APPLICATION NOTE

A Varactor Controlled Phase Shifter for PCS Base Station Applications

Introduction

Power amplifiers in today's base stations use compensation techniques to reduce distortion. There are many well-known compensation techniques available, all relying on similar principles of phase and amplitude control. Therefore, most (and possibly all) of the compensation techniques use the same control components: voltage-controlled attenuators and voltage-controlled phase shifters.

The quality of these control components strongly determines compensation circuit performance. The ideal phase shifter provides a linear (vs. voltage) 0 to 360 degrees phase shift with 0 dB change in the signal level; similarly, the ideal attenuator would provide a linear (vs. voltage) attenuation change with a 0-degree phase shift between attenuation settings.

This Application Note describes the design of a high-performance phase shifter for PCS-band base station applications. The phase shifter uses Skyworks low-cost SMV1245-011 varactor as the phase-control element and the HY19-12, 90-degree hybrid. The PCS band was selected because the large number of PCS infrastructure base stations requires an efficient, low-cost solution. However, the methodology of this design is applicable to other wireless platforms.

Phase Shifter Fundamentals

A typical phase shifter architecture using a quadrature coupler (90-degree hybrid) is shown in Figure 1. The input signal (PIN) is divided by the coupler and directed to two branches (with a 90-degree phase shift) that are terminated with varactor diodes D1 and D2, changing the phase of each signal equally. The reflected signals (PREF/2) are then re-combined and are in phase at the output port (POUT). The reflected signals at the input port are 180 degrees out of phase and cancel each other. The phase shift provided by this circuit is equal to the reflection phase shift provided by a single varactor. The small vectors in Figure 1 show the phase relationships at the output and input ports.

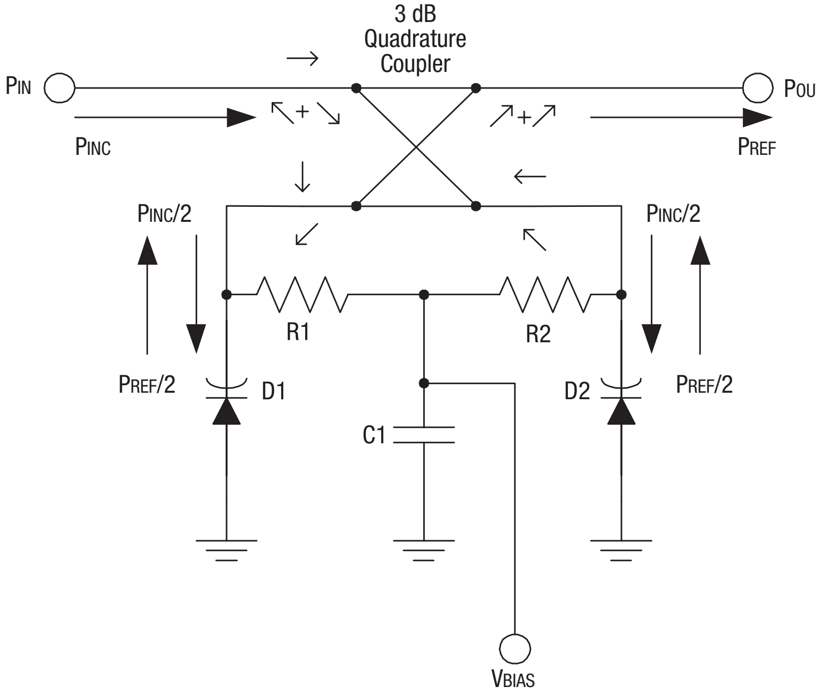

Figure 1. Typical Phase Shifter Design

A circulator terminated by a varactor may also be used to separate the reflected and incident waves and provide a phase shift. However, this solution would be costly. Instead, the circuit in Figure 1 provides a lower cost alternative, although it uses two phase shifting varactor circuits.

The varactor components in Figure 1 act as ideal, lossless reactive loads with a reflection coefficient from 0 degrees (open circuit – zero varactor capacitance) to –180 degrees (short circuit – infinite varactor capacitance). The reflection phase shift for different elementary circuits was calculated and is shown in Figure 2. For an ideal variable capacitor that changes from 0 pF to infinity, a total phase shift from 0 to –180 degrees occurs. For an ideal variable inductor, the phase changes from –180 to 0 degrees. If both were connected in series, the ideal result would be a 360-degree phase shift change.

