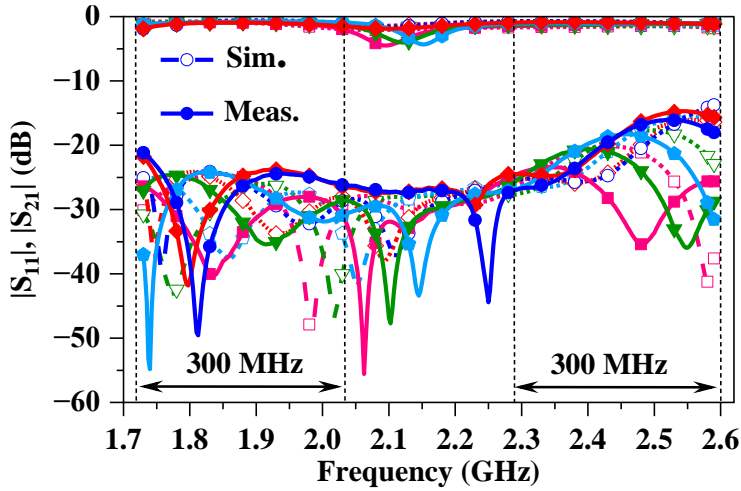
Fig. 5.5. Simulation and measurement results of higher band operation:  
(a) PSR and (b)  $S$ -parameter responses.

### 5.3. Both Bands Operation

Fig. 5.6 shows the simulation and measurement results of the third case where relative phase shift at both operating bands are tuned simultaneously. In this case, maximum PSR of  $149.33^\circ$  with PDE of  $\pm 8.45^\circ$  are measured within bandwidth of 300 MHz at  $f_L$ , while maximum PSR of  $125.25^\circ$  with PDE of  $\pm 8.36^\circ$  are measured within bandwidth of 300 MHz at  $f_H$ . The measured insertion losses vary from 1 dB to 1.96 dB at  $f_L$  and from 1.1 dB to 1.81 dB at  $f_H$ . The insertion loss can be improved by using a varactor diode with low parasitic resistance. While tuning relative PSR, the measured input/output return losses are higher than 21.1 dB at lower band operating frequency and 17.36 dB at higher band operating frequency.



(a)



(b)

Fig. 5.5. Simulation and measurement results of the both band operation:

(a) PSR and (b)  $S$ -parameter responses.

Table III shows the performances comparison of the proposed tunable DPS with previously reported works. In this work, the figure of merit (FoM) is defined as (5.1) by considering PSR, insertion loss (IL), return loss (RL), and bandwidth (BW).

$$\text{FoM} = \frac{BW(\text{GHz}) \times \text{PSR}(\text{rad})}{f_0(\text{GHz}) \times \text{PDE}(\text{rad})} \times \frac{10^{\left(\frac{-\text{IL}(\text{dB})}{20}\right)}}{10^{\left(\frac{-\text{RL}(\text{dB})}{20}\right)}} \quad (5.1)$$

Most of the previously reported tunable phase shifters are designed for single-band frequency operation [4], [5], [6], [7]. In comparison to previously reported DPSs, the proposed work provides high PSR with highest FoM. Furthermore, the proposed dual-band tunable phase shifter allows independent phase shift tuning at each operating frequency as well as simultaneous phase shift tuning at both bands.

Table III  
Performances comparison with state-of-the-arts

	$f_0$ (GHz)	BW (GHz)	FBW (%)	PSR (°)	PDE (°)	IL (dB)	RL <sub>min</sub> (dB)	D/I	FOM
[10]	1.46	0.47	32.2	90*	±5	<0.73	>15	Y/N	NA
	4.35	0.45	10.34	270*	±5	<1.28	>15		
[11]	5.9	0.2	3.39	106	±7	<2.8	>10	Y/Y	1.18
	16	0.4	2.5	108	±7	<3.5	>10		0.82
[12]	1.88	0.1	5.32	114	±8.4	<1.86	>19.7	Y/Y	5.60
	2.44	0.1	4	114	±5.4	<1.89	>16.8		4.83
<b>This Work</b>	<b>1.88</b>	<b>0.3</b>	<b>15.96</b>	<b>149.33</b>	<b>±8.45</b>	<b>&lt;1.96</b>	<b>&gt;21.1</b>	<b>Y/Y</b>	<b>26.08</b>
	<b>2.44</b>	<b>0.3</b>	<b>12.30</b>	<b>125.25</b>	<b>±8.36</b>	<b>&lt;1.81</b>	<b>&gt;17.3</b>		<b>10.96</b>

FBW: Fractional Bandwidth, PSR: Relative phase shift range, PDE: phase derivation error within certain bandwidth. D: Dual-band phase shifter, I: independent control phase shift, \*: differential phase shifter with fixed phase shift.

