

Electrically Tunable Switched-Line Diode Phase Shifters

Part 2: Multi-Section Circuits

By Leo G. Maloratsky
 Aerospace Electronics Co.

This article concludes the author's discussion of issues that determine the circuit configuration and construction method of switched-line phase shifters.

Multibit switched line phase shifters [3, 10] can be used to vary the phase shift up to 360°. Digital phase shifters provide a discrete set of phase states that are controlled by two-state “phase bits.” The number of binary weighted phase shifting “bits” can be cascaded to realize a variable phase shifter covering the desired range. Typically, the phase shifters are placed in tandem, with progressively greater phase shift angles to provide phase angle selectivity. Each switched delay line comprises a plurality of fixed time delays, which are combined to produce successive increments of delay in response to binary control signals. Figure 2e is a sketch of a traditional four-bit digital phase shifter. A four-bit phase shifter employs four switched-line phase shifters. By using the proper combination of on/off states, one can implement any discrete number of phase states between 0 and 360 degrees. The four-bit phase shifter (Fig. 2e) realizes $2^4 = 16$ discrete phase states at $360/16 = 22.5$ deg interval. Each bit is then cascaded together. To minimize phase quanti-

zation error, the number of bits, and hence the number of phase shifters, should be increased. The greater the number of bits, the higher the complexity and the RF loss, and the lower the tolerance interval of the side-lobe level for the antenna array pattern. Several modifications have been made to the traditional microstrip switched-line phase shifter layout to reduce the size and improve the performance [11]. Unfortunately, the overall size of the switched-line geometry of the traditional phase shifter (Fig. 2e) is comparable to the wavelength for each bit. Since multibit phase shifters are usually desired, this can result in a phase shifter that is much larger than the other microwave components in an RF system. Instead of cascading four 1-bit phase shifters (Fig. 2e), which is typically done, two cascaded 2-bit phase shifters (Fig. 2f) can be implemented. The overall area is thus reduced by a factor of 2.8 [11].

Figure 3a illustrates a switched-line phase shifter with two SPDT switches, one reference regular line of length $3L$, and two other parallel coupled lines of equal length $L = \lambda/4$, directly connected to each other at one end. This network is a modification of the well known Schiffman phase shifter [3, 12, 13]. Phase shift

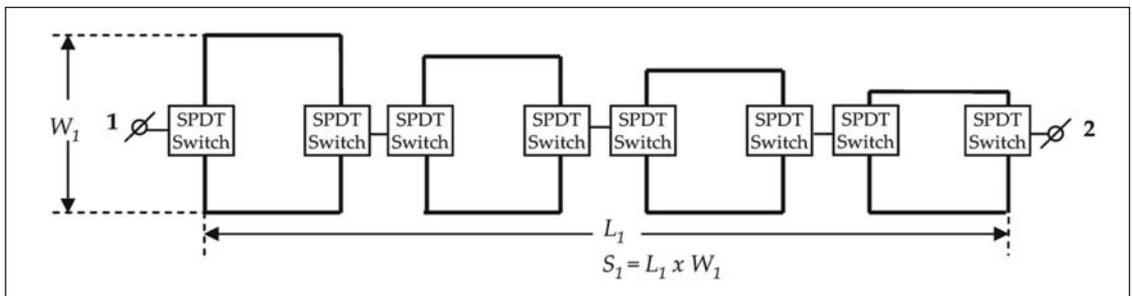


Figure 2e · Four-bit phase shifter configuration.

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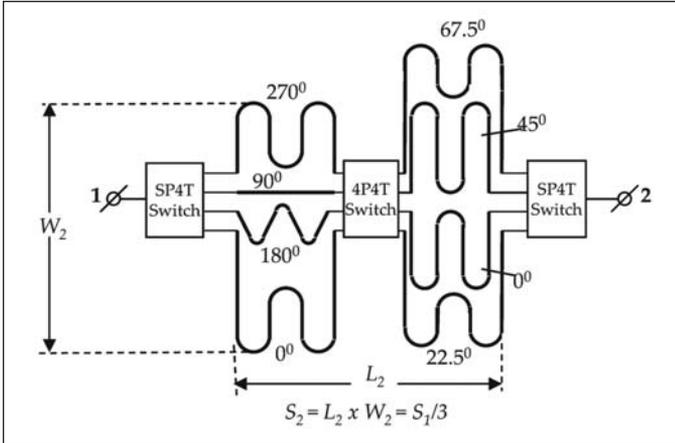