Figure 3 shows that adding a fixed inductor to a variable capacitor increases the phase shift range. In this case, 6 nH was added at 1.95 GHz, resulting in a phase shift of approximately 280 degrees. However, a continued increase of inductance reduces the effect of the varactor capacitance range and leads to a degradation of the overall phase shift range. Installing an additional capacitor (C_{PAR}) in parallel with the LC varactor network shown in Figure 4, reduces this effect.

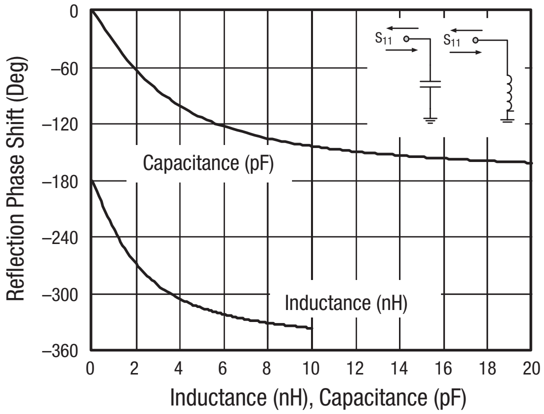

Figure 2. Reflection (S11) Phase Shift for Elementary L and C Circuits (Frequency = 1.95 GHz)

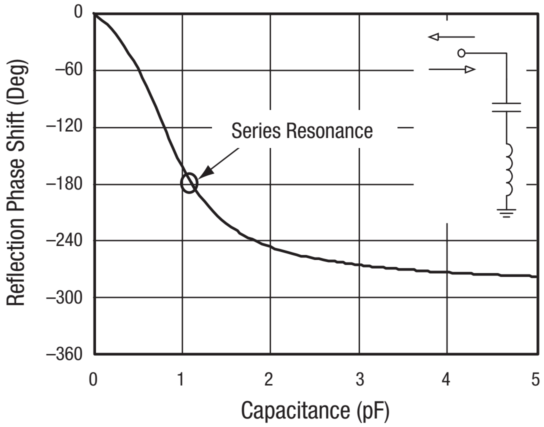

Figure 3. Reflection (S11) Phase Shift for Series LC Circuit (Frequency = 1.95 GHz, Inductance = 6 nH)

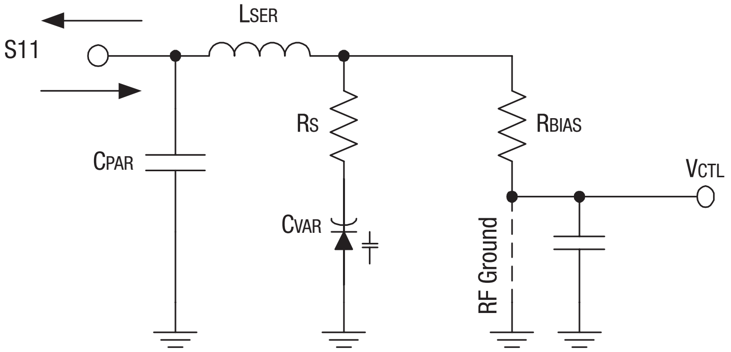

Figure 4. Equivalent Circuit of the Practical Phase Shifting Element

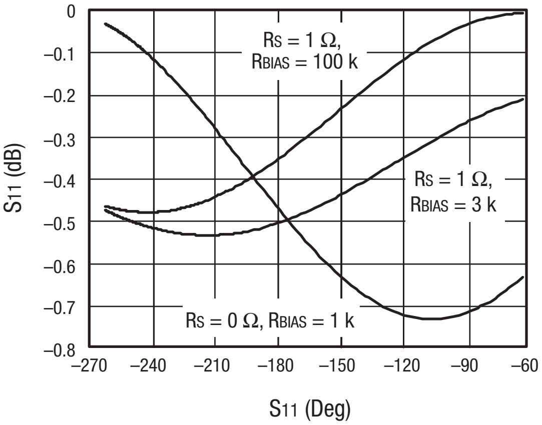

Figure 5. S11 State Chart for C_{VAR} = 0 to 10 pF

The components shown in Figure 4 are used in a typical design. Two additional resistive components are included: the parasitic varactor series resistance (R_S) and the added bias resistor (R_{BIAS}). Figure 5 shows the calculated loss, S11, for different combinations of R_S and R_{BIAS}.