## Chapter 6 Conclusion

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This work presented a design of reflection-type tunable DPS that allows to control independent phase shift at each operating band as well as simultaneous tunable phase shift at both bands. This independent phase shift control is achieved due to coupled lines

For verification of the design, a dual-band phase shifter operating at two operating frequencies of 1.88 GHz and 2.44 GHz was fabricated and measured. From the measurement results, the designed dual-band phase shifter showed a PSR of  $149.23^\circ$  and  $125.25^\circ$  at the operating frequencies, respectively, and PDEs are  $\pm 8.45^\circ$  and  $\pm 8.36^\circ$  within 300 MHz bandwidth. Additionally, insertion losses of within 1.96 dB and 1.81 dB, and reflection losses of more than 21.1 dB and 17.3 dB were achieved in both bands.

The proposed microwave dual-band phase shifter has the advantages of low phase deviation and high reflection loss characteristics within the band, making it widely applicable in next-generation wireless communication systems. Moreover, compared to previously researched dual-band phase shifters, it is more convenient to manufacture, and its capability to handle dual-band signals with a single application offers benefits in terms of miniaturization of the product.

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## Appendix: MATHLAB Code

Input value

$f_L$	$f_H$	BW	NP
1.88E+9	2.44E+9	300E+9	401
$Z_L$	$Z_H$	$Z_a$	$Z_b$
20:1:120	20:1:120	90:1:120	90:1:120
$C_L$	$C_H$	$\theta_a$	$\theta_b$
-6:0.1:-9	-6:0.1:-9	90:1:130	90:1:130
PSR <sub>ref</sub>	PDE <sub>max</sub>	$C_{V_L}$	$C_{V_H}$
>100	10	0.3:0.1:3.5	0.3:0.1:4.7

Main Code

```

clc; clear; close all;% close all;
Z0=50; fL=1.88E9; fH=2.44E9; BW=300E6; NP=401;
fL1=linspace(fL-BW/2,fL+BW/2,NP);
fL2=linspace(fH-BW/2,fH+BW/2,NP);
ZL=20:1:120;
Cdb_L=-8.5;
Za_L=120;
theta_a_L_deg=117;
ZH=72;
Cdb_H=-7.2;
Zb=120;
theta_a_H_deg=123;
%% Both-band Operation
Cpoint=20;
cv1=linspace(3.5E-12,0.3E-12,Cpoint);
cv2=linspace(4.7E-12,0.3E-12,Cpoint);
%% Low band operation
for b=1:length(cv1);
    PSR_Lowband(:,b)=PSR_lowband(cv1(b),cv2(1));
    PSR_Lowbandref(:,1)=PSR_lowband(cv1(1),cv2(1));
    PSR_Low(:,b)=PSR_Lowband(:,b)-PSR_Lowbandref(:,1);
    %% High band
    PSR_Highband(:,b)=PSR_highband(cv1(b),cv2(Cpoint));
    PSR_Highbandref(:,1)=PSR_highband(cv1(1),cv2(Cpoint));

