JACK BROWNE | Technology Contributor

When Time Delays Make More Sense Than Phase Shifts

The differences between RF/microwave phase shifters and delay lines are actually quite slight.

Phase shifters and delay lines are commonly used components in many high-frequency systems, included for their signal-altering capabilities. Although a delay in the phase or the timing of a signal are essentially the same thing, phase shifters and delay lines are designed with different goals in mind: to provide signal adjustments in the frequency and time domains, respectively, over a design frequency range.

Phase shifters are usually designed for changes in insertion phase of as much as 360 deg., or one wavelength, at a maximum frequency of interest. When a greater amount of phase shift or delay is required at a particular frequency, the solution lies in an RF/microwave delay line, which is specified in terms of the delay time, rather than the phase shift, at a frequency of interest.

In a phased-array antenna, for example, the different phases of multiple antenna elements must be adjusted so that the signals radiated by the different elements add in phase, providing the functionality of a physically much larger conventional antenna. Phase shifters provide the means of making phase adjustments to the antenna elements and their individual amplifiers or transmit/receiver (T/R) modules, so that signal contributions of each antenna element add in phase. Similarly, phase shifters can be used for antenna beam steering in a wide range of systems.

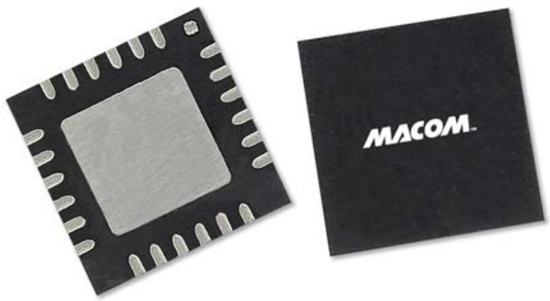
Phase shifters are passive components and, in fact, some passive components such as baluns and hybrid power combiners/dividers will also add a phase shift to a circuit. A quadrature hybrid divider, in theory, divides an input signal into two output signals that are 90 deg. apart in phase and 3 dB lower (typically more) in amplitude than the starting signal. Unlike a phase shifter, this 90-deg. shift in phase is independent of frequency. Ideally, a phase shifter changes the phase of an input signal without changing its amplitude (typically less).

Phase shifters can be implemented in a number of different ways, with the most straightforward being to extend the transmission path length. In doing so, the phase of the nominal or reference phase of a circuit or system is increased. The amount of phase shift achieved by the additional length of transmission line will be a function of the velocity of propagation (V_p) of the transmission medium.

In stripline, for example, in which a metal conductor is surrounded by dielectric material, EM propagation occurs entirely within the dielectric material, and V_p is the same for all signal traces—no matter how wide or where they are located. In microstrip, however, in which the metal conductor is exposed to the air, part of the EM propagation occurs in the air. The dielectric constant of a circuit is a combination of the dielectric circuit-board material and the air. For microstrip, V_p depends on the width of the trace and the height of the trace above the ground plane, and a phase shifter must be designed with attention to these details.

A simple phase shifter can be designed with a number of switchable transmission-line paths of different lengths, with a reference signal path representing a 0-deg. phase shift. Additional, longer signal paths are typically fabricated in quarter-wavelength ($\lambda/4$) increments of a design frequency, such as 90, 180, and 270, and 360 deg. By switching to the different paths, a phase shift proportional to the additional transmission-line length will be achieved. Switching can be accomplished by using semiconductor diodes (such as PIN, Schottky, or varactor diodes) to select a desired phase shift.

Low-frequency (below UHF) phase shifters are typically realized with lumped-element circuit approaches to reduce the size of the transmission paths that would otherwise be required at those lower frequencies. In general, switched line, loaded line, and reflection approaches are commonly used to



1. RF/microwave phase shifters come in many packages, including 4-b digital models in 4 × 4 mm PQFN plastic SMT packages. (Photo courtesy of MACOM)

create phase shifters, although a number of novel approaches have also been applied—for example, separating input signals into in-phase (I) and quadrature (Q) signal components, and recombining the I and Q signals in different ways to achieve broadband phase shifts.

Most recently, microelectromechanical-systems (MEMS) technology has been used to create RF/microwave phase shifter in semiconductor-sized circuits in which the different propagation paths are selected by mechanical switches. MEMS-based phase shifters, due to their mechanical nature, are particularly resistant to interference from surrounding EM fields and have been candidates for phase-shifting applications in hostile operating environments. Standard semiconductor processes, such as GaAs pHEMT technology, have also been used to implement RF/microwave phase shifters that can be housed in miniature surface-mount packages for ease of mounting on high-frequency circuit boards.

An RF/microwave phase shifter is an analog circuit, no matter which design method is used to achieve the phase shift, although both analog and digital control methods have been used to control the phase of a phase shifter. Analog phase shifters are usually operated by means of a control voltage and the changes in phase are usually continuous across the total phase-control range and frequency range. In contrast, digital phase shifters use different numbers of bits to select one of a number of discrete phase states.

