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Overview of Microstrip Line Phase Shifter

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Abstract: Phase shifter is fundamental element in transmit/receive module of RF frontend. In defence application phase shifters have been widely used in phased array antennas. But commercially they are not used widely due to its costs. Various parameters have been presented in the paper that deals with different types of phase shifter both analog and digital. Insertion loss, return loss and bandwidth are key parameters. Microstrip line, strip line and slotted strip line can be used in commercial applications as they provide lower cost design.

Keywords: Phased array antennas, transmission line phase shifters, transverse electromagnetic (TEM), reflection type, loaded line, switched line, switched network, quadrature hybrid, lange coupler.

I. INTRODUCTION

Phase shifter is important element in transmit/receive module. RF and microwave phase shifters have many applications in various types of equipments such as phase discriminators, BFNs, power dividers, balanced amplifiers and phased array antennas [7]. A phase array antenna has large number of radiating elements that emit phased signals to form a radio beam. The radio signal can be electronically steered by active manipulation of relative phasing of individual antenna elements. Thus phase shifters form fundamental element of phased array antenna. This allows to scan a beam or to reconfigure a shaped beam. Phased antenna arrays, such as avionics TCAS ANT, consist of number of individual elements, each on requiring a phase shifter that applies the necessary phase shift to steer the antenna beam. In some avionics amplitude monopulse systems, a phase shifter provides different directional and omni-directional antenna modes [6].

Fig. 1 depicts design flow used for printed phase shifters. First step is definition of system level specifications. This involves both system level requirements which are applied directly for printed phase shifters, as well as derived requirements which depend upon system requirements. Phase shifter specifications include cost, size and other requirements. Other specifications for RF and microwave printed phase shifters include FR, BW, phase variance, IL, switching speed, power handling, accuracy, resolution, input/output matching (VSWR or RL) and harmonics level. For all requirements designer choose consecutive integer values of weighing coefficients corresponding to each parameter. Maximum value can be less than or equal to number of parameters. Selection of phase shifter prototype depends upon selection of transmission line, technology process and corresponding weighing coefficients and switching elements. For minimum cost most phase shifters are designed using microstrip line.

However lower cost stripline or slotted stripline is desirable. Synthesis of prototype phase shifter is dependent upon both system and derived requirements. Synthesis results are physical dimensions of phase shifter and lumped element value if necessary. Analysis defines electrical performance of designed phase shifter based on physical dimensions [7].

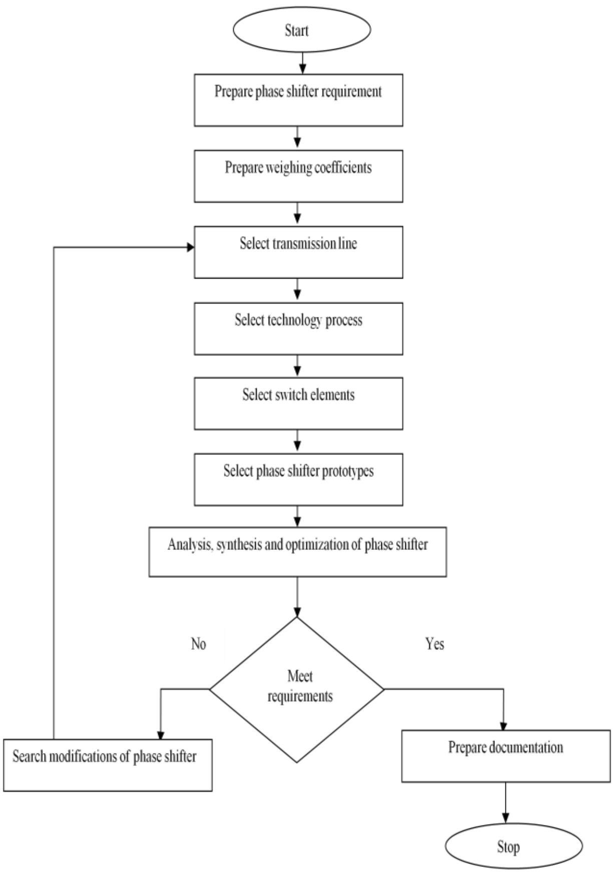

Fig. 1 A standard phased array antenna system

II. TYPES OF PHASE SHIFTERS

Typically phase shifters are of two types depending on required output. They are classified as analog phase shifter and digital phase shifter.

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A. Digital Phase Shifter

Typically phase shifters are of two types depending on required output. They are classified as analog phase shifter and digital phase shifter. Digital phase shifter divides phase into predetermined states that are changed by digitally controlling each bit [6]. Each bit is controlled by switching elements. Switching elements in digital phase shifter are PIN diodes and FETs. Switching in PIN diodes is obtained by changing bias point from forward to reverse direction and vice versa. It finds application in high speed and current controlled phase shifters. While in MMIC design switching elements are open FETs. GaAs phase shifters are small in order of square millimeters and hence has good application in thin film semiconductor manufacturing process. But on the other hand GaAs semiconductors are most expensive [2].