Figure 2f · Four-bit phase shifter configuration using two two-bit phase shifters.

function is determined by the phase difference of signals transmitted through the coupled section of length L and the reference line of length $3L$. The phase shift of the coupled-line section is determined by [3]

$$\cos \varphi_1 = \frac{\left(\frac{z_{0e}}{z_{0o}}\right) - \tan^2 \Theta}{\left(\frac{z_{0e}}{z_{0o}}\right) + \tan^2 \Theta}$$

where $\Theta = 2\pi l/\lambda$ is electrical length of the coupled-line section; z_{0e} and z_{0o} are even-mode and odd-mode impedances, respectively.

The scattering matrix coefficients of the coupled line section are:

$$S_{11} = S_{22} = -i \frac{(r^2 - p^2 + 1) \sin 2\Theta}{2(\rho \cos 2\Theta + r) + i \sin 2\Theta (1 - r^2 + \rho^2)}$$

$$S_{12} = S_{21} = \frac{2(r \cos 2\Theta + \rho)}{2(\rho \cos 2\Theta + r) + i \sin 2\Theta (1 - r^2 + \rho^2)}$$

where

$$r = \frac{z_{0e} + z_{0o}}{2}, \quad \rho = \frac{z_{0e} - z_{0o}}{2}$$

The matching condition ($S_{11} = 0$) for the coupled-lines section is

$$z_0 = \sqrt{z_{0e} \times z_{0o}}$$

where z_0 is the characteristic impedance of the coupled section.