```

```

        PSR_High(:,b)=PSR_Highband(:,b)-
PSR_Highbandref(:,1);
        PDerr_Low(b)=(max(PSR_Low(:,b))-
min(PSR_Low(:,b)))/2;
        PDerr_High(b)=(max(PSR_High(:,b))-
min(PSR_High(:,b)))/2;
end

if PSR_Highbandref(:,1) > PSR_Highband(:,b)
    PSR_Low(:,b)=PSR_Lowbandref(:,1)-PSR_Lowband(:,b);
else
    PSR_Low(:,b)=PSR_Lowband(:,b)-PSR_Lowbandref(:,1);
end

%% High Band operation
for a=1:length(cv2);
    PSR_Lowband1(:,a)=PSR_lowband(cv1(Cpoint),cv2(a));

PSR_Lowbandref1(:,1)=PSR_lowband(cv1(Cpoint),cv2(1));
    PSR_Low1(:,b)=PSR_Lowband1(:,a)-
PSR_Lowbandref1(:,1);
    %%High Band
    PSR_Highband1(:,a)=PSR_highband(cv1(1),cv2(a));
    PSR_Highbandref1(:,1)=PSR_highband(cv1(1),cv2(1));

    if PSR_Highbandref1(:,1) > PSR_Highband1(:,a)
        PSR_High1(:,a)=PSR_Highbandref1(:,1)-
PSR_Highband1(:,a);
    else
        PSR_High1(:,a)=PSR_Highband1(:,a)-
PSR_Highbandref1(:,1);
    end
%   PSR_High1(:,b)=PSR_Highbandref1(:,1)-
PSR_Highband1(:,b);
    PDerr_Low1(a)=(max(abs(PSR_Low1(:,a)))-
min(abs(PSR_Low1(:,a))))/2;

```

```

        PDerr_High1(a)=(max(abs(PSR_High1(:,a)))-
min(abs(PSR_High1(:,a))))/2;
    end
    subplot(2,2,1)
    plot(fL1*1e-9,PSR_Low);
    xlabel('Frequency (GHz)', 'FontSize',12);
    ylabel('PSR [degree]', 'FontSize',12);
    hold on;
    plot(fL2*1e-9,PSR_High)
    subplot(2,2,2);
    plot(cv1*1e12,PDerr_Low)
    xlabel('Cv', 'FontSize',12);
    ylabel('PD [degree]', 'FontSize',12);

    subplot(2,2,3)
    plot(fL1*1e-9,PSR_Low1);
    xlabel('Frequency (GHz)', 'FontSize',12);
    ylabel('PSR [degree]', 'FontSize',12);
    hold on;
    plot(fL2*1e-9,PSR_High1)
    subplot(2,2,4);
    plot(cv2*1e12,PDerr_High1)
    xlabel('Cv', 'FontSize',12);
    ylabel('PD [degree]', 'FontSize',12);

```

### Function at Lower Band Operation

```

function [PSR]=PSR_lowband(cv1,cv2)

Z0=50; fL=1.88E9; fH=2.44E9;BW=300e6;NP=401;
f=linspace(fL-BW/2,fL+BW/2,NP);
ZL=81;
Cdb_L=-8.3;
Za=120;
theta_a_L_deg=110;
ZH=70;
Cdb_H=-7;
Zb=120;
Y0=1/Z0;
theta_a_H_deg=123;

%% Low Band Operation
Z_cv_L=-j./(2*pi.*f.*cv1);
theta_L=(pi/2).*(f./fH);
theta_a_L=deg2rad(theta_a_L_deg).*(f./fH);
ZL_L=Za_L.*(Z_cv_L+j*Za_L.*tan(theta_a_L))./(Za_L+j
*Z_cv_L.*tan(theta_a_L));
YL_L=1./ZL_L;
C_L=10^(Cdb_L/20);
Yc_L=1./Zc_L;
p_L=Yc_L./sqrt((1+C_L).*(1-C_L));
m_L=-(C_L.*Yc_L)./sqrt((1+C_L).*(1-C_L));
D_L=YL_L-j*p_L.*cot(theta_L);
Y11_L=-
j*p_L.*cot(theta_L)+(p_L.*csc(theta_L)).^2./D_L;
Y12_L=-
j*m_L.*cot(theta_L)+(p_L.*m_L.*(csc(theta_L)).^2)./
D_L;
Y22_L=-
j*p_L.*cot(theta_L)+(m_L.*csc(theta_L)).^2./D_L;
Yin_LB=Y11_L-(Y12_L.^2)./(Y22_L);

S11Y_tot=(Y0-Yin_tot)./(Y0+Yin_tot);