B. Analog Phase Shifter

Analog phase shifters are those whose phase shift changes continuously with control input. Most commonly used control elements in analog phase shifters are varactor diodes. These diodes when operated in reverse-biased mode provide junction capacitance that varies with applied voltage and thus can be used as electrically variable capacitor in tuned circuit. These phase shifters can achieve large amount of phase shift and high speed and require less diodes than in digital phase shifters. But has less accuracy, relatively narrow bandwidth and low input power levels (less than 1W). Schottky diodes are also used in analog phase shifters but have low power handling capability and matching difficulty in broadband networks [3].

There many ways to implement microwave phase shifter. Switched-line, loaded line, switched network phase shifter and reflection type are basic ways. Switched-line, switched network and loaded line phase shifters are of transmission type [4].

III. SWITCHED LINE PHASE SHIFTER

Switched-line is the simplest and direct approach as it uses simple time delay difference between two direct paths to achieve desired phase shift. Switched line phase shifter includes phase elements, switch elements and control network. Selection of switch elements depends upon phase shifter requirements. It is dependent on length of transmission line used. An important advantage of this phase shifter is phase shift will be approximately linear function of frequency. This enables circuit to operate at a broader frequency range. Also as phase shift is dependent only on transmission line length used they are therefore; very stable over time and temperature.

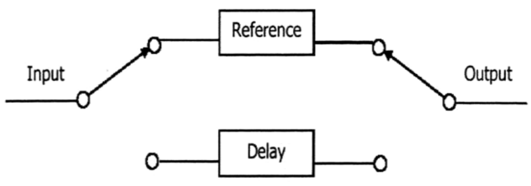

Fig. 2 Reference and Delay arm

Although control elements have an effect due to drift they do not affect phase shift much. But will have degradation in insertion loss of the circuit. For switched line phase shifter both peak power capability and IL are independent of phase shift [5].

Conventional switched line phase shifter comprises of two line segments of different lengths selectively connected to transmission line. One of the two lines is labelled as reference line and other as delay line as shown in fig 2. The different path lengths between two line segments determine phase shift to be introduced. Transmission line is switched over from one line segment of phase shifter to other when phase shift is removed. Schematic of switched line phase shifter is shown in fig 3 which uses SPDT switches to route signal between one of the two transmission lines of different length. Differential phase shift between two paths is given by equation 1.

$$\Delta\varnothing = \beta\,(l_2 - l_1) \qquad (1)$$

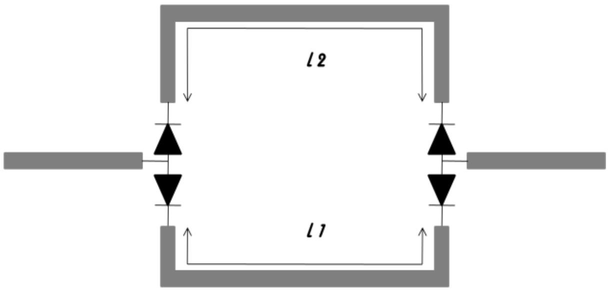

Fig. 3 Basic schematic of switched line phase shifter

Where, β is propagation constant of transmission line. If transmission line is TEM (or quasi- TEM like microstrip) then phase shift is linear function of frequency which implies true time delay between input and output ports. Insertion loss of switched line phase shifter is equal to SPDT switches loss and line losses. Switched line phase shifter is usually designed for discrete phase shifts like 45°, 90°, 180°etc. To reduce size of phase shifter reference line should be shorter in length. Lengths l_1 and l_2 must be carefully selected to avoid phase errors, high return loss and high insertion loss. Practical design of switched line phase shifter may introduce several errors. Resonance may occur in the line which is switched off due to its length and this will reflect in the return loss. Also resonant frequency will be shifted due to junction capacitances formed due to reverse biased diodes [5]. Multi bit phase shifters can be used to vary phase shift up to 360°. Digital phase shifters provide a discrete set of phase shifts that are controlled by two state phase bits (0 or 1). A ‘N’ bit phase shifter provides 2^N discrete states [6]. To minimize the phase quantization error, number of bits and hence number of phase shifters should be increased [2].

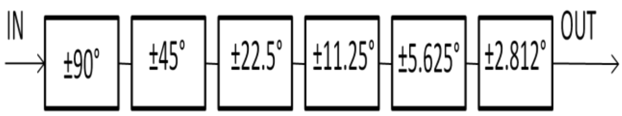

Fig. 4 6 bit digital phase shifter

6 bit digital phase shifter is shown in fig 4. Typical phase shifter switches between 0° to 360°. But this phase shifter switches between -180° to +180°. Reference circuit is designed using negative phases and delay circuit using positive phases. This phase shifter will provide 64 different phase shifts. Fig 5 shows operation of 6 bit digital phase shifter which provides 109.6875° phase shift by selecting +90°, +45°, -22.5°, -11.25°, +5.625° and +2.812° phase shifts.

