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Electrically Tunable Switched-Line Diode Phase Shifters Part 1: Design Procedure

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This article examines the design and performance of diode phase shifters, key building blocks for phased array, smart antenna, and measurement technologies

In building a strategy for effective integrated-circuit design, it is important to understand the characteristics of different printed phase shifters. Optimization of the printed phase shifter design process can reduce unnecessary costs and design iterations, thus allowing designers time to improve the quality of the product. The design process includes various stages from analysis of requirements to final design documentation, balancing and trading-off factors such as electrical performance, size, cost, etc. In this article we consider design strategy of switched-line PIN-diode phase shifters.

RF and microwave phase shifters have many applications in various equipment such as phase discriminators, beam forming networks, power dividers, and phase array antennas [1, 2, 3]. A phased array antenna has a large number of radiating elements that emit phased signals to form a radio beam. The radio signal can be electronically steered by the active manipulation of relative phasing of individual antenna elements. Phase shifters are fundamental parts of phased array antennas. They allow an array to scan a beam or reconfigure a shaped beam. Phased antenna arrays consist of a number of individual elements, each one requiring a phase shifter that applies the necessary phase shift to steer the antenna beam [4]. In some amplitude monopulse systems [5, 6], a phase shifter provides different directional and omnidirectional antenna modes.

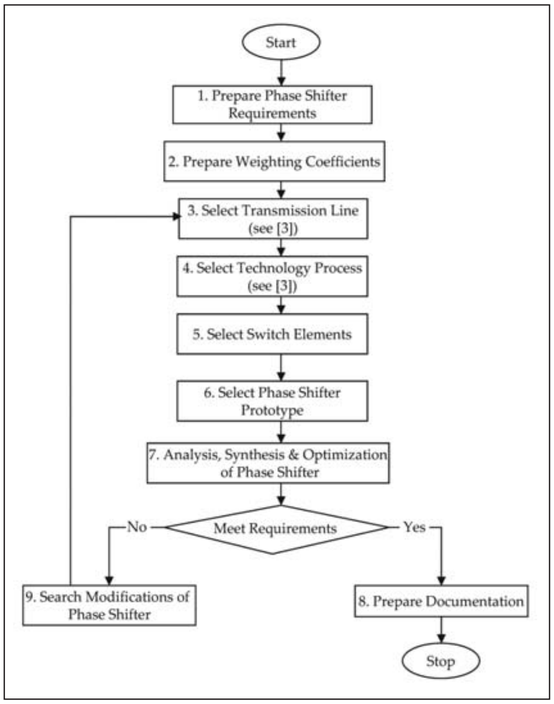


Figure 1 · Flow chart for the design of printed phase shifters.

Figure 1 illustrates the design flow of printed phase shifters. Definition of system level specifications is the first step in the design flow of printed phase shifters. This involves both system level requirements which are applied directly to phase shifters, as well as derived requirements which depend on system requirements. Phase shifter specifications include electrical, cost, size and other requirements. The major parameters which define RF and microwave print phase shifter are frequency range, bandwidth (BW), total phase variance ($\Delta\varphi$), insertion loss (IL), switching speed, power handling (P), accuracy and resolution, input/output matching

(VSWR) or return loss (*RL*), harmonics level. For all requirements, a designer has to choose consecutive integer values of weighting coefficients k_i corresponding to each parameter (step 2 of design flow in Fig. 1), starting with $k = 1$ for the most important parameter [7 - 9]. The maximum value of k can be less than or equal to the number of parameters, depending on whether some parameters are considered to have the same importance or not. Selection of a phase shifter prototype (step 6 of design flow Fig. 1) depends on all requirements, selected transmission line (step 3), technology process (step 4), and must take into account the corresponding weighting coefficients. The final choice of a phase shifter network and control element will depend on the required bandwidth, insertion loss, switching speed, total phase variance, power handling, accuracy and resolution, input/output matching, harmonics level.

The design strategy of printed transmission lines was described in [7]. The type of optimal transmission line depends on many different factors including the technology process. According to the phase shifter design flow (Fig. 1), a phase shifter prototype is selected (step 6) after the selection of the transmission line (step 3), technology process (step 4), and switch elements (step 5). The switching elements in digital phase shifters are PIN diodes and Field Effect Transistors (FET). The high-speed PIN diodes change resistance values from approximately 10,000 ohm to less than 1 ohm. Switching is achieved by changing the bias point of a PIN-diode from forward to reverse direction and vice versa. These PIN diodes are commonly utilized in high-speed, current controlled phase shifters. In MMIC design the switching elements are often realized with FETs. GaAs phase shifters are typically very small, on the order of a few square millimeters, which makes them good candidates for thin-film semiconductor manufacturing processes. GaAs, on the other hand, is one of the most expensive semiconductors.

