CHAPTER - 5

PIN DIODE RF PHASE SHIFTERS

NOTES

MICROWAVE PHASE SHIFTERS

INTRODUCTION

In Chapter Four it was mentioned that “all three characteristics of the RF Carrier Wave: Amplitude, Frequency, and Phase, can be modulated”. Since only Amplitude Modulation of PIN diodes was to be described, a more complete discussion of the RF Carrier Wave form was not required. In the present chapter on Phase Shifters, the phase of the RF Sinusoidal Wave form must be described so that the concept of Phase Shift through an RF or Microwave Circuit has more than an intuitive or heuristic significance to the reader.

TIME VARYING SINUSOIDAL WAVEFORMS

Input signals to RF and Microwave Circuits are usually described physically in terms of single sinusoidal wave forms, or for more complex wave forms, may be described as a composite or summation of a number of sinusoidal wave forms.

In its most frequent form for electronic-circuit applications, the sinusoidal voltage is a function of time of the general form:

$$v(t) = V_o \sin\{2\pi f t + \theta\} \qquad (5.1)$$

where: V_o is the amplitude, f is the frequency, and θ is the phase angle with respect to some arbitrary phase angle reference, as shown in Figure 5.1.

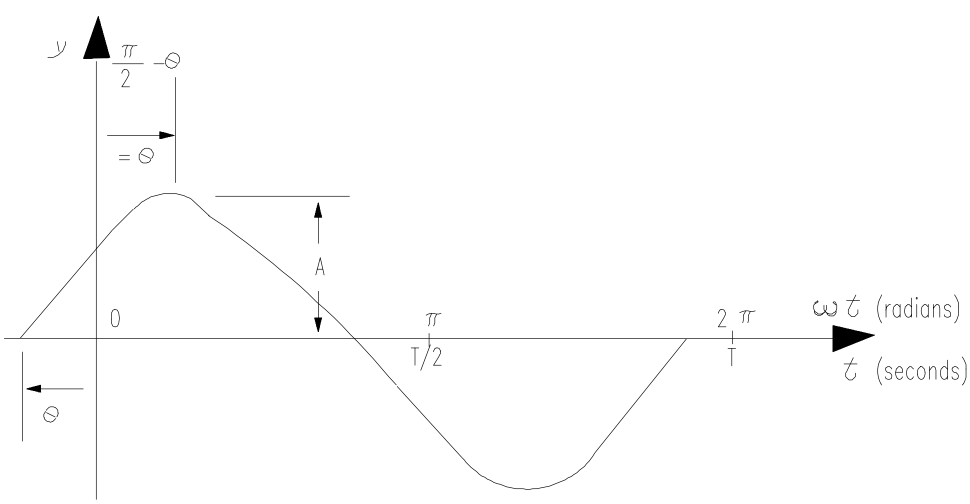

Figure 5.1 The Sinusoidal Function

In Figure 5.1, $A = V_o$, the frequency (f) is related to the inverse of the period (T) of the wave, and θ is the phase angle of the wave with respect to the phase reference. The phase reference can be chosen arbitrarily to define the initial value of the Phase Angle (θ) at the input to the circuit.

PHASE ANGLE

Phase Angle [1] is the measure of the progression of a periodic wave in time or space from a chosen instant or position. The Phase of a periodic wave, v(t), the frequency of which corresponds to period T, is the fractional part (t / T) of the period T through which t has advanced relative to an arbitrary origin or phase reference.

Circuit components have some physical size and the RF Voltage wave form passes through these components with a certain finite velocity and time of transit. The total phase angle, θ, will increase or "shift" by an amount related to this transit time through these components. This is the residual phase shift associated with a specific component and a specific wave form frequency. Small circuit-components operating at relatively low frequencies (i.e., HF Band) will exhibit very small residual θ. In the Microwave Bands, however, these same components will exhibit significantly larger residual phase shifts.