The varactor R_S introduces most loss at maximum capacitance (highest current in the varactor path). However, the bias resistance, in parallel with the varactor, introduces the highest loss at low capacitance, below the 180-degree phase shift point, where resonance occurs. From linear circuit theory, this resonance also depends on the value of R_{BIAS}. When these loss factors are taken into account, some flattening of the amplitude response may result, as shown in Figure 5.

In reality, the varactor resistance, R_S, may be a function of bias (reverse) voltage. In some “very” hyperabrupt junction varactors, the series resistance may vary 2 to 5 times from its maximum at 0 V to a minimum at the punch-through voltage. However, the series resistance of the SMV1245-011 used in this design is constant for the range of applied voltage.

The Phase Shifter Circuit Model

The circuit model (used for the Libra IV CAD software application) is shown in Figure 6. A quadrature hybrid (HYB1) is used with 0.6 dB loss, which effectively simulates the HY19-12 used in our design. Capacitors C1 and C2 are internal components within the HY19-12 that isolate the DC paths from input and output ports.

The 0.5 dB loss pad (PAD1) simulates the total loss of the input/output interface in the circuit board. In reality, the effect of the input/output interface, including SMA transitions and microstrip lines, is more complex than the pad used in the model.

The simplification is appropriate because the model concentrates on the phase and amplitude response vs. control voltage, which is not affected by the performance of the input/output interface.

