Phase Shifter Design Tutorial

Introduction

Phase shifters are devices used to adjust transmission phase in a system, they can be fixed phase digital phase shifters or analogue variable types.

Switched-Line Phase shifter

These phase shifters are similar to their attenuator equivalent where two SPDT switches are used to switch two line lengths, one of which is X degrees longer in electrical length than the other. The circuit is shown in Figure 1.

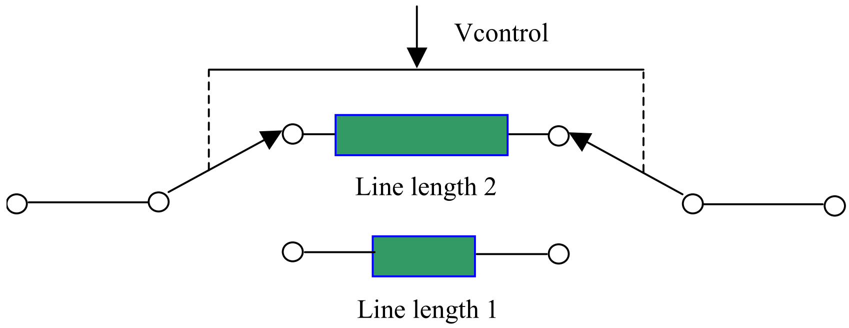


Figure 1 Switched-line phase shifter. Line length 2 has a longer electrical length than line length 1 so when switched in line will cause an in-line phase shift $\Delta\varphi=\beta(l_2-l_1)$.

Required phase shift $\Delta\phi = \beta(\ell_2 - \ell_1)$

Where $\beta = \dfrac{\omega}{Vp}$ and $Vp = \dfrac{1}{\sqrt{\varepsilon_{eff}}}$

Example

Design a switched-line phase shifter with a 22.5 degree phase shift at 4GHz, on a substrate with a dielectric constant of 9.9.

$$\Delta\ell = \frac{\Delta\phi}{\beta} \qquad 22.5\text{degrees} = \frac{22.5}{360}.2\omega = 0.392\text{rad}$$

$$@\,4\text{GHz}\,,\ \lambda_{air} = \frac{c}{f} = \frac{3x10^8}{4x10^9} = 0.075\text{m}$$

$$\lambda_g = \frac{\lambda_{air}}{\sqrt{\varepsilon_{eff}}} = \frac{0.075}{\sqrt{9.9}} = 0.0238\text{m} \qquad \beta = \frac{2\pi}{\lambda_g}$$

$$\therefore \Delta\ell = \frac{\Delta\phi}{\beta} = \frac{\lambda_g.\Delta\phi}{2\pi} = \frac{0.0238 * 0.392}{2\pi} = 1.485x10^{-3}\text{m} = 1.485\text{mm}$$

So we design the micro-strip lines such that line length 2 is 1.485mm longer than line length 1.

However, we have to be careful in our choice of line lengths so that we don't get lines lengths of 180 degrees (or multiples of 180 degrees) which, would then form a resonator when switched out of circuit.

Loaded-Line Phase shifter

For phase shifts of <45 degrees we can make use of loaded-line phase shifters as shown in .

These phase shifters work by adding a shunt reactance to the micro-strip line (in the form of an inductor or capacitor) causing the incident signal to undergo a phase shift.

(Note in micro-strip the reactive component can be formed by a micro-strip stub).