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MICROWAVE PIN DIODE PHASE SHIFTERS

Microwave Phase Shifters utilize these properties of wave propagation through circuit component structures. They are designed to produce the phase shift effects required for the operation of certain classes of Antenna Systems for RADAR and Communications applications. Reference [2] treats the subject of Semiconductor Phase Shifters for Antenna arrays in great detail. The treatment here deals specifically with PIN diode Phase Shifter circuit design.

The PIN diode may be considered as a lumped variable-impedance microwave circuit element. Microwave or RF signals passing through the PIN diodes experience some finite phase shift. A lumped element representation permits the design of compact phase shifter circuits at the RF frequency bands. However, in the higher microwave frequency bands, losses increase and power handling capability decreases. Figure 5.2 shows an example of a PIN diode phase shifter with driver-amplifier connections. Note that there is one driver circuit for each phase shifter bit.

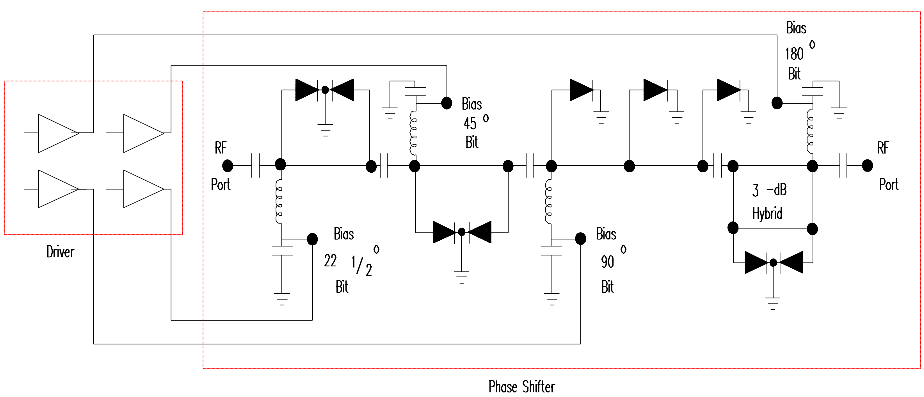


Figure 5.2 A PIN Diode Phase Shifter With Driver-Amplifier Connections

PIN diodes are utilized as series or shunt connected switches in phase shifter designs. The switched elements are either lengths of transmission line or reactive elements. The criteria for choosing PIN diodes for use in Phase Shifters are similar to those used for other switching applications.

In addition, there is the possibility of introducing phase distortion, particularly at high RF power levels or low reverse bias voltages. Microsemi PIN diodes are characterized by thick I-regions and long carrier lifetime and these are the characteristics that result in low phase distortion.

REAL TIME DELAY PHASE SHIFTER

The major application of electronically controllable, rapid-acting microwave phase shifters is in antenna systems for Phased Array Radar. In these systems, a phase shifter is placed in series with each radiator of an array of antennas. The radiating-phase-front direction is controlled by varying the time delay from the source of a common signal to each radiating element of the array. The steering of the array is independent of the radiation frequency.

The circuit used to produce this time delay is the real-time-delay phase shifter or the nondispersive phase shifter. It is essentially a switched section of transmission line. The time delay through the circuit must be independent of the phase-shift state. The phase shifter is nondispersive because its overall phase shift is not directly proportional to frequency.

The Phase-Frequency Characteristics of dispersive and nondispersive phase shifters are shown in Figure 5.3 and are discussed in the next section.