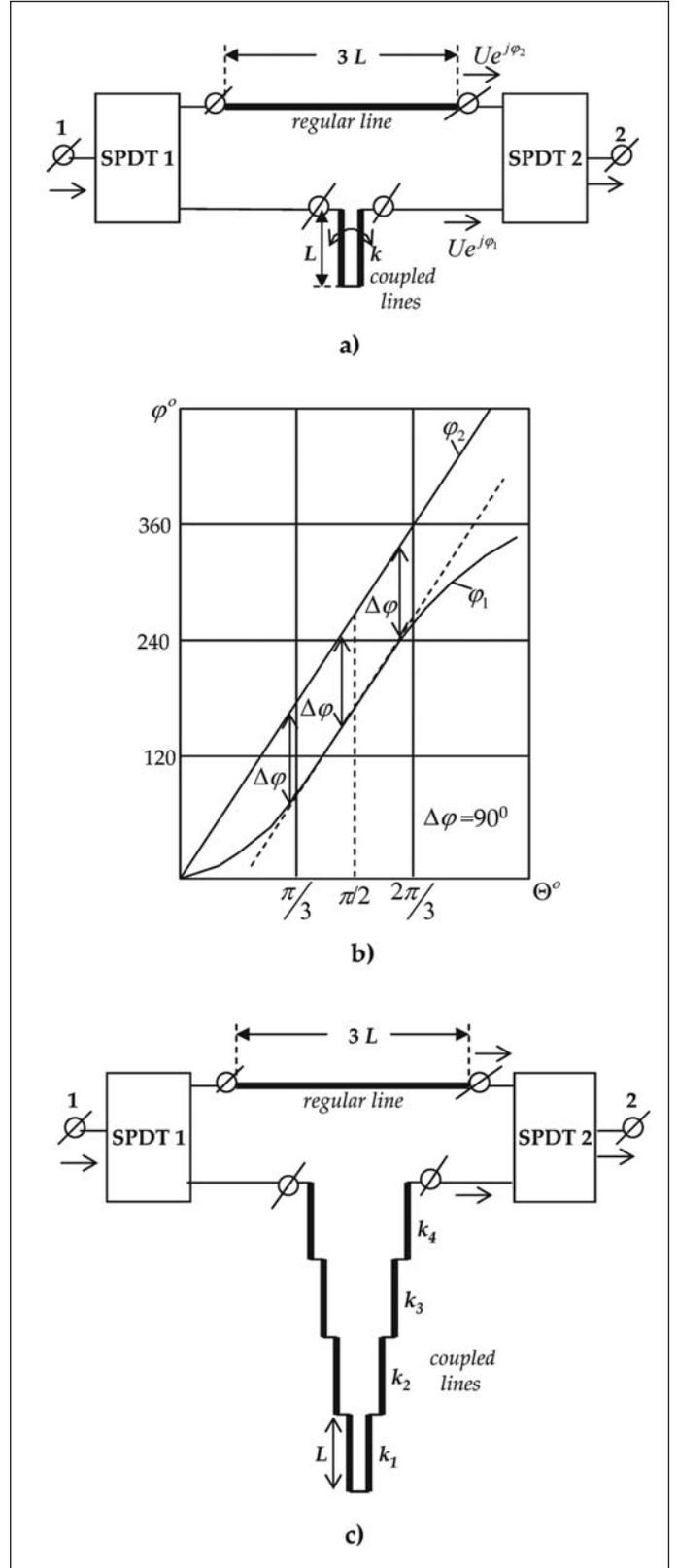


Figure 3 · Switched-line phase shifter with regular and coupled line sections, which maintains nearly constant phase shift over an octave bandwidth.

PHASE SHIFTERS

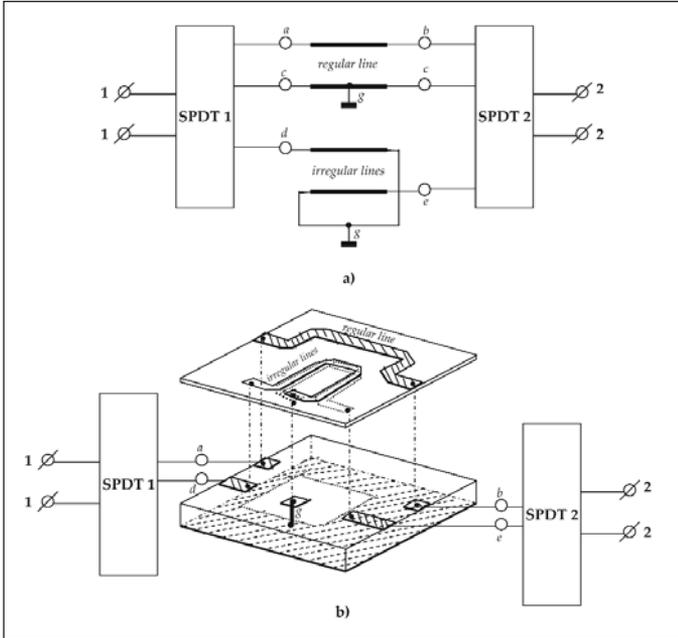


Figure 4 · Switched-line phase shifter with regular and irregular line sections.

The coupling coefficient for the mid-band operating frequency is

$$k = \frac{z_{0e} - z_{0o}}{z_{0e} + z_{0o}}$$

In the octave band, this section provides a nearly constant phase shift $\Delta\phi = 90^\circ$ with respect to the regular line with electrical length 3Θ (see Fig. 3b). For z_{0e} / z_{0o} , phase shift is equal 90° within $\pm 4.8^\circ$ for frequency ratio 2.27:1. For multi-octave operation, the plurality of sections interconnected in a cascade can be used (see Fig. 3c). It is a cascade of coupled sections of equal lengths (one quarter-wavelength at the center operating frequency) and different coupling coefficients ($k_1 \neq k_2 \neq k_3 \neq k_4$) [14].

Print transmission lines in phase shifters can be classified as regular or irregular [3]. The term “irregular line” will stand for coupled conductors with strong magnetic coupling, with minimum influence of the RF ground plane on the parameters of the line (ideally, the absence of ground plane in the coupling area). Strong magnetic coupling is realized without magnets or ferrites [3]. Figure 4 shows a switched-line phase shifter which includes a regular reference line and an irregular line. The irregular line [3, 15] includes coupled conductors with strong magnetic coupling which is realized without magnets or ferrites. In irregular lines, strong magnetic coupling between the lines provides for miniature dimensions and an increased bandwidth [3]. This coupling is characterized by the coefficient of magnetic coupling, k_m . The strong magnetic cou-

pling allows for the small length of the irregular lines. Figure 4 illustrates a circuit where the output port of the first coupled conductor is electrically connected to the diagonal end of the second coupled conductor and DC-coupled to ground. The segment providing the diagonal connection should be as short as possible. The RF ground has to be apart from the irregular line and close to the appropriate input/output lines, that is, there should be no RF ground plane in the area of coupled conductors. The electrical length of the irregular lines is equal to the electrical length of the regular line. The physical length of the irregular lines $l_i = (0.02...0.08)\lambda_i$ depends on the coefficient of magnetic coupling k_m . In Figure 4, regular and irregular lines are printed on a thin Kapton substrate [3], which is connected to the base dielectric substrate Duroid 5880. At 40% frequency band, this phase shifter provides a phase shift equal to $180^\circ \pm 5^\circ$.