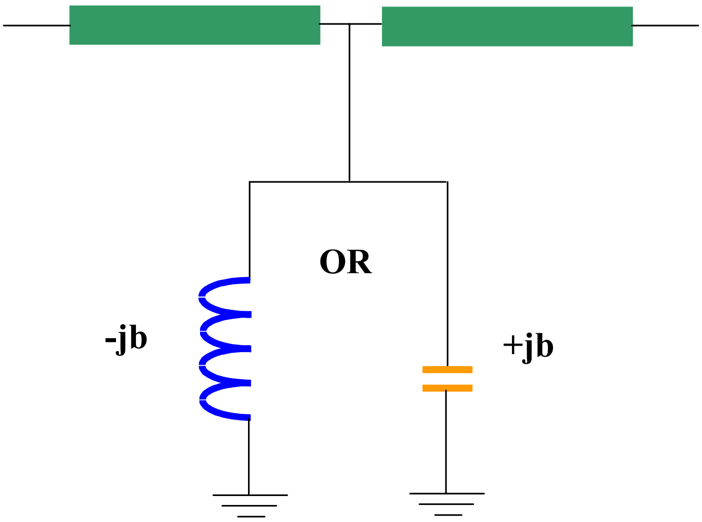


Figure 2 Switched-line phase shifter. A shunt susceptance inductive (-jB) or capacitive (+jB) is switched in across the line causing a phase shift on the incident signal.

Let jb be the normalised susceptance (from shunt elemant) ie jb = jB.Zo

$\Delta\phi = -\tan^{-1}\left(\frac{b}{2}\right)$ and insertion loss of phase shifter will be $10\log_{10}\left(1+\frac{b^2}{4}\right)$ (dB)

Example

Like the previous phase shifter we shall design for a phase shift of 22.5 degrees @4GHz.

Rearrange above $b = -2.\tan\Delta\phi \quad b = -0.8285$ ie inductive susceptance

Normalise back to 50ohms $= 0.8285 * 50 = 41.4$ohms

$$L = \frac{X_L}{2\pi.f} = \frac{41.4}{2\pi.4x10^9} = 1.65nH$$

With a resulting insertion loss of $10\log_{10}\left(1 + \frac{(-0.8285)^2}{4}\right) = 0.68dB$

The disadvantage of these phase shifters, are that in order to large values of phase shift, high values of b are required thus increasing the insertion loss.

45-degree phase shift (b = 2) will incur an insertion loss of 3dB. Also as these phase shifters rely on reflecting signals their return losses are very poor.

Modified loaded-line Phase shifter

The return losses of loaded-line phase shifters can be greatly improved by having two shunt susceptances separated by 90 degrees. If these susceptances are switched in or out by Pin diodes then a switchable phase shifter can be made as below. The equivalent circuit is a transmission line with phase θe.

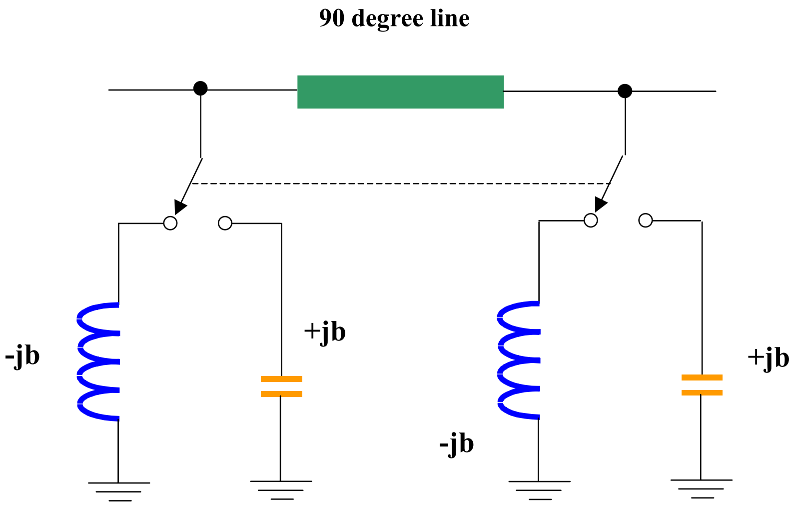


Figure 3 Improved switched-line phase shifter using two shunt susceptances and a quarter-wave length of transmission line. This circuit has very good input/output return losses.

Equivalent phase length $\vartheta_e = \cos^{-1}(-b)$

Also, Impedance of circuit $Ze = \frac{Zo}{\sqrt{1-b^2}}$

So, $|b| < 1$ and $\Rightarrow$ $Ze > Zo$

$$L = \frac{N}{\omega . B}$$

$$C = \frac{B}{2\pi f . N}$$

This time we have a 4GHz phase shifter where two switched states give susceptances of +10Ω and -10Ω, and we wish to know the resulting phase shift and equivalent line impedance.