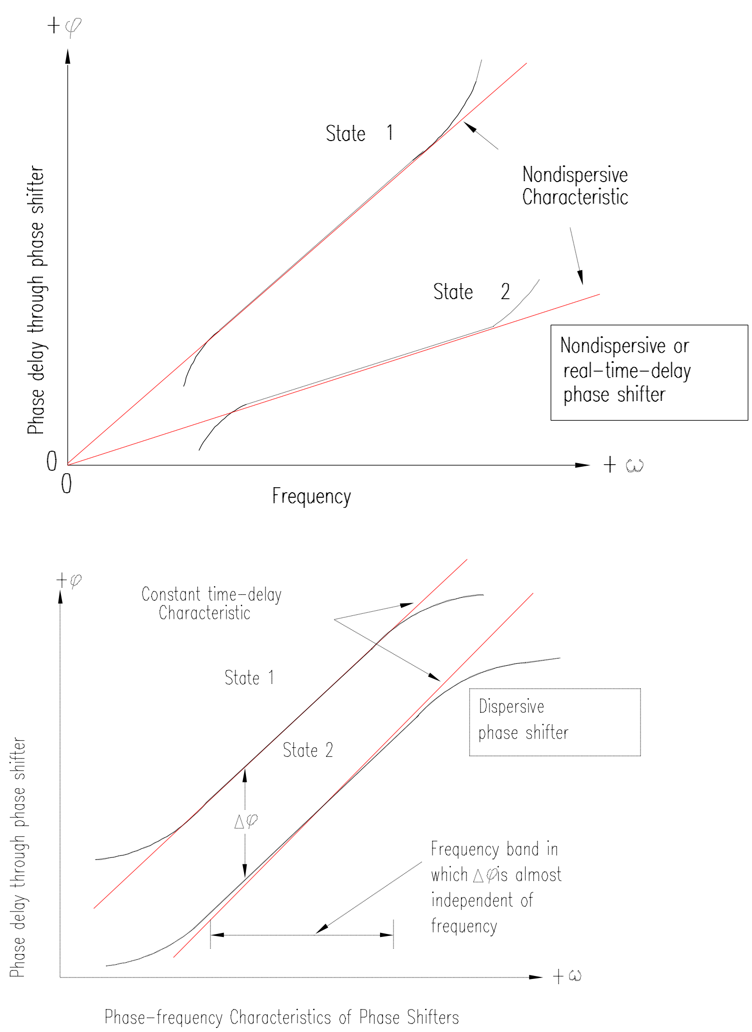


Figure 5.3 Phase-frequency Characteristics of Phase Shifters

TYPES OF REAL TIME - DELAY PHASE SHIFTERS

The simplest design for a real-time-delay phase shifter uses a circulator or a 3 dB coupler to provide matched input and output for the switched elements, as shown in Figure 5.4.

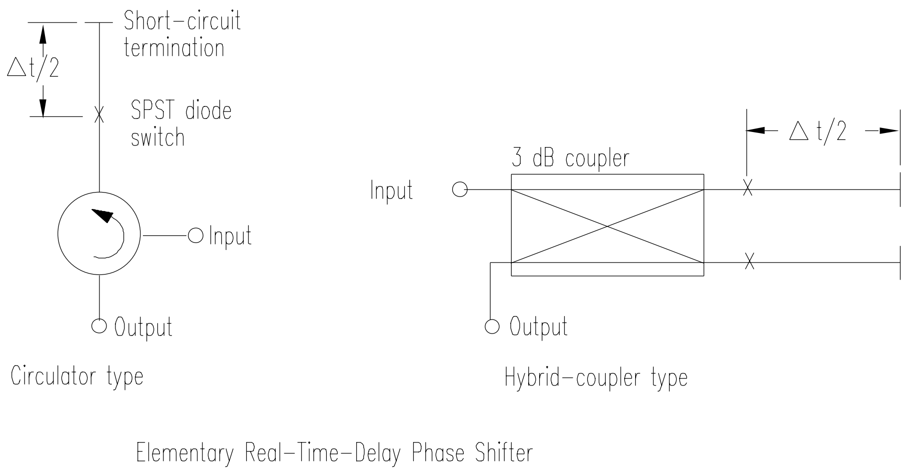


Figure 5.4 Elementary Real-Time-Delay Phase Shifters

In both phase shifters, The SPST diode switches are used as either short circuits or open circuits over a finite bandwidth. Dependence on a section of line for the time delay causes a bandwidth limitation on this class of phase shifters, even if ideal couplers or circulators and identical SPST switches are used. The narrow band performance of the delay lines produces the dispersion that results in nonconstant time delay. For narrow band systems, this design is a viable approach.