Figure 5 illustrates different configurations of the reflection-type phase shifter. In the phase shifter shown in Figure 5a, the two output ports are terminated with voltage variable capacitors to ground. The divider splits the input signal of equal amplitude with a phase difference of 90° . Then the signals are reflected from capacitors back to the hybrid and combined at the output port 2. If the magnitudes and the angles of reflection signals are equal, there will be two reflection signals that are equal in amplitude and phase quadrature. These signals will combine at the isolated port 2 and cancel at the input port 1. This reflection-type phase shifter provides a voltage variable phase shift of between 0° and close to -180° . The power divider including the two-branch hybrid and two reflected loads with shunt diodes $D1$ and $D2$ is shown in Figure 5b [15]. An input signal is divided by the quadrature divider among the two ports of the hybrid. The diodes are biased in the same state (forward or reverse biased). The input signal is divided into two quadrature components with equal amplitudes on the output ports. Turning the diodes ON or OFF changes the total path length for both reflected waves by $\Delta\phi$, producing a phase shift of $\Delta\phi$ at output 2.

The structure provides a wide bandwidth, depending on the bandwidth of the quadrature hybrid itself. Figure 5c illustrates a reflection-type phase shifter which uses a divider/combiner based on the Lange coupler and varactor diodes $D1$ and $D2$. The ideal varactor diode is a variable capacitor with capacitance changing as a function of the DC bias. Capacitance can be controlled as a function of the reverse voltage applied to the PIN junction. The input signal is divided by the coupler and directed to two branches that are terminated with varactor diodes $D1$ and $D2$, changing the phase of each signal equally. The reflected signals are then re-combined and are in phase at the output port. The reflected signals at the input port are out of phase and cancel each other. The phase shift pro-