$b_{on} = 10/50$ (capacitive) $= 0.2$ &
$b_{off} = -10/50$ (inductive) $= -0.2$

$\therefore \cos\theta_{eon} = -b_{on} = -0.2 \quad \theta_{eon} \Rightarrow 101.5$ degrees

$\therefore \cos\theta_{eoff} = -b_{off} = 0.2 \quad \theta_{offn} \Rightarrow 78.46$ degrees

$\therefore$ Differential phase shift $= 101.5 - 78.46 = 23$ degrees

$$\text{Equivalent line impedance} = \frac{Zo}{\sqrt{1-b^2}} = \frac{50}{\sqrt{1-0.2^2}} = 51\Omega$$

$$L = \frac{N}{\omega . B} = \frac{50}{2\pi .4x10^9 .0.2} = 9.9nH$$

$$C = \frac{B}{2\pi f . N} = \frac{0.2}{2\pi 4x10^9 .50} = 0.159pF$$

The ADS simulation shown in Figure 4 shows the switched line attenuator using a 90-degree micro-strip line designed for 4GHz. For one simulation the inductors are connected resulting in the plots shown in Figure 6 and the other simulation the capacitors are connected resulting in the plots shown in Figure 5.

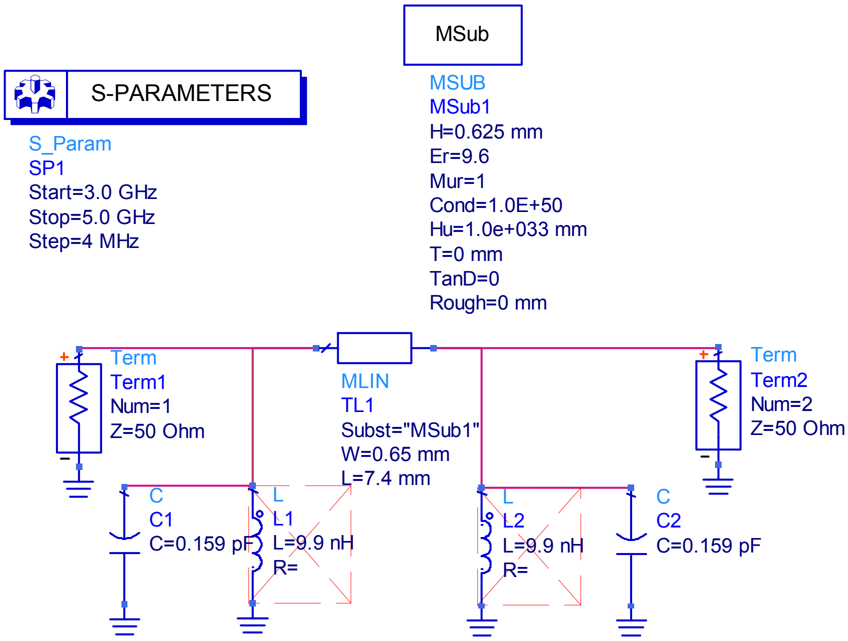


Figure 4 ADS simulation of the improved switched-line phase shifter given in the example. In this case the inductors have been de-activated to leave the capacitors in circuit resulting in a phase shift of 101.5 degrees.