POWER LIMITATIONS

The choice of diodes limits the maximum power that can be carried by these phase shifters. PIN diodes have sufficient stored charge to prevent them from producing wave form distortion. Their capability is limited by thermal dissipation of absorbed RF power and RF voltage breakdown. To choose a PIN diode for a specific design, we specify a maximum allowable RF current or voltage applicable to the forward- or reverse-biased diode. Using these two values, we can calculate the maximum power that a phase shifter design may carry. For the hybrid-coupled phase shifter of Figure 5.4, we calculate from the structure of the SPST diode switch that each switch may carry I_{max} Amperes in the forward biased state and V_{max} Volts in the reverse biased state. We then state that

$$P_{max} = [I_{max}^2 \times Z_o] / 8 \qquad (5.2)$$

where Z_o is the characteristic impedance of the transmission line in which the SPST is built (which must be matched to the generator) and P_{max} is the maximum incident power that may be carried by this line when the switch is in the maximum current state.

DISPERSIVE PHASE SHIFTERS

The distinguishing feature of this type of phase shifter is the production of a frequency-independent phase change. Figure 5.5 illustrates a hybrid-coupler type of dispersive phase shifter, which uses PIN diodes as the shunt Susceptance across the transmission lines. An entire Phase Shifter would contain a number of these "unit Cells" that each contribute a specific Phase Shift Bit, of value d ψ. For example, one "Cell" could be designed to be a 22.5 degree Bit, another "Cell", a 45 degree Bit and so on.

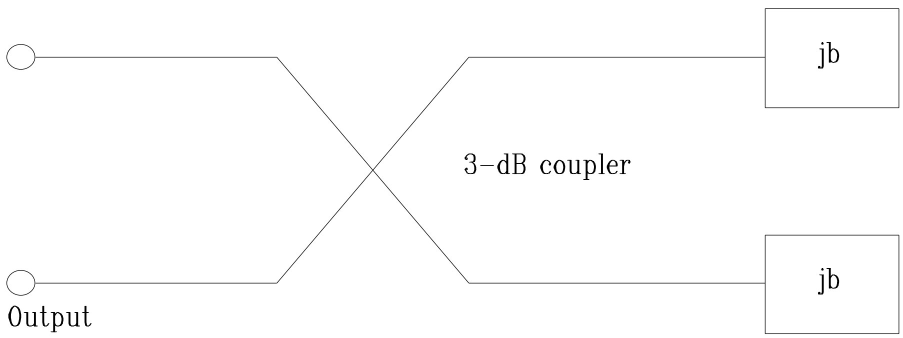
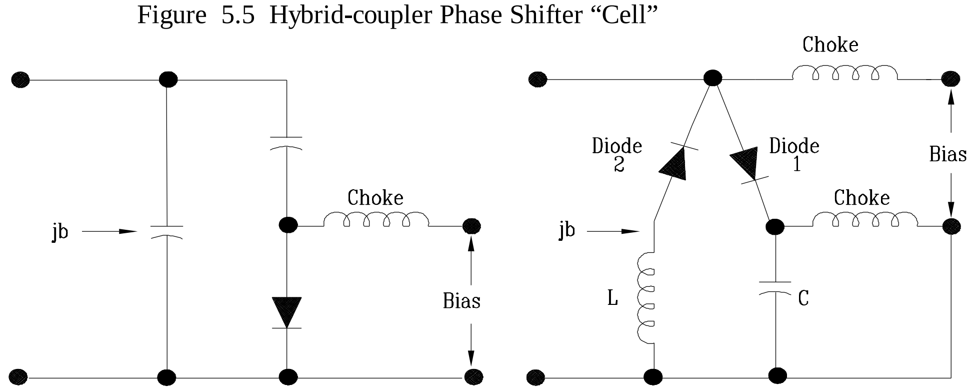


Figure 5.5 Hybrid-coupler Phase Shifter "Cell"



(a) (b)

Figure 5.6 Two Possible Loading Elements of the 3 dB Hybrid-coupler in Figure 5.5.

One PIN diode alone is a switchable Capacitance terminating the transmission line. Forward and reverse bias values are chosen such that, in the forward bias case, C+ is $C_o + \Delta C$, and when reverse biased, C- is $C_o - \Delta C$, where C_o and ΔC determine the Phase Shifter Bit value desired [2,3].

