

Phase Shifters

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Phase Shifters are devices, in which the phase of an electromagnetic wave of a given frequency can be shifted when propagating through a transmission line.

In many fields of electronics, it is often necessary to change the phase of signals.

RF and microwave Phase Shifters have many applications in various equipments such as phase discriminators, beam forming networks, power dividers, linearization of power amplifiers, and phase array antennas.

The major parameters which define the RF and microwave Phase Shifters are:

- frequency range,
- bandwidth (BW),
- total phase variance ($\Delta\phi$),
- insertion loss (IL),
- switching speed,
- power handling (P),
- accuracy and resolution,
- input/output matching (VSWR) or return loss (RL),
- harmonics level.

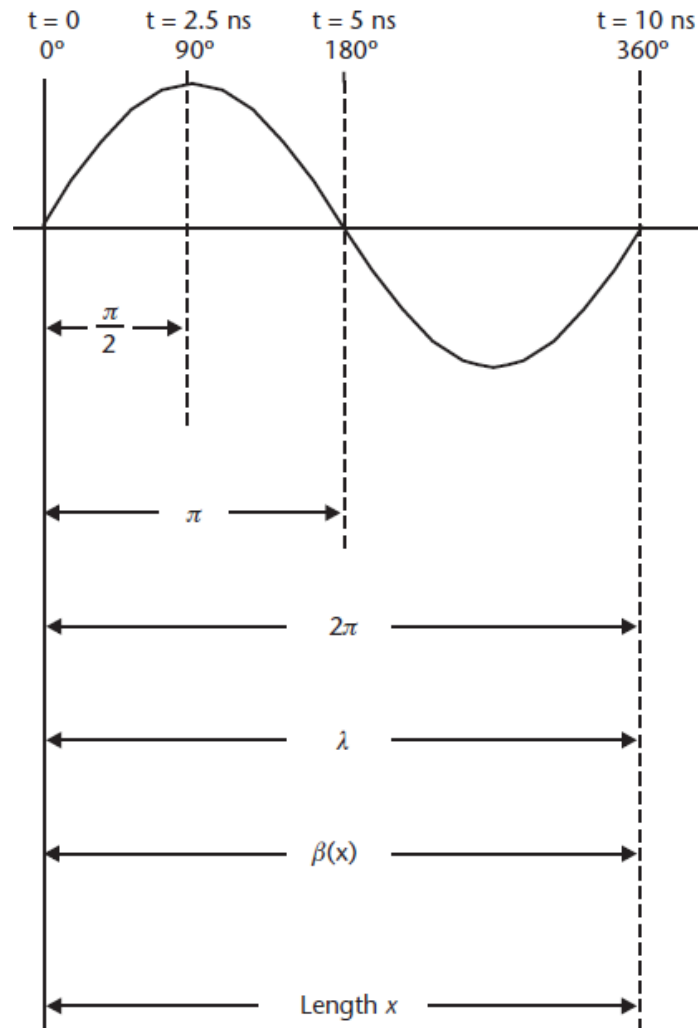
Relation between Propagation Constant, Phase Shift, Delay, and Wavelength

In a transmission line the **Propagation Constant** is a complex number having two parts:

- the real portion is the **attenuation constant** (α , neper per unit length)
- the imaginary portion βx is called the **phase constant** (β , radians per unit length).

- The **attenuation constant** α determines the way a signal is reduced in amplitude as it propagates down the line, while the **phase constant** β shows the difference in phase between the voltage at the sending end of the line and at a **distance x**.
- The phase constant βx shows the phase shift of the voltage (or current) at a point located at a distance x along a transmission line with respect to the sending voltage (or current).
- A phase shift of 360° (or 2π radians) equals one wavelength and, as shown in figure below, marks the distance between successive points on the waveform (such as zero crossings).
- The wavelength λ is the distance x required to make the phase angle βx increase by 2π radians.

$$\lambda = 2\pi / \beta$$



Relationship between Degrees ($^{\circ}$), Radians (2π), Phase Shift (β), and Wavelength (λ)

From the figure above can be stated that a **Phase Shift** may also be seen as a **Delay**. The relation between the Phase Shift and the Time Delay is given by:

$$\text{Time Delay (seconds)} = [\text{Phase Shift } (^{\circ})] / [360 \times \text{Frequency (Hz)}]$$

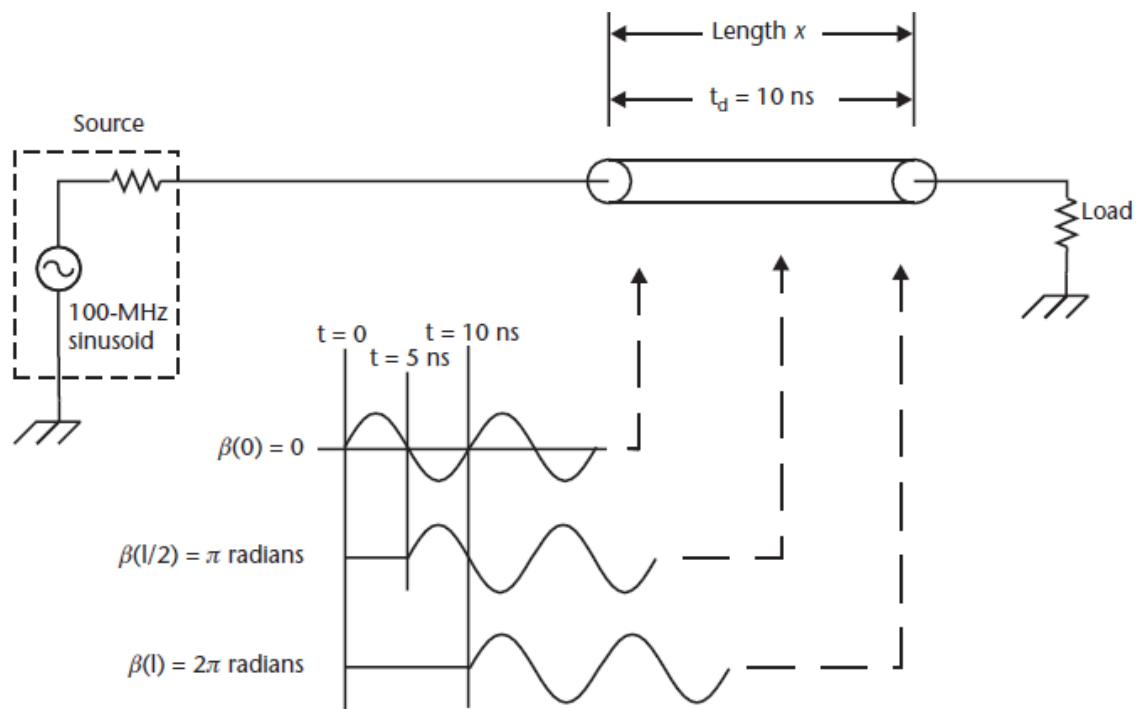
- The time delay is proportional to the inverse of velocity V_p .