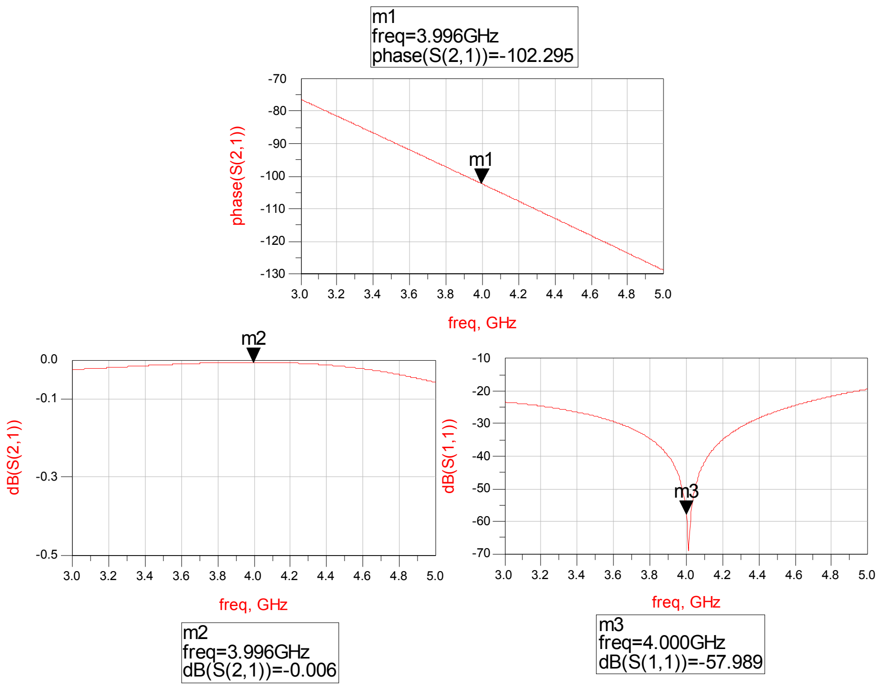


Figure 5 Improved switched-line phase shifter with capacitors switched in circuit.

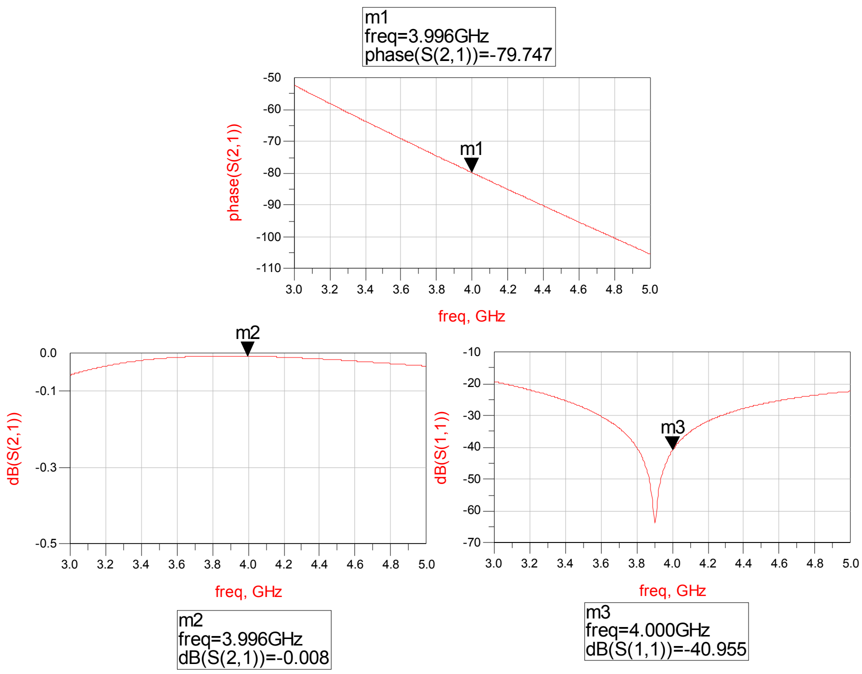


Figure 6 Improved switched-line phase shifter with inductors switched in circuit.

Reflection Phase shifter

Reflection phase shifters work by having switchable terminations which, create switchable reflection coefficients. The main type of reflection phase shifter uses switched line lengths either by using a PIN switch or by a variable reactance (eg varactor) to alter electrical length. In both cases the signal incurs twice the extra electrical length as the signal is reflected back.

Switched Line reflection phase shifter

The simplest example is to use a 90-degree hybrid (eg Lange or Rat-race) and two PIN diodes to either short to ground bypassing line length 2 or switched out thus adding line length 2 and adding a longer path for the signal to travel. The schematic of the circuit is shown in Figure 7.