The total Bit phase change is the difference between the forward and reverse biased phase changes:

$$\Delta \psi = (\psi+) - (\psi-) \qquad (5.3)$$

which we desire to be frequency - independent. Thus we impose the condition:

$$d(\psi+)/df = d(\psi-)/df \qquad (5.4)$$

which is the condition for equal time delay in the two bias stated. This is the characteristic that distinguishes the dispersive from the nondispersive phase shifter.

The dispersive phase shifter, using one PIN diode per branch, is shown in Figure 5.6 (a). It is suitable for values of Δψ up to approximately 120 degrees. A dispersive phase shifter, using two PIN diodes per branch, is shown in Figure 5.6 (b). This configuration can produce phase changes in excess of 180 degrees.

A GENERAL DISCUSSION OF PIN DIODE PHASE SHIFTER CIRCUITS

A schematic diagram of a 4-bit phase shifter[2] which gives 16 steps in increments of 22.5 degrees, is shown in Figure 5.7.

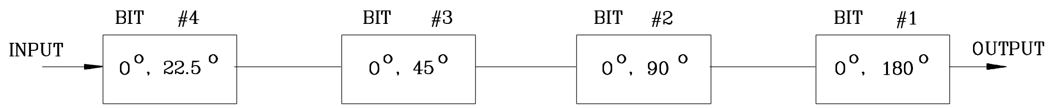


Figure 5.7 Schematic of Transmission 4-bit Phase Shifter

Any of the phase bits may take on three basic circuit topologies.

Switched -line phase bit (Figure 5.8)

Hybrid-coupled phase bit (Figure 5.9)

Periodically loaded-line phase bit (Figure 5.10)

The choice of circuit topology of the phase bit depends on factors such as the number of PIN diodes required, power level, fabrication ease, and cost. Minimum insertion loss condition implies equal loss in each bit state.