Analog phase shifters are devices whose phase shift changes continuously with the control input and therefore offer almost unlimited resolution with monotonic performance. The most commonly used semiconductor control elements in analog phase shifters are varactor diodes. Varactor diodes operating in a reverse-biased condition provide a junction capacitance that varies with applied voltage and can be used as an electrically variable capacitor in a tuned circuit. Varactor analog phase shifters can achieve a large amount of phase shift and high speed and require fewer diodes than digital phase shifters, but at the cost of decreased accuracy, relatively narrow bandwidth, and low input power levels (less than 1 W). Schottky diodes are also used as variable elements in analog phase shifters, but they suffer from limited power handling capability and matching difficulty in broadband networks.

Sometimes the phase shifter prototype does not satisfy some requirements because of the selected transmission line. In this case the transmission line should be reselected to satisfy the phase shifter requirements. For minimum cost, most phase shifters use microstrip line, however, a lower loss stripline or a suspended stripline design is more desirable. The final selection of a phase shifter prototype can be made by analysis of the circle diagram [7-9]. The optimum prototype is determined by minimizing the area between real and goal performance. Synthesis of print the phase shifter is based on both system requirements and derived requirements. Synthesis results are physical dimensions of a phase shifter and lumped element values if necessary. Analysis of a print phase shifter entails definition of electrical performance based on the known physical dimensions.

There are many different ways to implement the RF phase shifter. Some of the most notable methods are based on switched-line, loaded line, and reflection theories. The switched line method is the most straightforward approach of the three because it uses the simple time delay difference between two direct paths to provide desired phase shift.

The PIN-diode switched-line phase shifter can be classified according to following types of characteristics:

- transmission line (regular, irregular, and coupled);
- number of bits;
- structure (reflection or non-reflection);
- with reciprocal and non-reciprocal devices;
- number of switched inputs/outputs (SPST, SPDT, SP3T, etc.);
- PIN diode connection with transmission line (series, shunt, series-shunt);
- bandwidth (narrow or broadband);
- configuration of elements (distributed, lumped-elements, or combination of lumped and distributed);
- maximum power (low or high).

The switched-line phase shifter includes phase elements, switch elements (PIN diodes), and control network. The selection of switch elements (step 5, Fig. 1) depends on the phase shifter requirements. Shunt diode switches are commonly used for systems with high isolation and where handling of higher power is necessary. The isolation of the off-path with shunt PIN diode is approximately 6 dB larger than in the configuration with series switches. Series diode switches are commonly used in broadband circuits. The series-shunt configuration provides greater isolation than both the series and the shunt versions, but requires a bias current from both positive and negative sources that would significantly increase the DC power dissipation.