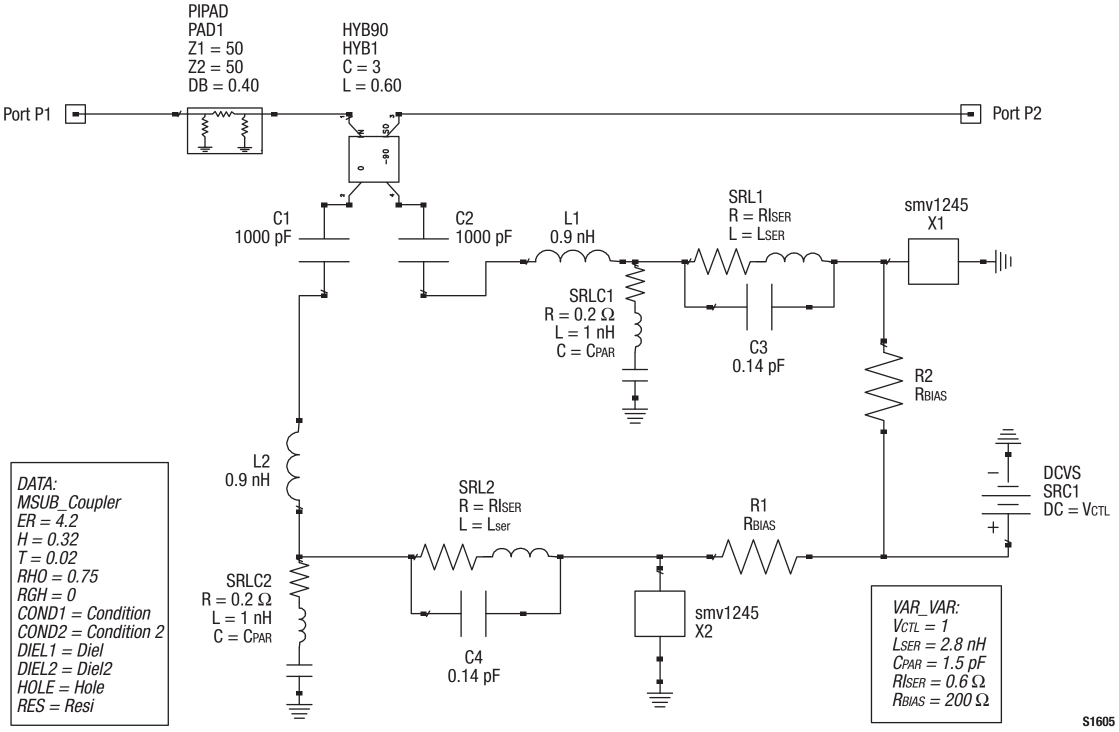

Figure 6. Phase Shifter Circuit Model

Inductors L1 and L2 (both 0.9 nH) effectively simulate the HY19-12 lead and package inductances. Parallel capacitors SRLC1 and SRLC2 are simulated as a series R-L-C network with a package inductance of 0.75 nH and series resistance of 0.2 Ω. The discrete inductors SRL1 and SRL2 are modeled as lossy parallel R-L-C networks with series resistance, RI_{SER} = 0.6 Ω, and parallel capacitance equal to 0.14 pF, which is typical for the majority of multilayer inductors with inductance values within 2 to 5 nH.

SMV1245-011 SPICE Model

The SMV1245-011 is a low capacitance, hyperabrupt varactor diode in an SOD-323 package.

The SPICE model for the SMV1245-011 varactor diode, defined for the Libra IV environment, is shown in Figure 7 with a description of the parameters used.

Table 1 describes the model parameters and provides default values appropriate for silicon varactor diodes that may be used by the Libra IV (or similar) simulator.

According to the SPICE model, the varactor capacitance, C_V, is a function of the applied reverse DC voltage, V_R, and may be expressed as follows:

$$C_V = \frac{C_{JO}}{\left(1+\frac{V_R}{V_J}\right)^M} + C_P$$

Where: C_V = Total varactor capacitance (pF)
C_{JO} = Zero-bias junction capacitance (pF)
V_R = Reverse DC voltage (V)
V_J = Junction potential (V)
M = Grading coefficient
C_P = Parasitic package capacitance (pF)

The above equation is a mathematical expression of the capacitance characteristic. The model is most accurate for abrupt junction varactors such as Skyworks SMV1408-001. However, for hyperabrupt junction varactors, the model is less accurate because the coefficients are dependent on the applied voltage.

To improve the equation for hyperabrupt junction varactors, the coefficients need to be optimized for the best capacitance vs. voltage fit. Such simulated coefficients may not have physical meaning.