SWITCHED-LINE BIT PHASE SHIFTER

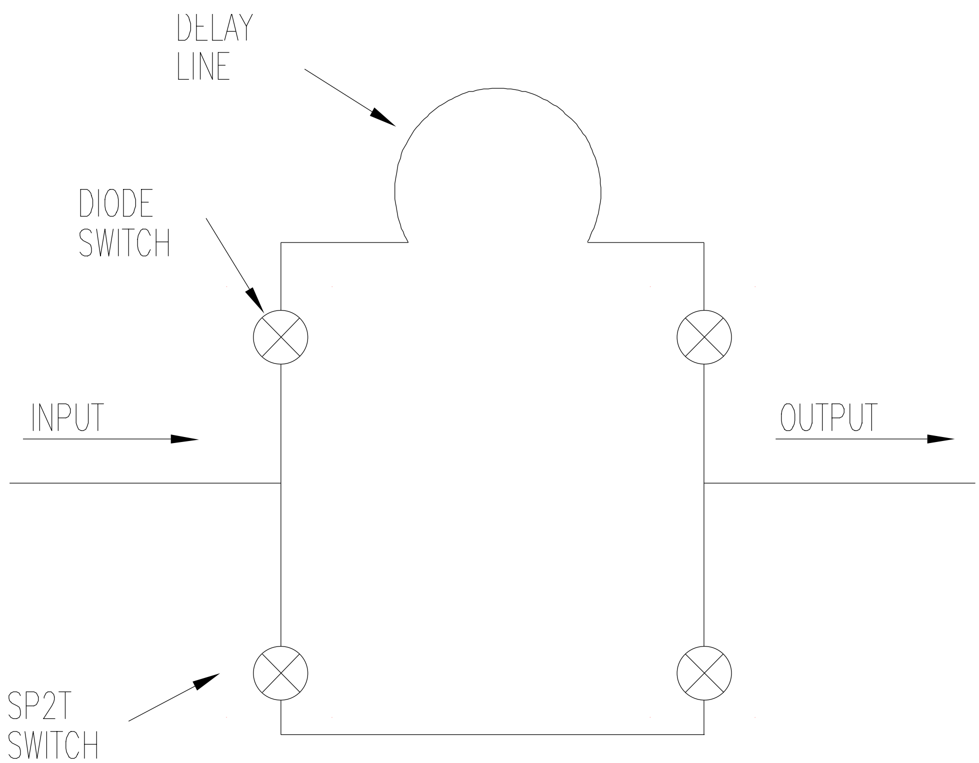


Figure 5.8 Switched-Line Bit Phase Shifter

The switched-line phase shifter is shown in Figure 5.8. This circuit consists of two SPST switches and two lengths of transmission line for each bit. Four PIN diodes are required as a minimum. The transmission line lengths are arbitrary, so the circuit can be used for bit phase values from 0 to 360 degrees. It can also be used as a time delay network. The Isolation per switch in the OFF branch must be greater than 20 dB to avoid phase errors.

Minimum loss occurs in each SPDT switch when the energy absorbed in the OFF branch is equal to the loss of the ON or pass branch. If the diode resistance is equal in both states, the minimum loss for the bit occurs when the Characteristic Impedance of the T-junction is equal to the average Capacitive Reactance of the PIN diodes. Analysis [2] for this type of bit shows that if the circuit is optimized for minimum loss by properly choosing the Z_o of the T-junction, the peak-power capacity is twice that of any other type of phase bit. If line loss is neglected, the Insertion Loss is the same for all bit sizes.

HYBRID - COUPLED- BIT PHASE SHIFTER

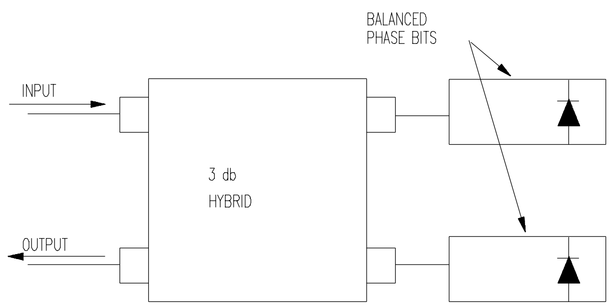


Figure 5.9 Hybrid-Coupled-Bit Phase Shifter

The Hybrid-coupled-bit phase shifter, Figure 5.9, has a 3 dB hybrid junction with balanced phase bits attached to the coupled branches. Analysis of this type [2] shows that the voltage (VBR) required of the PIN diodes depends on the bit size in which the diode is used, if it is assumed that equal power is incident on all cascaded bits. VBR is highest for the 180 degree bit and is reduced by $\sqrt{\sin(\psi/2)}$ for the smaller bits. Similarly, the insertion loss is also a function of bit size. If the loss of the 180 degree bit is L_o, then the loss of the smaller bits is $L_o \sin(\psi / 2)$. The hybrid-coupled-bit phase shifter has the least loss of the three types and uses only two PIN diodes per bit.

An analysis [2] for the hybrid-coupled 180^o phase bit shows that the peak-power capability and optimum impedance level for equal loss in both switch states are given by:

$$P = V^2 / 4Z_o \qquad (5.5)$$

where $Z_o = X_c \sqrt{R_F / R_r}$

Equation (5.5) shows that to obtain high-power handling capacity, the PIN diodes must have high VBR, relatively high Capacitance, and operate in transmission lines with low impedance levels.

The breakdown voltage required of the PIN diodes depends on the bit size in which the diode is used. This requirement is the highest for the 180^o bit and is reduced by the factor, $\sqrt{\sin(\psi/2)}$, for the smaller bits. If the dissipation loss for the 180^0 bit is L_O, the loss of the smaller bits is $L_O \sin(\psi/2)$. The Hybrid - Coupled Bit Phase Shifter has the least loss of the three types being considered here, and uses the least number of diodes.

Shorter bits can be obtained from the 180 degree bit by using the transformed-switch technique[2], which consists of placing an impedance transformer one-eighth wavelength before the input port of the 180 degree bit. The impedance transformation ratio of the transformer is varied to produce the various phase-bit sizes.