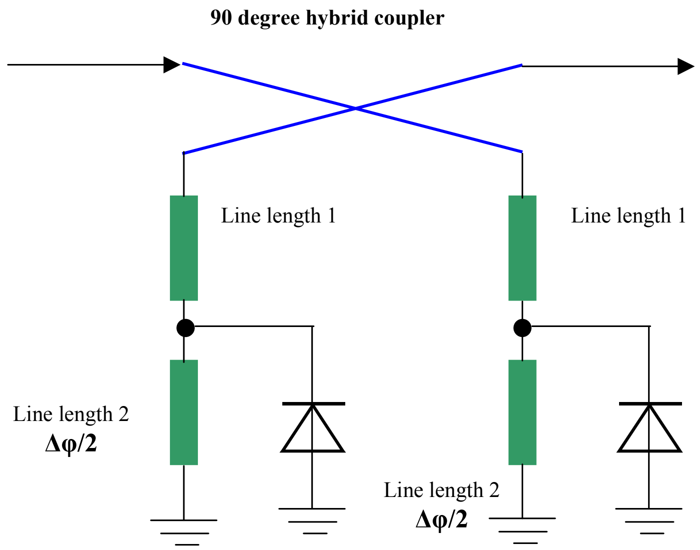


Figure 7 Reflection phase shifter using two PIN diodes to switch in or out the additional line lengths 2.

$$\Gamma_{ON} = e^{j\varphi}$$

$$\Gamma_{OFF} = e^{j(\varphi + \Delta\phi)}$$

For best operation $\Gamma_{ON} = \Gamma_{OFF}^{*}$ ie $\Gamma_{ON} = e^{-j(\varphi+\Delta\phi)}$

$$\text{Giving}: \phi = -(\varphi + \Delta\phi) + 2k\pi \Rightarrow 2k\pi - \Delta\phi, \text{ where } k = 0,1,2,3...$$

$$\Rightarrow \phi = k\pi - \Delta\frac{\phi}{2}$$

Example

Switched line reflection phase shifter to give 45 degrees phase shift at 8GHz. Lange coupler length will be ~4mm long.

$$\Gamma_{ON} = |\Gamma_o| \angle \phi_1$$

$$\Gamma_{OFF} = |\Gamma_o| \angle \phi_2$$

$$\Delta\phi = \phi_2 - \phi_1 = 45$$

For best return loss performance $\Gamma_{ON} = \Gamma_{OFF}^*$

$$\phi_1 = k\pi - \frac{\Delta\phi}{2} \quad \text{If k = 0 then} \quad \phi_1 = -\frac{\Delta\phi}{2} = -\frac{45}{2} = \text{- 22.5 degrees}$$

$$\Delta\phi = \phi_2 - \phi_1 = 45 \quad \therefore \Delta\phi + \phi = \phi_2 \quad = \quad 45 - 22.5 = 22.5 \text{ degrees}$$