The switched-line phase shifter is dependent only on

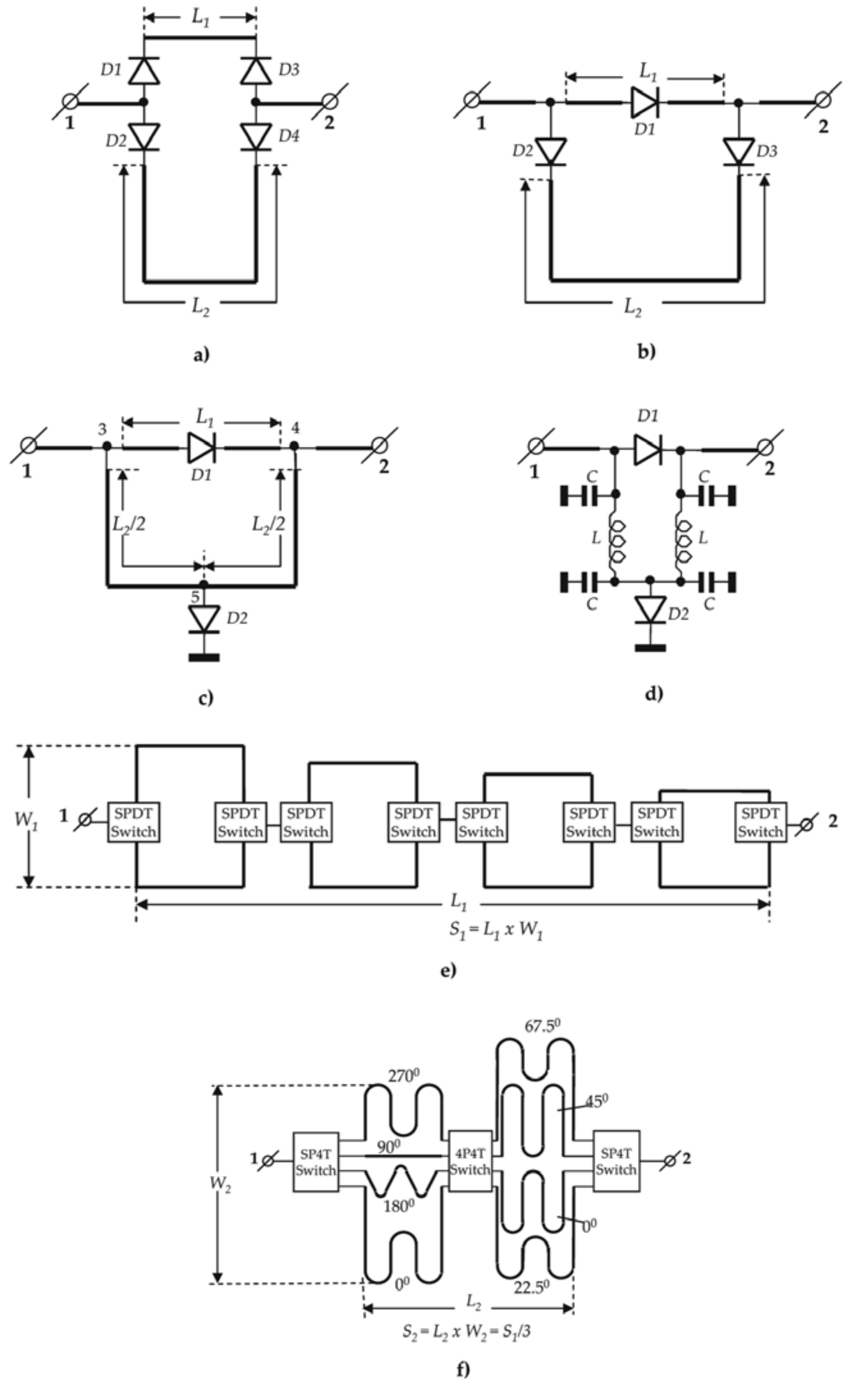


Figure 2 · Switched-line phase shifter circuit configuration options.

the lengths of line used. Also, the switched-line phase shifter is simple in both principle and design. One of the two lines is labeled as a "reference" line, and the other as a "delay" line. An important advantage of this circuit is that the phase shift will be approximately a linear function of frequency. This enables the circuit to operate at a broader frequency range. Also, the phase shift created by the switched-line phase shifters is dependent on transmission line lengths only, and they are therefore very stable over time and temperature. The PIN diodes of this phase shifter may suffer from parameter drift, but this usually provides degradation in the insertion loss of the circuit and not the phase shift. For the switched-line phase shifter, both the peak power capability and the insertion losses are independent of the phase shift.