The amount of delay a transmission line introduces per distance x is:

$$\text{Time Delay} = x / V_p = (\beta x / \omega)$$

- Group delay is the average delay time that a specified narrow range of frequencies experiences when passing through a circuit.
- Group delay is proportional to the rate of phase shift at each frequency of interest.

$$\text{Group Delay (seconds)} = [1 / 360] \times [\Delta\phi / \Delta f]$$



- For a stripline, the velocity of propagation (and thus the delay per distance x) is the same for all traces, but for microstrip the velocity (and thus the delay) depends on the trace's width and height above the ground plane, making this the fundamental difference between stripline and microstrip designs.

A microwave Phase Shifter is a circuit which gives a preset phase shift amount to a high-frequency signal and is normally configured by combining several transmission lines, a switch circuit, or some similar circuits.

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 semiconductor control elements used in analog Phase Shifters are varactor diodes.

Varactor diode operates in a reverse-biased condition providing 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.

Most usual methods to implement Phase Shifters are based on switched line, loaded line, and reflection theories.

The **Switched-Line** approach is the most straightforward approach because it uses the simple time delay difference between two direct paths to provide desired phase shift. The switching elements in digital phase shifters are: mechanical switches (or relays), PIN diodes, Field Effect Transistors (FET), or microelectromechanical systems (MEMS).

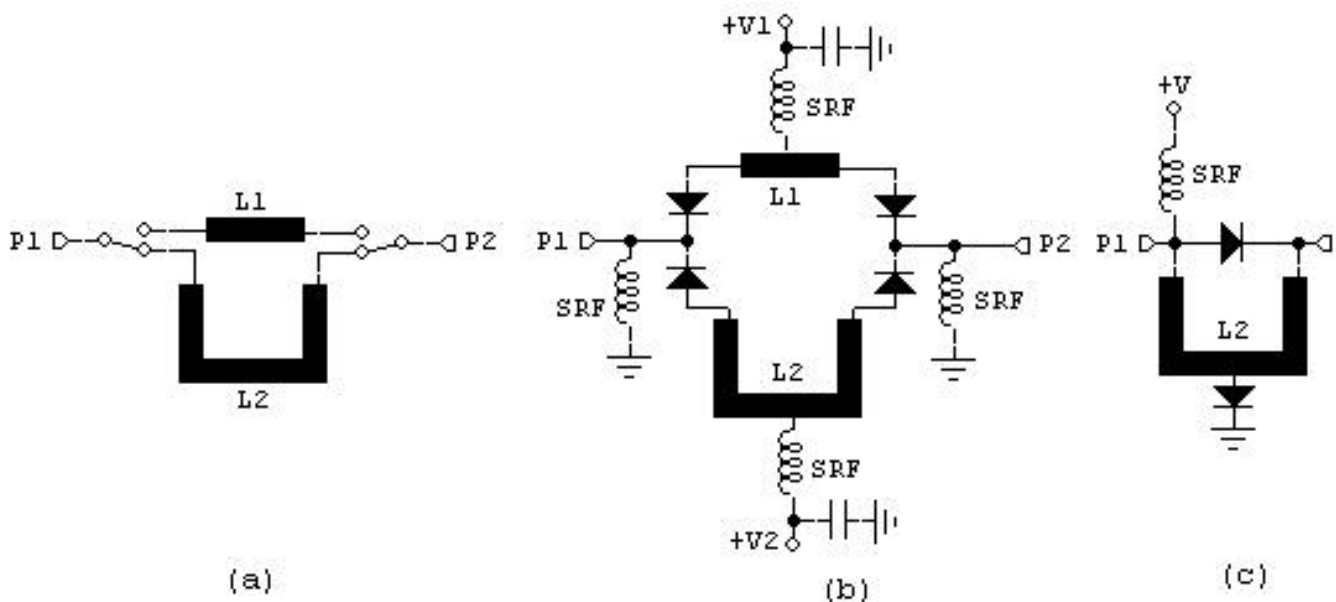
PIN diodes are commonly used in Phase Shifters due their high-speed switching time, low loss, and relatively simple bias circuits, which provides changes of PIN resistance approximately from 10 kilo-ohms to 1 ohm.

The PIN diode switched line Phase Shifters can be classified as follow:

- Type of the 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);

The standard switched-line Phase Shifter is using switched transmission line segments, getting different path length and determining in this way the amount of phase shift.