LOADED-LINE PHASE SHIFTER

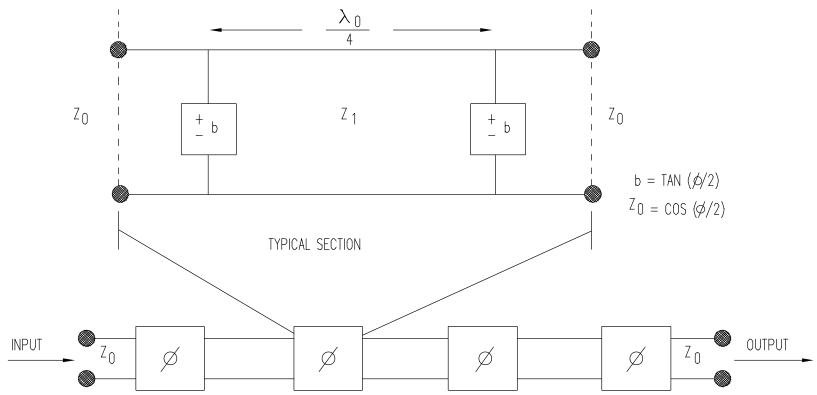


Figure 5.10 Loaded-Line Phase Shifter

The loaded-line circuit uses switched loading Susceptances spaced a quarter-wavelength apart along a transmission line (Figure 5.10). Adjacent loading Susceptances are equal and are switched into either a Capacitive or an Inductive state. Impedance-matched transmission for both states is maintained by choosing the impedance level of the transmission-line section between the PIN diodes

The magnitude of the loading Susceptance, B, and the characteristic Impedance of the connecting transmission line, Z_1, are related to the required phase shift, ψ, per section and the Phase Shifter optimum impedance Z_o by the equations

$$Z_1 = Z_o \cos(\psi / 2) \qquad (5.6)$$

$$B = \tan(\psi / 2) \qquad (5.7)$$

The PIN diodes can be either directly mounted or stub mounted across the transmission line. Average power handling in this configuration is limited by the VBR of the PIN diode and the practical level to which the characteristic impedance can be reduced.

The peak power capacity is a function of the VBR and the phase step size.

For equal insertion loss in each state of the phase step, the peak power capacity for the loaded line phase shifter is one half of the hybrid-coupled-bit design.

The insertion loss of n small phase steps cascaded to achieve 180 degree phase shift is $\pi / 2$ times the loss of the 180 degree hybrid-coupled-bit circuit.

To achieve high power capability, the loaded-line phase shifter uses many PIN diodes and small phase increments.

CONCLUSIONS:

In comparison with the loaded line phase shifter, the hybrid coupled design can handle up to twice the average or peak power when using the same PIN diodes. In both hybrid and loaded line designs, the power handling capability of the maximum bit size is related to the maximum RF current and the peak RF Voltage that the PIN diodes can withstand. The characteristic impedance of the bit circuits is a variable that can be used to adjust the current and voltage stress to be within the device ratings. This means that Z_o is reduced below 50 Ohms to reduce the voltage stress in favor of higher RF currents. The maximum current rating of Microsemi PIN diodes depends on the power dissipation rating while the maximum voltage stress is dependent on I-region thickness.

DEVICE	HIGH VOLTAGE >2000 V	HIGH AVERAGE POWER >100 W	HIGH PEAK POWER >10 KW	HIGH POWER CW DUPLEXERS >100 W	ANTENNA SWITCHING >100 W	HIGH FREQUENCY > 1GHz	LOW FREQUENCY <10 MHz	ULTRA LOW FREQUENCY <1 MHz	L C R <
HUM2020	X	X	X	X	X		X		
UM2100		X	X	X	X		X	X	
UM2300		X	X	X	X		X	X	
UM4000		X	X	X	X		X		
HUM4020	X	X	X	X	X		X		
UM4300		X	X	X	X		X		
UM7000		X	X	X					
UM7100		X	X	X					
UM7200									
UM7300		X	X	X	X		X		
UM7500		X	X	X					
UM9401		X	X	X					
UM9415					X				
UMM5050	X		X	X	X				
UPP9401		X		X					
UPP1004		X		X					