```

```

mag_tot=abs(S11Y_tot);
PSR=rad2deg(unwrap(angle(S11Y_tot)));

%% High-band operation
Z_cv_H=-j./(2*pi.*f.*cv2);
theta_H=(pi/2).*(f./fL);
theta_a_H=deg2rad(theta_a_H_deg).*(f./fL);
ZL_H=Za_H.*(Z_cv_H+j*Za_H.*tan(theta_a_H))./(Za_H+j
*Z_cv_H.*tan(theta_a_H));
YL_H=1./ZL_H;
Yc_H=1./Zc_H;
C_H=10^(Cdb_H/20);
p_H=Yc_H./sqrt((1+C_H).*(1-C_H));
m_H=-C_H.*Yc_H./sqrt((1+C_H).*(1-C_H));
D_H=YL_H-j*p_H.*cot(theta_H);
Y11_H=-
j*p_H.*cot(theta_H)+(p_H.*csc(theta_H)).^2./D_H;
Y12_H=-
j*m_H.*cot(theta_H)+(p_H.*m_H.*(csc(theta_H)).^2)./
D_H;
Y22_H=-
j*p_H.*cot(theta_H)+(m_H.*csc(theta_H)).^2./D_H;
Yin_HB=Y11_H-(Y12_H.^2)./(Y22_H);

%% Combine both-band operation
Yin_tot=Yin_LB+Yin_HB;
S11Y_tot=(Y0-Yin_tot)./(Y0+Yin_tot);
mag_tot=abs(S11Y_tot);
PSR=rad2deg(unwrap(angle(S11Y_tot)));

```

### Function at Higher Band Operation

```
function [PSR]=PSR_highband(cv1,cv2)

Z0=50; fL=1.88E9; fH=2.44E9; BW=300e6; NP=401;
f=linspace(fH-BW/2, fH+BW/2, NP);
ZL=81;
Cdb_L=-8.3;
Za=120;
theta_a_L_deg=110;
ZH=70;
Cdb_H=-7;
Zb=120;
Y0=1/Z0;
theta_a_H_deg=123;

%% Low Band Operation
Z_cv_L=-j./(2*pi.*f.*cv1);
theta_L=(pi/2).*(f./fH);
theta_a_L=deg2rad(theta_a_L_deg).*(f./fH);
ZL_L=Za_L.*(Z_cv_L+j*Za_L.*tan(theta_a_L))./(Za_L+j*Z_cv_L.*tan(theta_a_L));
YL_L=1./ZL_L;
C_L=10^(Cdb_L/20);
Yc_L=1./Zc_L;
p_L=Yc_L./sqrt((1+C_L).*(1-C_L));
m_L=-(C_L.*Yc_L)./sqrt((1+C_L).*(1-C_L));
D_L=YL_L-j*p_L.*cot(theta_L);
Y11_L=-j*p_L.*cot(theta_L)+(p_L.*csc(theta_L)).^2./D_L;
Y12_L=-
j*m_L.*cot(theta_L)+(p_L.*m_L.*(csc(theta_L)).^2)./D_L;
Y22_L=-j*p_L.*cot(theta_L)+(m_L.*csc(theta_L)).^2./D_L;
Yin_LB=Y11_L-(Y12_L.^2)./(Y22_L);

%% High-band operation
Z_cv_H=-j./(2*pi.*f.*cv2);
theta_H=(pi/2).*(f./fL);
```

```

theta_a_H=deg2rad(theta_a_H_deg).*(f./fL);
ZL_H=Za_H.*(Z_cv_H+j*Za_H.*tan(theta_a_H))./(Za_H+j*Z_cv
_H.*tan(theta_a_H));
YL_H=1./ZL_H;
Yc_H=1./Zc_H;
C_H=10^(Cdb_H/20);
p_H=Yc_H./sqrt((1+C_H).*(1-C_H));
m_H=-C_H.*Yc_H./sqrt((1+C_H).*(1-C_H));
D_H=YL_H-j*p_H.*cot(theta_H);

Y11_H=-j*p_H.*cot(theta_H)+(p_H.*csc(theta_H)).^2./D_H;
Y12_H=-
j*m_H.*cot(theta_H)+(p_H.*m_H.*(csc(theta_H)).^2)./D_H;
Y22_H=-j*p_H.*cot(theta_H)+(m_H.*csc(theta_H)).^2./D_H;
Yin_HB=Y11_H-(Y12_H.^2)./(Y22_H);

%% Combine both-band operation
Yin_tot=Yin_LB+Yin_HB;
S11Y_tot=(Y0-Yin_tot)./(Y0+Yin_tot);
mag_tot=abs(S11Y_tot);
PSR=rad2deg(unwrap(angle(S11Y_tot)));

```