For example, a 4-b phase shifter, with its 16 different phase states, will provide control of a total 360-deg. phase range in 22.5-deg. steps. A 6-b phase shifter, with 64 different phase states, will divide the 360-deg. phase-shift range into 5.625-deg. steps for finer resolution. Although not always the case, better phase accuracy of each step is usually achieved by digital control with a larger number of bits.

In terms of physical size, RF/microwave phase shifters can be as small as the MEMS or semiconductor-based chips that are housed in miniature plastic surface-mount-technology (SMT) packages *(Fig. 1)*, or much larger components with

2. Larger coaxial RF/microwave phase shifters can be designed with added features to simplify an application, such as a digital readout of phase. (Photo courtesy of ARRA)

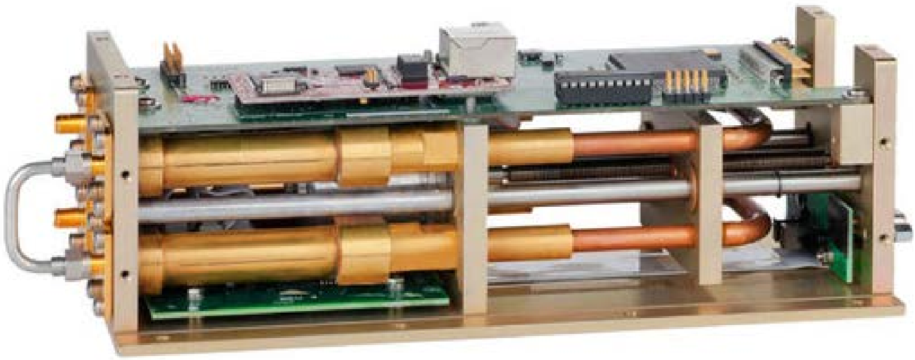
add-on features such as digital readouts of phase *(Fig. 2)*. RF/microwave phase shifters are available from a larger number of suppliers in many forms, including as packaged chips; in coaxial packages with a variety of different connector types; and even as subassemblies with filters and amplifiers to offset the signal losses caused by the phase shifters.

CREATING A DELAY

As noted earlier, when a total delay of more than one wavelength (360 deg.) is needed at a target frequency, as might be the case with many radars, EW systems, and test-and-measurement applications, an RF/microwave delay line provides a practical means of achieving those longer delays. In a radar system, for example, a delay line makes it possible to perform signal analysis on a large number of acquired pulses by delaying some of the pulses in time. In a communications system with multiple clock sources, delay lines make it possible to introduce delays to a faster clock to synchronize its timing with a slower clock. Delay lines are also useful for amplifier linearization,

As with phase shifters, delay lines employ a number of different technologies in an attempt to create long transmission paths in small spaces. One of the simplest delay lines is a coaxial cable—although the problem with using coaxial cables at delay lines, especially at lower frequencies (longer wavelengths)—is the length and physical size of the cable coil required for any kind of long delay time. Delay lines have also been based on creating long transmission-line paths on microstrip circuits, using winding circuit configurations to achieve the longest signal paths (and delays) in the smallest size possible. Multiple microstrip circuits can be cascaded to increase the length of the delays.

The time delays possible with a given delay-line technology



3. Delay lines based on trombone delay structures can achieve extremely long delay times with low loss over wide frequency ranges. (Photo courtesy of Colby Instruments)

depend on the propagation velocity of the delay line circuit medium, such as the crystal or glass substrates used to fabricate surface-acoustic-wave (SAW) or bulk-acoustic-wave (BAW) delay lines. In these components, RF/microwave signals are converted to acoustic signals which experience significant delays across the substrate materials, enabling the components to achieve long delay times in smaller packages (although they are limited to RF and lower microwave frequencies).

Delay lines have been implemented as analog and digital circuits and as mechanically tuned structures, such as mechanical trombone structures that are capable of long delays over extremely broad frequency spans *(Fig. 3)*. Trombone delay-line structures have been combined with stepper motors to form programmable delay lines with delays available in high-resolution steps, with as much as 100 ns total delay possible over bandwidths as wide as DC to 18 GHz.

Although the trombone delay-line approach exhibits low loss, even lower loss is possible through a delay-line technology known as RF over fiber. In this method, an RF input signal is converted to an optical signal and transmitted over a fiber-optic link to a receiver which provides the signal delays. The optical signals are then reconverted to RF/microwave signals.

While RF-over-fiber delay lines are more of a subsystems nature, typically packaged in rack-mount enclosures, they are well suited for applications requiring extremely long delay lines but with losses that are considerably lower than with other coaxial or waveguide delay-line design methods. They can be customized to meet specific requirements, such as inclusion of amplifiers to produce signal gain along with the delay.