- The simplest switched-line Phase Shifter is dependent only on the lengths of line used. One of the two transmission 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, getting a wideband frequency range of the circuit.
- The phase shift created is dependent only by the length of the transmission lines, making the Phase Shifter very stable over time and temperature.
- PIN diodes may suffer for insertion loss tolerance or peak power capability, but both characteristics don't affect the phase shift.



Switched-line Phase Shifters

Figure above illustrates the schematics of the conventional switched-line Phase Shifter with RF input P1 and RF output P2.

Schematic (a) use two SPDT mechanical switches (or relays), when figure (b) use four PIN diodes, and two transmission lines L1 and L2. Only one arm should be ON at a time.

- Typically, to avoid the phase errors the isolation of the switches must exceed 20dB in the required frequency band.
- Insertion loss of the switched-line Phase Shifter is equal to the loss of the SPDT switches plus the line losses.
- By switching the signal between two pre-determined lengths of transmission lines it is possible to realize a specific phase shift ($\Delta\phi$) at a given frequency.

$$\Delta\phi = 2\pi \times (\Delta L / \lambda)$$

where $\Delta\phi$ is the phase shift, ΔL is the difference between the physical lengths of the delay line (L2) and the reference line (L1), and λ is the guide wavelength.

- The phase shift value deviates linearly from the intended value as the frequency of the signal deviates in either direction from the center (nominal) frequency.
- Switched-line Phase Shifters generally are used for 180° and 90° phase shifts. When path L2 is a half wavelength ($\lambda/2$) longer than path L1, switching from path L1 to path L2 introduces an increased phase delay of 180°. So, to get a 180° phase shift the required physical length difference should be $\Delta L = \lambda/2$.
- In a practical design resonance could appear in the OFF line when the line length is a multiple of $\lambda/2$, and the phases will interfere in a way to reflect much of the incoming power back to the input port. Thus, both lengths (L1 and L2) must not be multiples of $\lambda/2$. The resonant frequency will be slightly shifted due to the series junction capacitances of the reversed biased diodes, or of the parasitic capacitances of the SPDT mechanical switches.
- The lengths L1 and L2 must be carefully selected to avoid phase errors, high return loss, and high insertion loss.

To reduce the number of PIN diodes could be used the circuit in figure (c), replacing the reference L1 line with a series PIN diode.

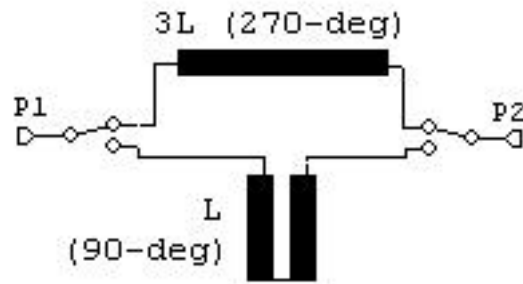
In this circuit, for the 180° phase shifting, both PIN diodes are in the OFF position, and the RF signal passes through line L2 with $\lambda/2$ length, providing a 180° phase shift.

The shunt diode is placed at the middle of L2, at $\lambda/4$ wavelength from its ends.

In 1958 Bernard Schiffman published for the first time a Phase Shifter using a $\lambda/4$ wavelength coupler section which provides flat wideband phase shift response.

The **Schiffman Phase Shifter** shown in the picture below use a switched-line 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.

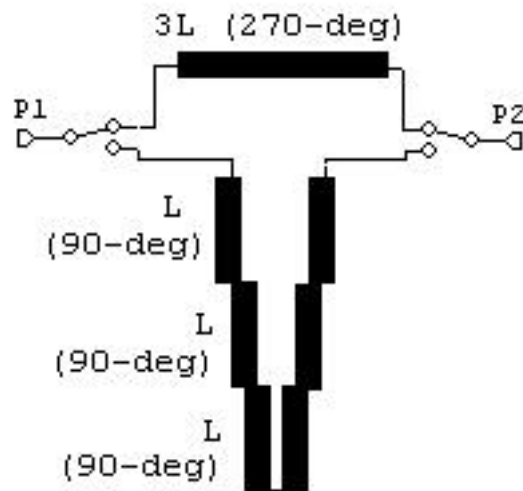
Phase shift function is determined by the phase difference of signals transmitted through the coupled section of length L and the reference line of length $3L$.



Schiffman Phase Shifter

The contribution of the Schiffman Phase Shifter is that the phase difference between a quarter-wave coupled section, compared to a $3/4$ wave straight section, would provide a nearly flat 90° phase differential.

For multi-octave operation, the number of coupled sections interconnected in a cascade can be used, as shown in the picture below.



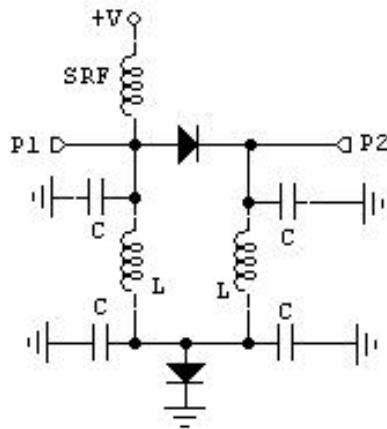
Multi-octave Schiffman Phase Shifter

It is a cascade of coupled sections of equal lengths (one quarter wavelength $\lambda/4$ at the center operating frequency), but using different coupling coefficients ($k_1 \neq k_2 \neq k_3$)

At low frequencies, to minimize the dimensions of the circuit, the quarter-wavelength $\lambda/4$ segments of the Phase Shifter delay line could be substituted with equivalent lumped element circuits as shown in the figure below.