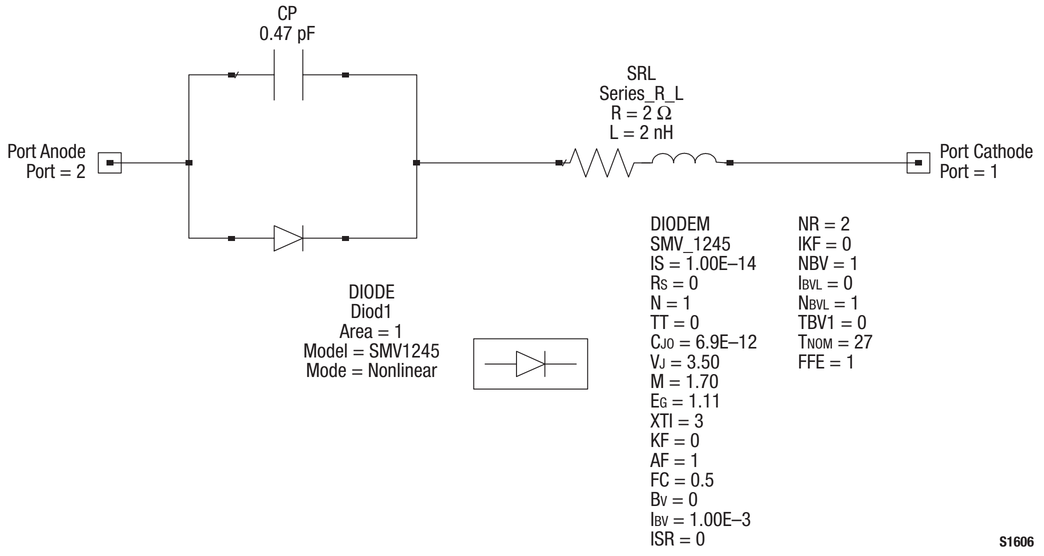

Figure 7. SMV1245-011 SPICE Model

Table 1. Silicon Diode Default Values in Libra IV

Parameter	Description	Unit	Silicon Varactor Diode Default Values
IS	Saturation current. With N, determines the DC characteristics of the diode.	A	10^{-14}
R_S	Series resistance	Ω	0
N	Emission coefficient. With IS, determines the DC characteristics of the diode.	–	1
TT	Transit time	sec	0
C_{JO}	Zero-bias junction capacitance. With V_J and M, defines the nonlinear junction capacitance of the diode.	F	0
V_J	Junction potential. With V_J and M, defines the nonlinear junction capacitance of the diode.	V	1
M	Grading coefficient. With V_J and M, defines the nonlinear junction capacitance of the diode.	–	0.5
E_G	Energy gap. With XTI, helps define the dependence of IS on temperature.	EV	1.11
XTI	Saturation current temperature exponent. With E_G, helps define the dependence of IS on temperature.	–	3
KF	Flicker noise coefficient.	–	0
AF	Flicker noise exponent.	–	1
FC	Forward-bias depletion capacitance coefficient.	–	0.5
B_V	Reverse breakdown voltage	V	Infinity
I_{BV}	Current at reverse breakdown voltage	A	10^{-3}
ISR	Recombination current parameter	A	0
NR	Emission coefficient for ISR	–	2
IKF	High injection knee current	A	Infinity
NBV	Reverse breakdown ideality factor	–	1
I_{BVL}	Low-level reverse breakdown knee current	A	0
N_{BVL}	Low-level reverse breakdown ideality factor	–	1
TBV1	Reverse breakdown voltage linear temperature coefficient	1/°C	0
T_{NOM}	Nominal ambient temperature at which these model parameters were derived	°C	27
FFE	Flicker noise frequency exponent	–	1

Table 2. SPICE Parameters for the SMV1245-011 Varactor

C_{JO} (pF)	M	V_J (V)	C_P (pF)	R_S (Ω)	L_S (nH)
6.9	1.7	3.5	0.47	2	2

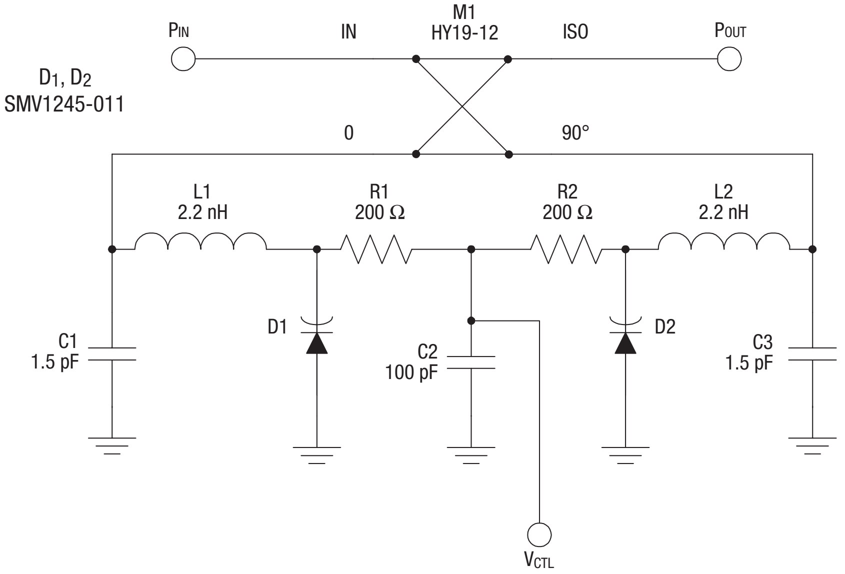

Figure 8. Phase Shifter Circuit Diagram

SPICE model values for the capacitance, C_V, of the SMV1245-011 used in the phase-shifter design are provided in Table 2. Note that, in the Libra model, C_P is given in picofarads, while C_{GO} is provided in farads to comply with the default unit system used in Libra.

Phase Shifter Design, Materials, and Layout

The circuit diagram for the phase shifter is shown in Figure 8 and the PC board layout is shown in Figure 9. A Bill of Materials for the phase shifter is provided in Table 3.

The PC board is made of 0.5 mm thick, standard FR4 material with two-sided copper (0.02 mm thick) metallization. For test purposes, the RF signals were fed through SMA connectors.

The 90-degree hybrid coupler is Skyworks model HY19-12, a GaAs I/C optimized for PCS band applications. Although it is manufactured using GaAs, this product is passive and does not require an external bias. All RF leads of the HY19-12 are DC isolated, minimizing the number of added DC blocking capacitors. Sufficient grounding is provided through the four vias under the I/C body.