The ADS simulation for this circuit is shown in

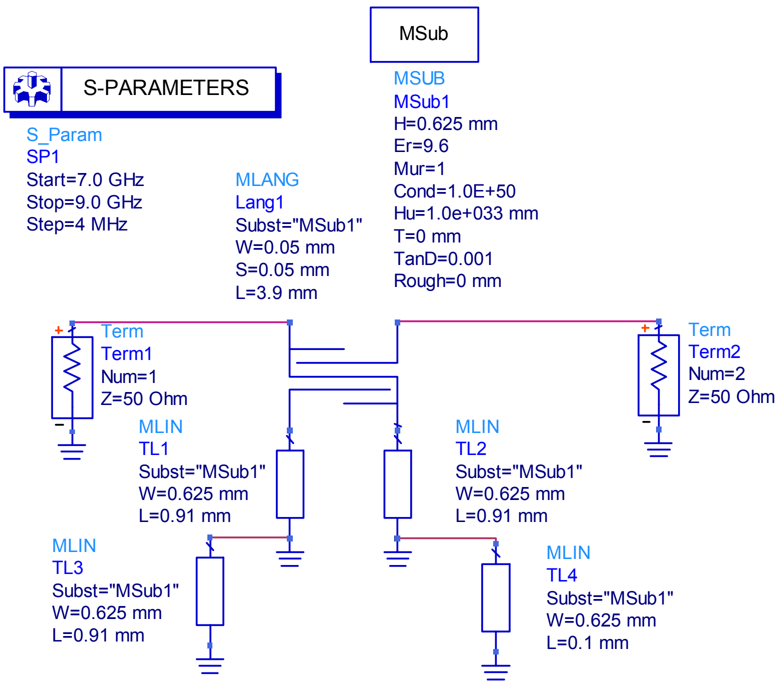


Figure 8 ADS simulation of the switched line reflection phase shifter given in the example. In this case we are simulating the PIN diodes on and shorted to ground by the two ground points at the end of 22.5 degree micro-strip lines TL1 and TL2. The resulting simulation of this circuit is shown in Figure 9. The other case is with the grounds disabled simulating the PINs switched off and the signal having to travel additionally along TL3 & TL4 (and of course back again). The resulting simulation of this is shown in

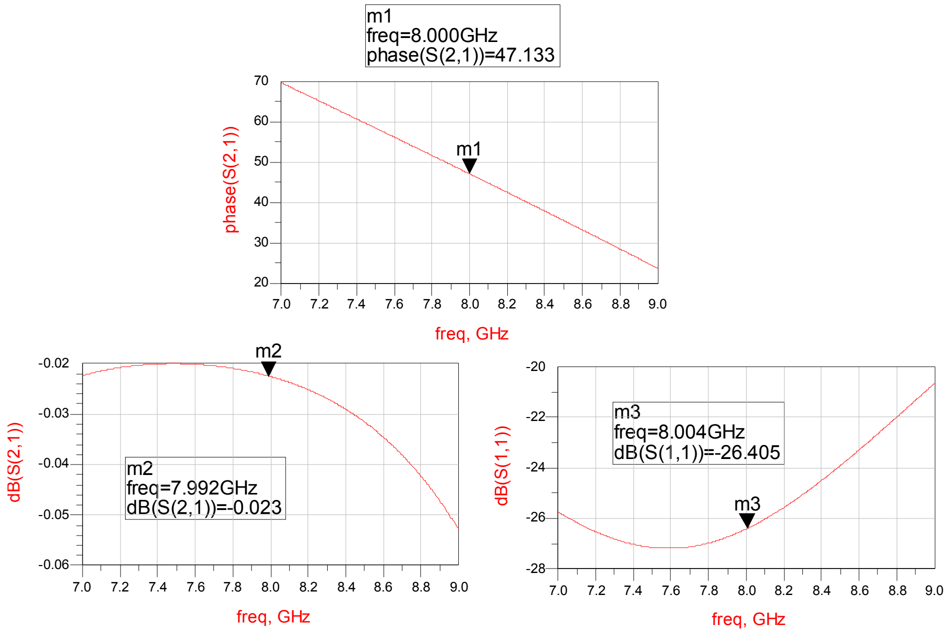


Figure 9 Resulting simulation from the circuit shown in Figure 8 with the diodes switched on – shorting to ground and effectively switching out TL3 & TL4.