Each sine-wave component has its phase shifted by reactances within a circuit.

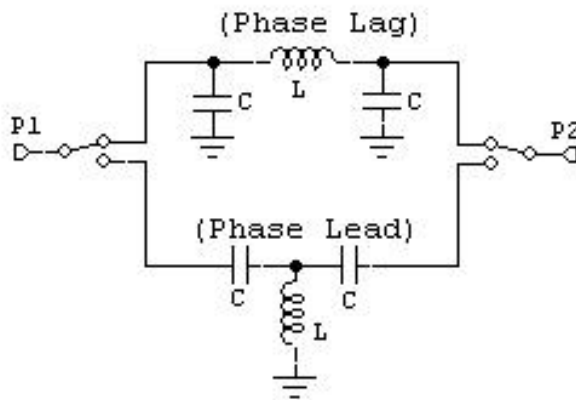
The **lumped element** configuration of the 180° Phase Shifter (figure below) can be recommended for applications for low frequencies (HF) up to UHF ranges.



Lumped element Phase Shifter

- A single-pole RL, RC, circuit contributes up to 90° phase shift per pole, and to get 180° phase shift, at least two poles must be used.
- For example, in oscillator design, because 180° of phase shift is required for oscillation, at least two poles must be used.
- Phase shift in oscillator situation determines the oscillation frequency because the circuit oscillates at whatever frequency accumulates a 180° phase shift.
- The sensitivity of phase to frequency, $d\phi / d\omega$, determines the frequency stability.
- In the region where the phase shift is 180° , the frequency of oscillation is very sensitive to the phase shift. Thus, a tight frequency specification requires that the phase shift, $d\phi$, be kept within exceedingly narrow limits for there to be only small variations in frequency, $d\omega$, at 180° .

The 180° phase shift is commonly designed using **switched Low-Pass and High-Pass** topology as shown in the figure below:



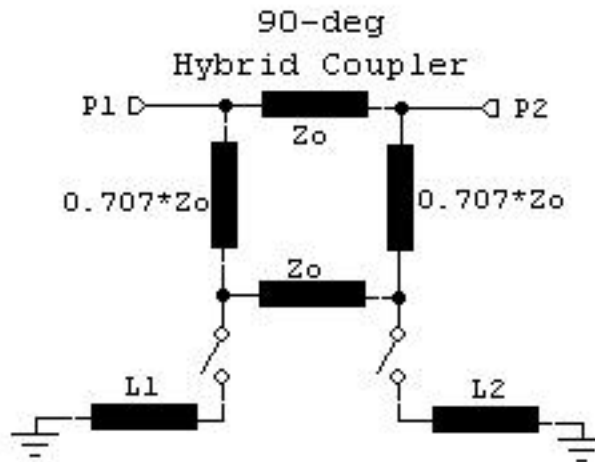
$$C = -\frac{\tan\left(\frac{\phi}{2}\right)}{\omega \cdot Z_0} \quad L = -\frac{Z_0 \sin(\phi)}{\omega}$$

Switched Low-Pass and High-Pass Phase Shifter

- The cut-off frequencies of the Low Pass and High Pass filter networks must be outside of the phase shift band for this scheme to work.
- Note that for higher frequencies the phase shift of LP-HP networks gets a nearly flat response, which is not possible from a switched line Phase Shifter.
- The equations for L and C for PI-network with characteristic length ϕ are given.

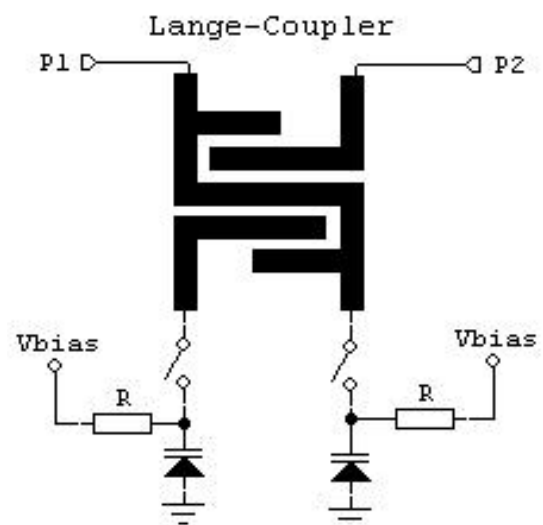
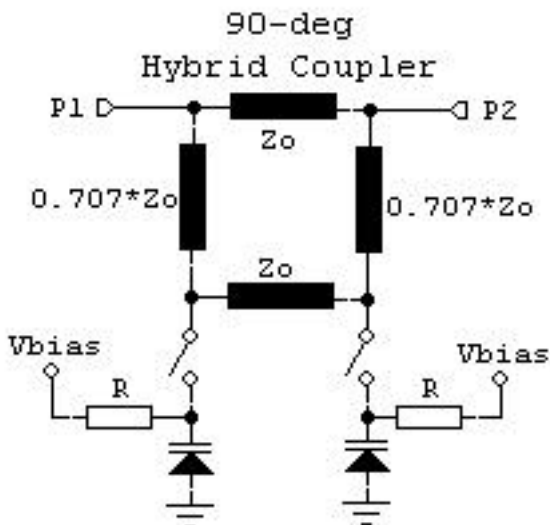
The **Quadrature Phase Shifter** is a load-line Phase Shifter sometimes named **Reflective Phase Shifter**.

This is mainly a quadrature coupler which splits the input signal into two signals 90° out of phase. These signals reflect from a pair of switched loads, and combine in phase at the phase shifter output, as long as the loads are identical in reflection coefficient (both magnitude and phase).