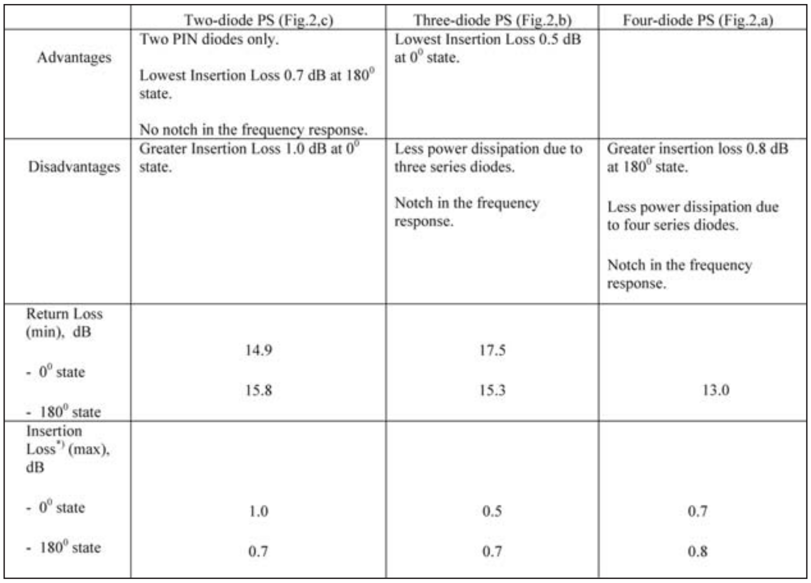
The conventional switched-line phase shifter is comprised of two line segments of different length selectively connected to the transmission line. The different path lengths between the two line segments determines the amount of phase shift to be introduced. The transmission line is switched over from one line segment of the phase shifter to the other when the phase shift is removed. Figure 2a illustrates the schematic of the conventional switched-line phase shifter with RF input 1, RF output 2, four PIN diodes *D1, D2, D3,* and *D4,* and two transmission lines L_1 and L_2. Only one arm should be ON at a time. When the PIN diodes *D1* and *D3* are ON while PIN diodes *D2* and *D4* are OFF, the reference delay line L_1 is in the circuit. When the PIN diodes *D2* and *D4* are ON while PIN diodes *D1* and *D3* are OFF, the delay line L_2 is in the circuit. By switching the signal between two lines L_1 and L_2 of different lengths, it is possible to realize a specific phase shift:

$$\Delta\varphi = 2\pi \times \frac{\Delta L}{\lambda}$$

where ΔL is the difference between the physical lengths of the delay line (*L2*) and the reference line (*L1*); λ is the guide wavelength.

Switched-line phase shifters are often used for two largest phase shifts (180 and 90 degrees). When path L_2 is a half guide wavelength longer than path L_1, switching from path L_1 to path L_2 introduces an increased phase delay of 180 degrees. For the required 180° phase shift the difference in physical length should be $\Delta L = \lambda/2$. By switching the signal between two pre-determined lengths of transmission line it is therefore possible to realize a specific phase shift at a given frequency. However, the phase shift value tends to deviate linearly from the intended value as the frequency of the signal deviates in either direction from the center (nominal) frequency. In order to reduce the size of the switched-line phase shifter, the reference line should be shorter. The lengths L1 and L2 must be carefully selected to avoid phase errors, high return loss, and high insertion loss.

The practical design of the existing switched-line 180-deg phase shifters faces several problems. One is associated with the half guide wavelength arm ("delay line" L_2). Resonances can occur in the off line when the line length is a multiple of 0.5 λ. This line will appear resonant due to its length, and the phases will interfere in a way to reflect much of the incoming power back to the input port. The resonant frequency will be slightly shifted due to the series junction capacitances of the reversed biased diodes.



	Two-diode PS (Fig.2,c)	Three-diode PS (Fig.2,b)	Four-diode PS (Fig.2,a)
Advantages	Two PIN diodes only. Lowest Insertion Loss 0.7 dB at 180^0 state. No notch in the frequency response.	Lowest Insertion Loss 0.5 dB at 0^0 state.	
Disadvantages	Greater Insertion Loss 1.0 dB at 0^0 state.	Less power dissipation due to three series diodes. Notch in the frequency response.	Greater insertion loss 0.8 dB at 180^0 state. Less power dissipation due to four series diodes. Notch in the frequency response.
Return Loss (min), dB			
- 0^0 state	14.9	17.5	
- 180^0 state	15.8	15.3	13.0
Insertion Loss$^{*)}$ (max), dB			
- 0^0 state	1.0	0.5	0.7
- 180^0 state	0.7	0.7	0.8

Table 1 · Performance of 0°/180° switched-line phase shifters.

Another disadvantage of this phase shifter is a large number of the PIN diodes: the typical switched-line phase shifter (Fig. 2a) consists of two SPST switches with four diodes *D1, D2, D3,* and *D4*. Insertion loss of the switched-line phase shifter is equal to the loss of the single-pole, double-throw switches plus the line losses. Typically, the isolation of the two switches must exceed 20 dB in the required frequency band.