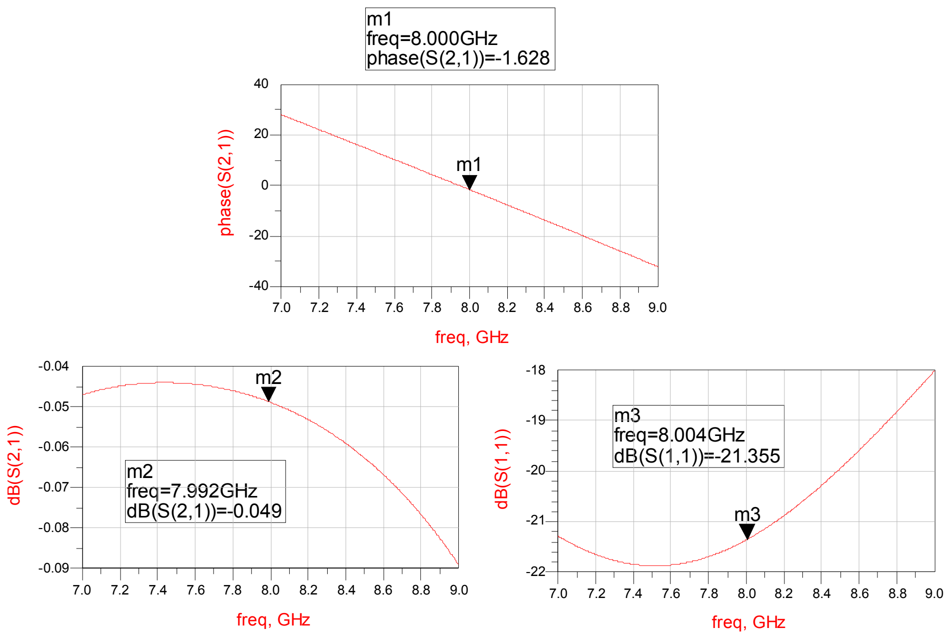


Figure 10 Resulting simulation from the circuit shown in Figure 8 with the diodes switched off (by disabling the grounds at the end of TL1 & TL2) – adding TL3 & TL4 transmission lines.

As can be seen there is approximately a 45 degree phase shift (the accuracy of this depends on the Lange coupler dimensions).

Variable reactance reflection phase shifter

This circuit again uses a 90-degree hybrid but instead of switched line lengths variable reactances are used. A variable reactance is in effect a variable electrical length therefore, using a variable reactance such as a varactor we can form a variable phase shifter. The schematic of the variable reactance reflection phase shifter is shown in Figure 11.

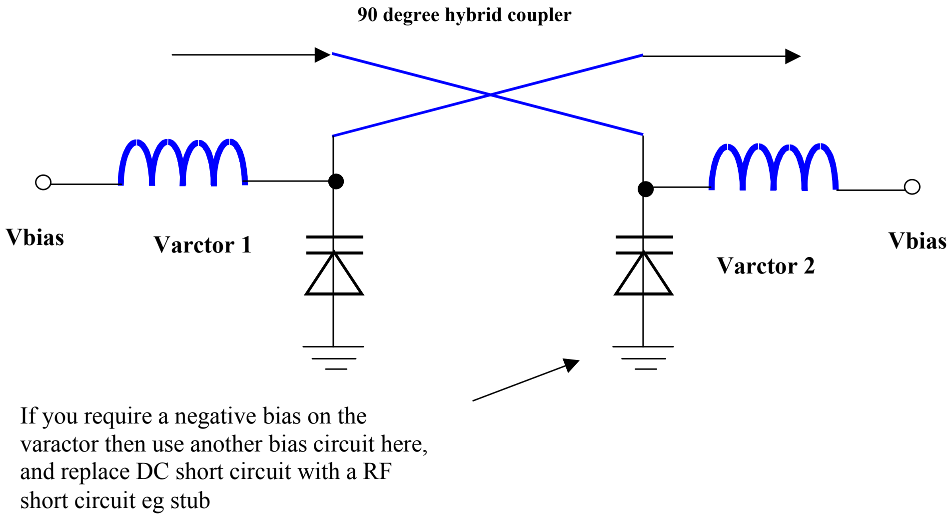


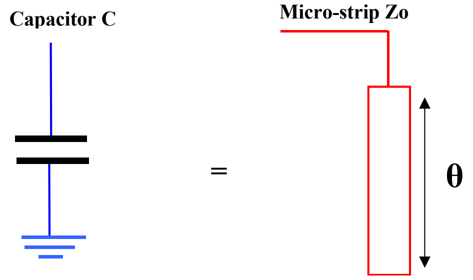
Figure 11 Variable reactance reflection phase shifter, using varactors as the variable reactance.

Each varactor is bias via a choke with the same bias. There may be a requirement to use a varactor reference instead of 0V (caused by the DC ground). In this situation the DC ground is replaced by a RF short eg a quarter-wave capacitive stub and another bias circuit added.

For example calculate the phase shift of a 4GHz variable reactance reflection phase shifter using Macom varactors type MA46422.

The MA46422 has a capacitance range of 0.6pF to 6pF (20V to 0.1V). The electrical length needs to be calculated for each capacitor value remembering that the phase is doubled due to the signal reflecting back from the short circuit on the other end of the varactor.