Quadrature Phase Shifter using switched-lines

- The quadrature Phase Shifter can be used to provide any desired phase shift.
- Ideally, the loads should present purely reactive impedances, which can range from a short circuit to an open circuit or anything in between.
- This structure provides a bandwidth of up to an octave, depending on the bandwidth of the quadrature coupler itself.
- The coupler can be a Lange Coupler, a Hybrid Coupler, or a Rat-Race Coupler on microstrip, or an overlay coupler in a stripline circuit.
- The main type of reflective Phase Shifter uses switched-line lengths either by using a PIN diode switch or by a variable reactance (e.g. varactor) to alter electrical length.



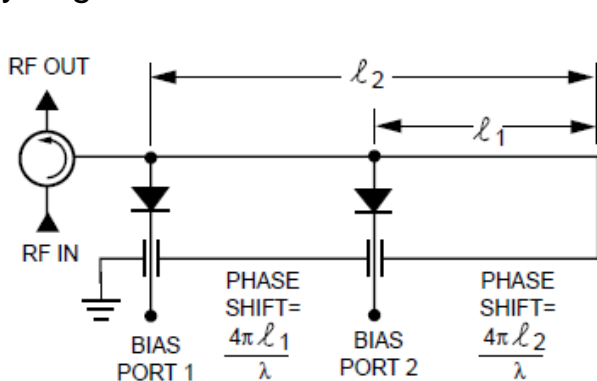
Quadrature Phase Shifters (Hybrid and Lange) using varactors

The quadrature Phase Shifters in the figure above uses a 90° hybrid coupler (left picture), or a Lange coupler (right picture). Instead of switched-lines the circuits use variable reactances.

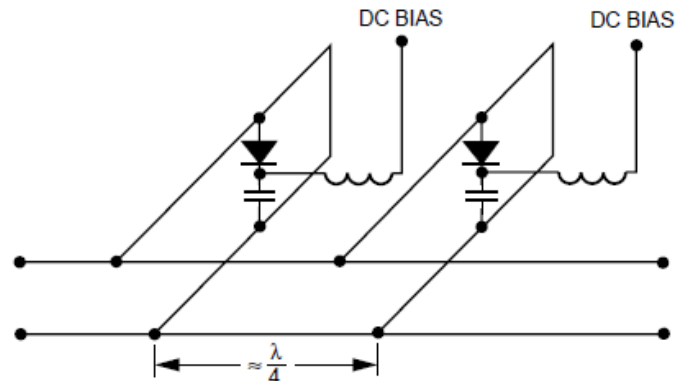
- A variable reactance is in effect a variable electrical length; therefore, using a variable reactance such as a varactor we can form a variable Phase Shifter.
- The varactor components act as ideal, lossless reactive loads with reflection coefficient from 0° (open circuit - zero varactor capacitance) to -180° (short circuit - infinite varactor capacitance).
- Instead of a varactor a variable inductor can be used. For an ideal variable inductor, the phase changes from -180° to 0°. If both were connected in series, the ideal result would be a 360° phase shift change.
- By resonating the capacitance of the varactor with a series inductor, the phase control range can be significantly increased, up to an ideal 360° phase shift change.
- One significant benefit of this configuration is the fact that the input and output impedance matching is preserved, although the coupler is terminated with reactive loads. In other words, the coupler serves as an impedance isolator.

Other Phase Shifter circuits, as shown in the pictures below, are usually more expensive (circulator cost) or require more diodes.

The loaded line circuit which had been popular in early Phase Shifter designs requires a very large number of diodes.



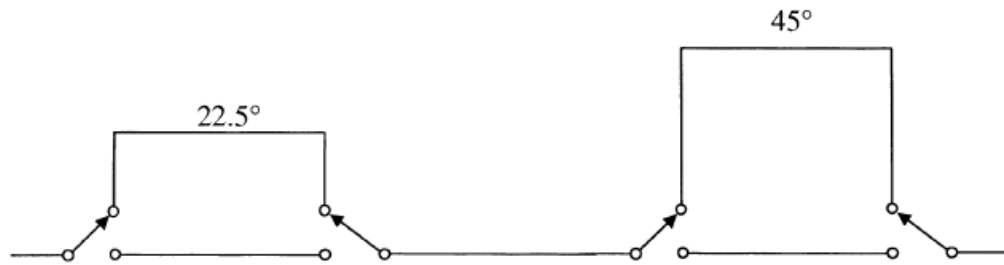
Phase Shifter using Isolator and switched-lines



Phase Shifter using Load-Line

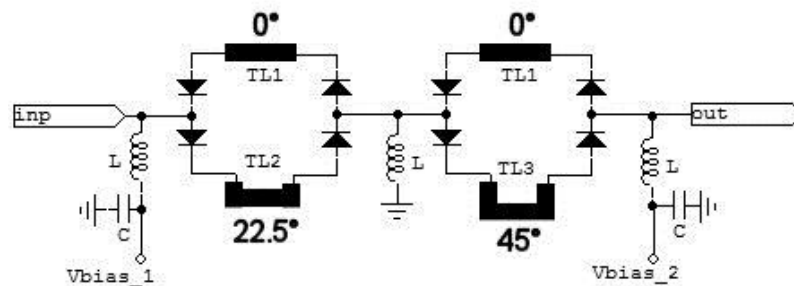
Digital Multi-bit Phase Shifters can be used to vary the phase shift up to 360°.

- Digital Phase Shifters provide a discrete set of phase states that are controlled by two states “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.