Figure 2b illustrates the schematic of three-diode switched-line phase shifter. Instead of two PIN diodes for switching the reference line L1 (Fig. 2a) in this circuit, one series PIN diode *D1* is used. Figure 2c is an example of the 180-deg switched-line phase shifter with two PIN diodes. In this circuit, for the 180-deg phase shifting, the diodes *D1* and *D2* are in the OFF position, and RF signal passes through line L_2 with the one-half guide wavelength length providing a 180-deg phase shift. The segments of lines between junction 5 and junctions 3, 4 have the length equal to one quarter guide wavelength plus length of short bypass line L_1. For the 0-deg phase shifting, diodes *D1* and *D2* are controlled to be in the ON position. Therefore, during the 0-deg phase shifter status, these quarter guide wavelength lines transform the short circuit of diode *D2* (the shunt PIN diode *D2* is activated by forward bias) into open circuit at junctions 3 and 4, and an RF signal passes through bypass line L_1. In this case the reference line is activated because the series diode *D1* is ON with minimum series diode resistance under the forward bias. The lengths of reference line L_1 and delay line L_2 must be carefully selected to avoid phase errors, high insertion losses and high return losses. The large errors don't occur because there are two quarter-wavelength shorted lines in the delay line L_2. Thus, both lengths (L_1 and L_2) must not be multiples of a half wavelength. Also, for the 180-deg phase shifter, the reference line length L_1 is not zero because of the finite dimensions of series PIN diode and of PADs for solder of the diode package. The disclosed phase shifter overcomes the resonant effect by using the reference line electrical length of greater than 0 degrees depending on the insertion loss limitation. In this case the delay line length should be greater than half guide wavelength in the required frequency band. The problem of switched-line phase shifter (Fig. 2c) is the difficulty of simultaneous realization of 180-deg phase shifting and the minimum insertion loss in the reference mode, because for this mode the lengths between the shunt diode connection and each of the junctions 3 and 4 should be quarter-wavelength. Therefore, the total delay line length is $L_2 = \lambda/2$, but for the 180° mode the delay line length should be greater than half-wavelength: $L_2 = \lambda/2 + L_1$. If the intended phase shift is 180 degrees, the differential path length is equal to the half wavelength of the center frequency of the signal of the transmission line. The PIN diodes suffer from parametric drift. This usually leads to the degradation in the insertion loss of the switch but not in the phase shift. The isolation per switch in the OFF line must be greater than 20 dB to avoid phase errors.

The advantage of the switched-line phase shifter is simplicity in both principle and design. The disadvantages include losses in signal path due to semiconductor devices and losses which depend on the phase shift due to unequal transmission line paths. The main disadvantage of the switched-line phase shifter network for use in broadband systems is that the bandwidth of operation is limited by the variation of differential phase shift with frequency. Also, if one of switches fails, the whole phase shifter fails. Another disadvantage of this phase shifter is the contradictory conditions for the required 180-degree phase shift and the minimum loss during 0-deg phase shift status. Table 1 illustrates performance of the 0/180-deg two-, three-, and four-diode switched-line phase shifters.

The switched-line 180-deg phase shifter is relatively large for low-frequency applications. Figure 2d illustrates lumped element 180-deg switched-line phase shifter. The quarter guide wavelength segments of the phase shifter delay line are substituted with equivalent lumped element circuits. A short segment of transmission line of characteristic impedance z and electrical length $\Theta = 2\pi l/\lambda$ (l is the physical length of transmission line, λ is the guide wavelength) is equivalent to a π-section circuit. For the quarter-wavelength segments of the phase shifter delay section, the equivalent lumped elements of the π-section are $L = z/2\pi f_0$, $C = 1/2\pi f_0 z$, where z is the characteristic impedance of the input/output line, f_0 is the center frequency of the phase shifter. The lumped element configuration of the 180-deg phase shifter can be recommended for the HF, VHF, and UHF ranges.

This article will conclude next month, examining multi-step printed-line phase shifter circuits. References will be included with Part 2.

Author Information

Leo G. Maloratsky received his MSEE degree from the Moscow Aviation Institute and his PhD from the Moscow Institute of Communications in 1962 and 1967, respectively. Since 1962, he has involved in the research, development and production of RF and microwave integrated circuits at the Electrotechnical Institute, and he was assistant professor at the Moscow Institute of Radioelectronics. From 1992 to 1997, he was a staff engineer at Allied Signal. From 1997 to 2008, he was a principal engineer at Rockwell Collins where he worked on RF and microwave integrated circuits for avionics systems. Since 2008 he joined Aerospace Electronics Co. He is author of four monographs, one text-book, over 50 articles, and 20 patents. His latest book is *Passive RF and Microwave Integrated Circuits,* 2004, Elsevier. He can be reached at: lmaloratsky@cfl.rr.com