Performance Discussion

Measured performance with simulated data is shown in Figures 10 and 11. Three sets of circuit values were measured and analyzed as shown on the graphs. The largest phase shift, 240 degrees, occurred at L_{SER} = 2.2 nH and C_{PAR} = 2.0 pF for a varactor voltage change from 0 to 12 V. In this case, the amplitude variation was about ±1.5 dB.

For C_{PAR} = 1.5 pF, there was an approximate 190 degree phase shift with ±0.75 dB amplitude variation. With L_{SER} = 2.2 nH and C_{PAR} = 1.8 pF, there was an approximate 220 degree phase shift with ±1.2 dB amplitude variation.

It is interesting to note that the "linear" range of phase shift (linear vs. voltage) is similar for the three designs and is about 120 degrees (from 60 to 180 degrees). The highest phase/voltage sensitivity was for C_{PAR} = 2.0 pF estimated at about 40 to 50 V. Higher phase shift values are achievable with higher C_{PAR} values, but larger amplitude variations would occur.

The measured and simulated phase responses were noticeably similar, validating the assumptions in the model that predict phase properties. The simulated amplitude responses were not as close to the measured data. Some of the discrepancies may be attributed to the simplified, idealized model of the 90-degree hybrid coupler.

Figure 9. Phase Shifter PCB Layout

Table 3. Phase Shifter Bill of Materials

Component	Value	Size	Manufacturer	Part Number
C1, C3	1 pF	0603	AVX/Kyocera	CM105CG1ROK10AB
C2	100 pF	0603	AVX/Kyocera	CM105CG200K10AB
M1	–	SOIC-8	Skyworks Solutions	HY19-12
R1, R2	200 Ω	0603	AVX	CR105-201J-T
D1, D2	–	SOD-323	Skyworks Solutions	SMV1245-011
L1, L2	2.2 nH	0603	ACX	HI1608-1B2N2_N_K_B

In this design, only the SMV1245-011 varactor diode was considered out of a large selection of available varactors. Varactors with higher tuning sensitivity, such as the SMV1247 or SMV1263, provide a higher range of phase shift but with more amplitude variation. Abrupt junction varactors from the SMV1400 series operate with lower tuning sensitivities and less phase control but with lower loss and better amplitude linearity.

For additional information, refer to the Skyworks Application Note, *Varactor SPICE Models for RF VCO Applications*, document number 200315.

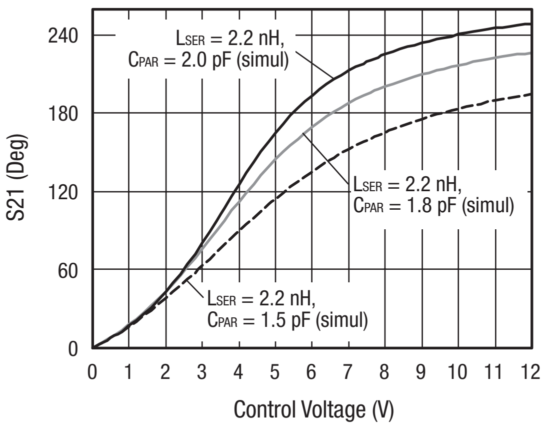

Figure 10. Measured and Simulated Phase Response

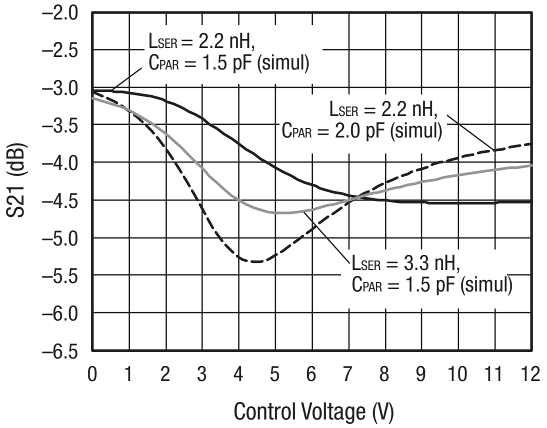

Figure 11. Measured and Simulated Amplitude Response

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