2-Bit Phase Shifter using SPDT switches

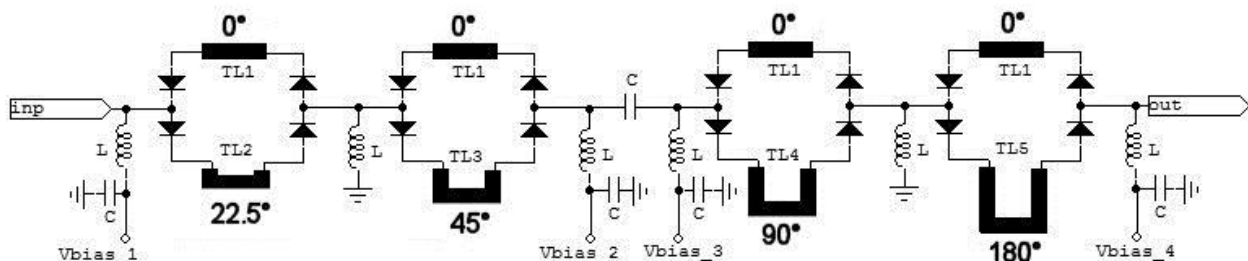
The Phase Shifter in the figure above illustrates an example of a **2-bit Phase Shifter**. This 2-bit phase shifter can get 4 distinct phases: 0° (reference), 22.5° , 45° , and 67.5° . Other lengths (phase shift) for the transmission lines could be used if is required. The 2-bit phase shifter could be implemented using PIN diodes:



2-Bit Phase Shifter using PIN diodes and delay transmission lines

- The inductors **L** are RF chokes with high reactance at working frequency, and **C** are capacitors with low reactance at working frequency.
- The DC voltages V_{bias_1} and V_{bias_2} are negative voltages when we want to switch to reference path 0° (TL1), and positive voltages when we want to switch to the delayed paths that use the transmission lines TL2 or TL3.
- The advantage of using positive/negative voltages for biasing the PIN diodes, is that will be necessary only one power supply for each bit.
- Second benefit of using positive/negative voltages is that, when the PIN diodes on the switch-ON path are forward biased, the PIN diodes on the switch-OFF path are reverse biased, which improves the RF isolation on that path.

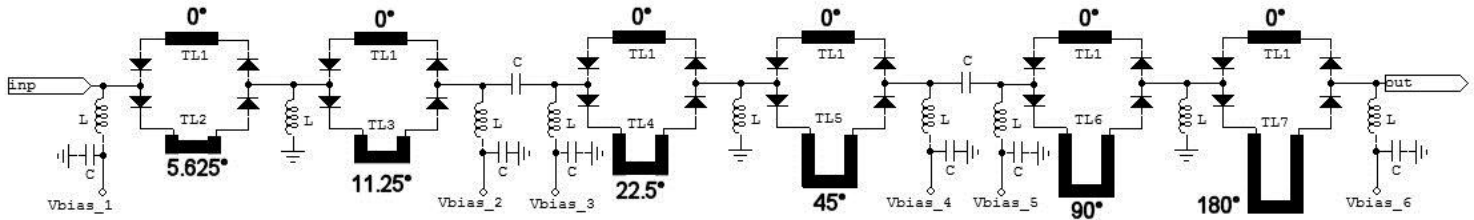
The same approach of using PIN diodes, delay transmission lines, and positive/negative bias voltages could be used to implement a 4-bit phase shifter.



4-Bit Phase Shifter using PIN diodes and delay transmission lines

This 4-bit phase shifter can get 16 distinct phases: from the reference 0° (or 360°) to 337.5° in 22.5° steps.

Moving forward increasing the resolution of the switched lines phase shifters, the same approaches presented above could be used implementing a 6-bit phase shifter:



6-Bit Phase Shifter using PIN diodes and delay transmission lines

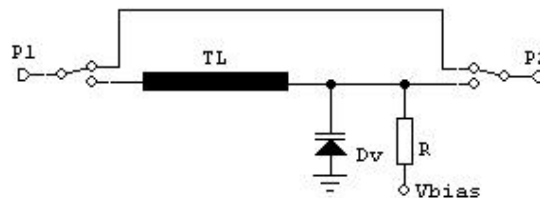
This 6-bit phase shifter covers the entire range from 0° (360°) to 354.375° in 5.625° steps. The phase shifter can get 64 distinct phases.

In the switched delay lines phase shifters presented above, the phase shift (length of the delay lines T2 to T7) follow an ascendant function.

But in reality, the delay lines are arranged in the way that an EM simulator get the most optimized results in terms of phase shift consistency and minimum path loss.

- To minimize phase quantization 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 of the Phase Shifter and greater the insertion loss.

A **Distributed Phase Shifter** is created by adding tunable reactance to a transmission line TL.



Distributed Phase Shifter using a Varactor as tunable reactance

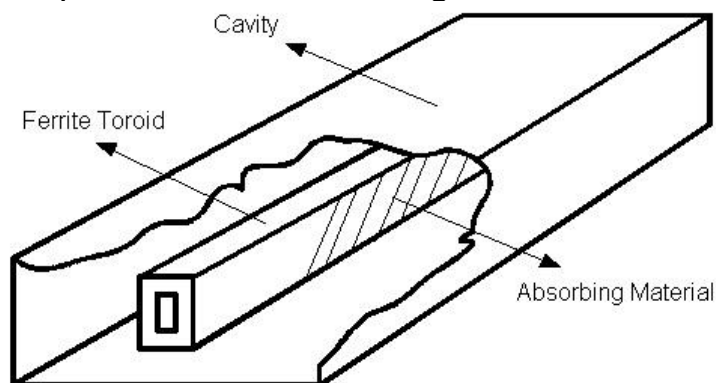
- Adjusting the reactance alters the phase velocity of the signal propagating along the line, varying its electrical length, and therefore the phase shift.
- Changing the phase velocity also changes the characteristic impedance of the transmission line, so an impedance mismatch can occur as the circuit is tuned.
- In general, it should be possible to add both series and shunt tunable reactance to the transmission line to keep an impedance match with tuning;

The majority of distributed Phase Shifters focus on adding tunable shunt capacitances, because tunable inductors are harder to make.