From the Micro-strip tutorial we found the following relationship for a shunt capacitor:-



$$\omega C = \frac{\tan\theta}{Zo}$$

$$\text{Where } \theta < 90^0 \left(90^0 \ \frac{\lambda_{op}}{4} \right)$$

(1) Capacitor set to 6pF (ie Control voltage of 0V)

$$\text{Rearrange} \quad \omega C = \frac{\tan\varphi}{Zo}$$

$$\varphi_{6pF} = 2 * \tan^{-1}(\omega.C.Zo) = 2 * \tan^{-1}\left(2\pi.4x10^9.6x10^{-12}.50\right) = 164^\circ$$

(2) Capacitor set to 0.6pF (ie Control voltage of 20V)

$$\varphi_{0.6pF} = 2 * \tan^{-1}(\omega.C.Zo) = 2 * \tan^{-1}\left(2\pi.4x10^9.0.6x10^{-12}.50\right) = 74^\circ$$

$$\text{Therefore, } \Delta\phi = \varphi_{6pF} - \varphi_{0.6pF} = 164 - 74 = 90 \text{ degrees}$$

The ADS simulation in Figure 12 was initially run with the varactors set to 6pF and the PhaseShift element was then set to give 0 degree phase shift at 4GHz to set a reference. The simulation was then run again this time with the varactors set to 0.6pF resulting in the plots shown in Figure 13.

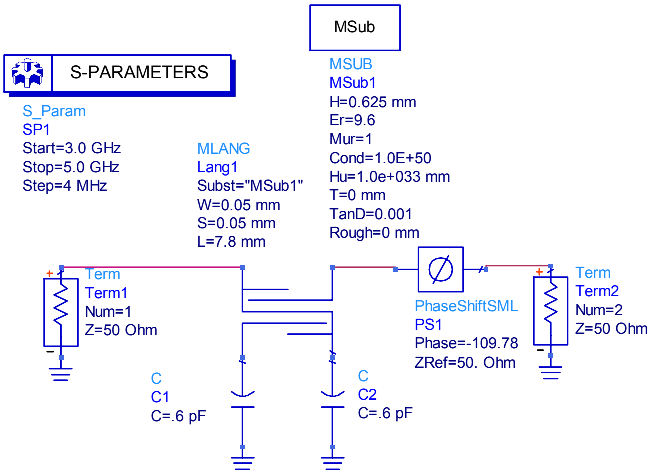


Figure 12 Variable reactance reflection phase shifter. The phase shift was set to give zero phase shift with the varactors set to 6pF (0V) as a reference, then the simulation was run again this time setting the varactors to 0.6pF (20V). The result of the second simulation is shown in Figure 13.

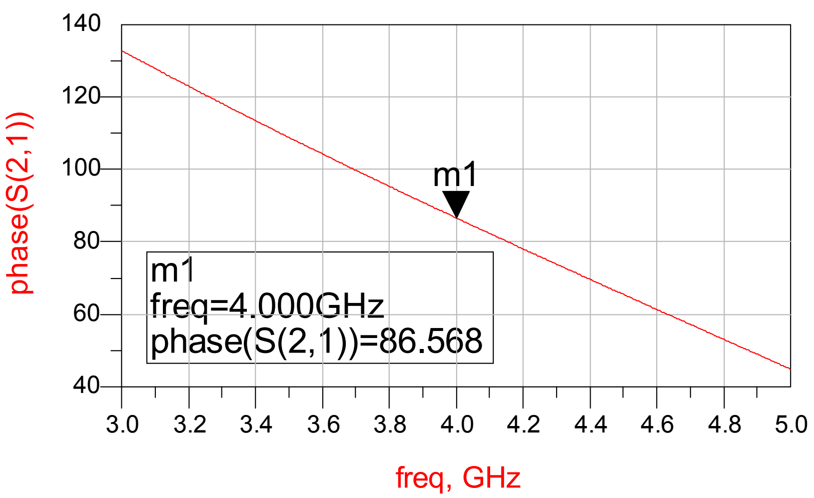


Figure 13 Simulation from ADS schematic shown in Figure 12, with capacitors now set to 0.6pF (from 6pF) to show that maximum phase shift available if using the MaCOM MA46473 diodes.