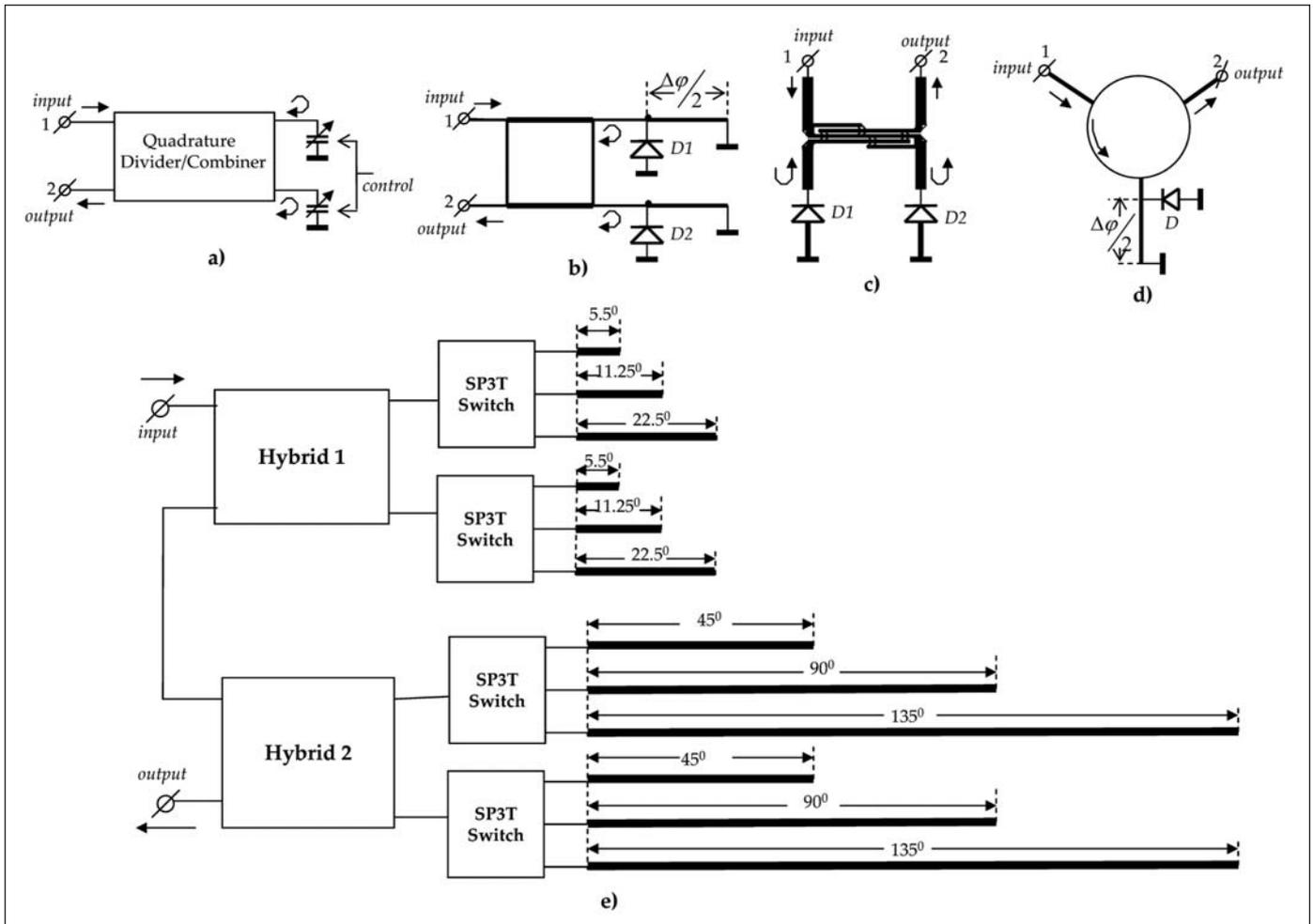


Figure 5 · Various configurations of reflection-type phase shifters.

vided by this circuit is equal to the reflection phase shift provided by a single varactor. To decrease phase shifter insertion loss, GaAs varactor diodes with high Q -factor can be used. Varactors with higher tuning sensitivity provide a higher range of phase shift but have more amplitude variation. Varactors with lower tuning sensitivity and less phase control have lower loss and better amplitude linearity. Figure 5d illustrates the reflection-type phase shifter of the circulator type. The phase shift of this phase shifter is

$$\Delta\phi = \frac{2\pi\Delta l}{\lambda}$$

where Δl is twice the transmission line length. It has been reported by Garver [16] that a circulator having 20 dB isolation gives $\pm 22.8^\circ$ maximum phase error and 30 dB isolation gives $\pm 7.2^\circ$ maximum phase error.

The switched-line reflection phase shifter (Fig. 5e) is based on reflect stubs (open-end transmission lines) that

are switched using SP3T switches. Separation of incident and reflected signals is realized by quadrature hybrids [3], such as the 3-dB branch-line couplers or Lange couplers. The input signal is divided into two quadrature components with equal amplitudes on the output ports. These two signals are reflected from one of the three opened stubs and recombined in phase on the normally decoupled port.

Practical phase shifter design faces three problems. One is associated with size, the second with insertion loss, and the third with cost. Selection of the type of phase shifter depends on system configuration and the RF power level. An ideal phase shifter should have low insertion loss, acceptable phase accuracy, and minimum amplitude variation. For an active antenna array, the accuracy of phase and size of the phase shifter are more critical than the insertion loss because the signal power is amplified after the phase shift. The design trade-offs for the phase shifters are insertion loss, balance between phase states, and phase accuracy. Phase shift linearity and max-

imum value can be increased by utilizing the multi-section approach, but cost, size and insertion loss of this approach will be higher. Low cost PIN diodes have parasitic elements which adversely affect their performance. As a result, these diodes are far from ideal. In the digital design, as total phase shift increases, total accuracy generally decreases. This results from the cumulative effect of multiple internal reflections in the unit. Larger phase shifts tend to require more elements, which in turn leads to higher cost and complexity. While the differential phase shift tends to be broadband, it can be difficult to balance the insertion loss between the states.

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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 textbook, over 50 articles, and 20 patents. His latest book is *Passive RF and Microwave Integrated Circuits*, 2004, Elsevier. He is listed in the encyclopedias *Who is Who in the World*, *Who is Who in America*, and *2000 Outstanding Scientists*. Dr. Maloratsky may be contacted at: lmaloratsky@cfl.rr.com

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