For example ferroelectric varactors, MEMS, and PIN diodes are all capable to add a periodically shunt capacitance as discrete elements to the transmission line.

This capacitance loading makes the distributed Phase Shifter a periodic structure, with a pass-band and a stop-band. The design has to ensure the frequencies of interest fall into the pass-band, keeping the other parameters of the Phase Shifter.

The **Toroidal Ferrite Phase Shifter** employs the use of a toroidal shaped ferrite bar placed in a rectangular waveguide. A drive wire is inserted longitudinally through the center core of the toroid to provide transverse magnetization in the toroid.



Toroidal Ferrite Phase Shifter

- Phase shift values from -180° to $+180^\circ$ is achieved by varying the current in the drive wire, hence varying the biasing magnetic field in the toroid. The magnitude and timing of the current is carefully controlled by sophisticated drive electronics in order to maintain accurate and consistent phase shift values over a wide temperature range.
- This Phase Shifter can operate as an analog device by using a long toroid and varying the phase shift by means of changing the holding current in the drive wire.
- It can also operate as a digital device by magnetically latching the toroid (no holding current) to the various minor hysteresis loops. The amount of phase shift is determined by the magnitude and the time duration of the voltage pulse.
- In applications where fast switching speed is required, the long toroid can be split into smaller sections, each section corresponding to a binary phase bit. In this case each section is magnetized into saturation and is quickly switchable since the volume of ferrite material for each section is significantly smaller.

The Toroidal Phase Shifter is a non-reciprocal type, since the phase shift must be reset between transmit and receive modes.

Phase Shifters in Phased Array Antennas

In **electronically scanned antenna arrays** the Phase Shifters are the devices that allow the antenna beam to be steered in the desired direction without physically repositioning the antenna.

A phased array antenna consists of two or more of radiating elements which are spatially arranged that emit phased signals to form a radio beam.

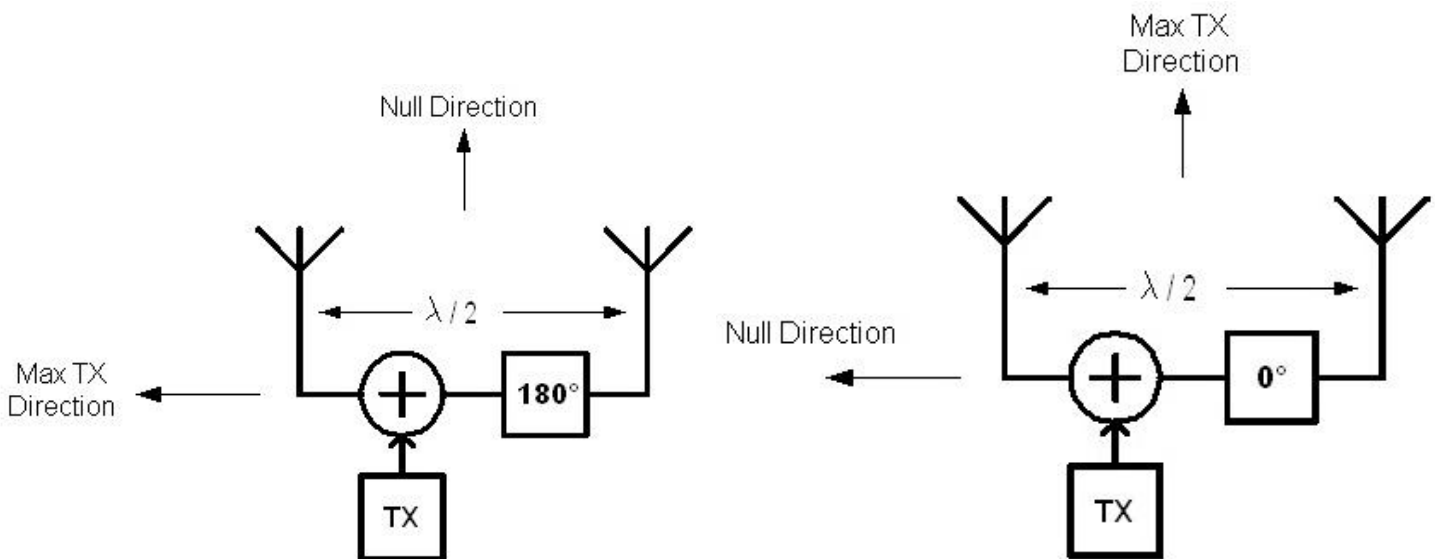
Each radiating element requires a Phase Shifter that applies the necessary phase shift to steer the antenna beam.

When you steer the beam, you adjust the phase of the elements so that individual signals line up at the desired beam-pointing angle (θ). Having phase settings that don't change with frequency helps keeping the beam pointed where you want when you shift frequencies.

- Array beam forming techniques exist that can yield multiple, simultaneously available beams.
- The beams can be made to have high gain and low sidelobes, or controlled beamwidth.
- The simplest way of controlling signal phase is to systematically vary the cable lengths to the elements. Cables delay the signal and so shift the phase. However, this does not allow the antenna to be dynamically steered.

Antenna Beam forming

- In beam forming, both the amplitude and the phase of each antenna element are controlled.
- Combined amplitude and phase control can be used to adjust side lobe levels and steer nulls better than can be achieved by phase control alone.
- A beam former radio transmitter applies the complex weight to the transmit signal (shifts the phase and sets the amplitude) for each element of the antenna array.



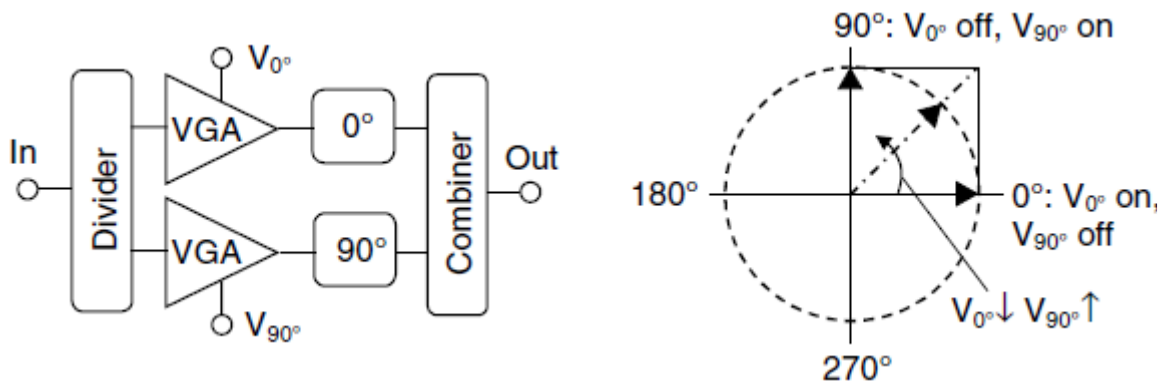
Simple Phase Shift beam forming for Two-Antenna System

Vector Modulator Phase Shifter

Another application of the Phase Shifters is the Vector Modulator.

Vector modulators Phase Shifter structure can cover a phase shift up to 360° .

Figure below shows the diagram of a vector modulator with phase control range of 90° .



Vector modulation with 90° phase control range and its vector diagram

The input signal is divided in two paths with defined phase offsets (usually 90° or 120°), which amplitudes are controlled by variable gain amplifiers or variable attenuators. After generation of phase offset between these two paths, the signals are combined.

Four signal paths with phase offsets of 90° , or three paths with 120° phase offset, can be used for 360° vector modulators.

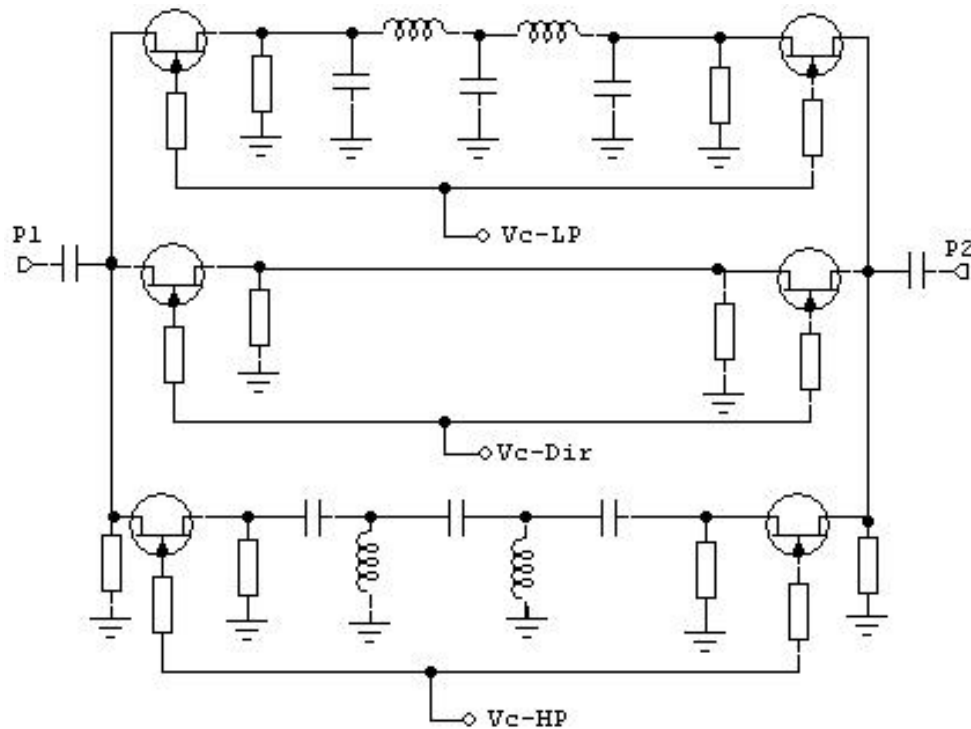
- Every desired phase within the 360° phase control range can be obtained by weighting the amplitudes of the phase paths.
- The amplitude of the amplifiers can be set by analog control voltages, but the amplitude in variable gain amplifiers cannot be controlled without influencing the phase shift.
- In real circuits amplitude control is always associated with a certain phase variation.
- Typically, the amplitude control should be at least 20dB.
- Input and output impedances of the circuit should be constant vs amplitude control, otherwise phase variations can appear when more stages are connected.
- The gain should be a linear function of voltage and ideally the phase deviation across the assumed gain range should be equal to zero.

In the passive vector modulator approach shown in the picture below, the amplitudes of vectors are controlled by cold FET's, used as variable resistors.

The 120° phase offset of the signal is generated by High-Pass and Low-Pass networks, and a 0° direct path.

Varying the control voltages V_{c-LP} , V_{c-dir} and V_{c-HP} the amplitude of the signal paths can be controlled.

In the same time the control voltage is used to compensate for phase errors introduced by the FETs vs gain control.



Passive Vector Modulator Phase Shifter type

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