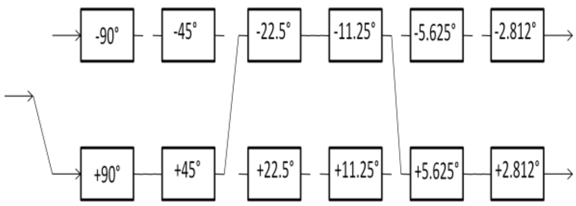

Fig. 5 Operation of 6 bit phase shifter which creates 109.6875° phase shift

IV. LOADED LINE PHASE SHIFTER

Loaded line phase shifters are loaded with shunt reactance in the form of inductor or capacitor causing the signal to undergo phase shift. Schematic of conventional loaded line phase shifter is shown in fig 6. Each section of loaded line PS consists of λ/4 transmission line symmetrically loaded at its ends by small susceptances for mutually cancelling reflections due to λ/4 separation. This feature provides phase shifter section a good match in both control states. Susceptance values are controlled by semiconductor switches such as PIN diodes. Desired phase shift is obtained by changing electrical length through switching PIN diodes. The loading admittance of these elements is controlled with switching diodes to electrically shorten or lengthen the transmission line. The design of loaded line phase shifter using microstrip lines requires characteristic impedance (Z_T) of quarter wave transformer (λ/4 line) and electrical length (βι) of short stub. Two susceptances separated by λ/4 spacing offer wider bandwidth [13].

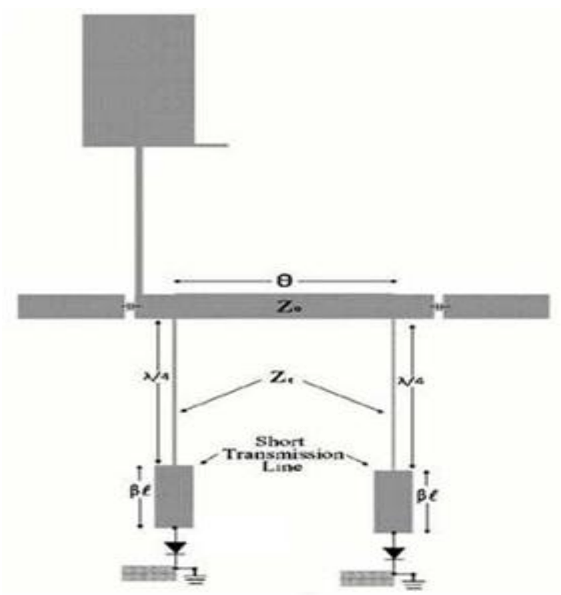

Fig. 6 Layout of loaded line phase shifter

Loaded line phase shifter has advantages of simplicity and low insertion loss for phase shifts less than 45°. Insertion loss can be improved using lower loss dielectric material. Disadvantage of this type of phase shifter is for larger values of phase shifts high values of susceptances are required that increase insertion loss. Capacitance is best element as susceptance than inductor in loaded line phase shifter as shunt capacitor elements lengthen a transmission line electrically and shunt inductance shorten it.

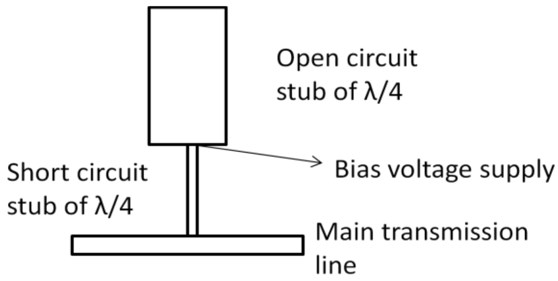

Fig. 6 Layout of loaded line phase shifter

V. REFLECTION TYPE PHASE SHIFTER

Reflection type phase shifter consists of two parts 3 dB hybrid (quadrature combiner or divider) and two tunable terminations as shown in fig 8. The input signal is first split into two parts, and then reflected by the two loads. When the loads are same, the voltage at the output port is given in equation 2. Termination can be variable capacitors or diodes [8].

$$V_{out} = j\,\Gamma\, V_{in} \qquad (2)$$

$$\Delta\varnothing = \varnothing_1 - \varnothing_2 \qquad (3)$$

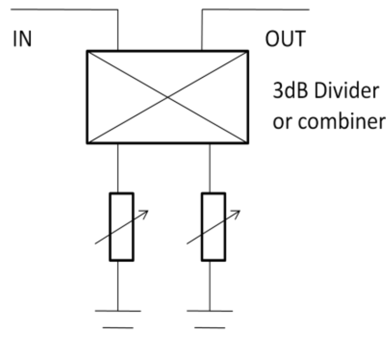

Fig. 8 Basic schematic of reflection type phase shifter

Compared with the transmission phase used in the transmission type phase shifters, reflection type phase shifters transform the reflection coefficient phase to the transmission phase first, and the phase shift is calculated from equation 3. When the power is fully reflected from the loads, the insertion loss is minimized. The bandwidth of the reflection type phase shifter is determined by both the hybrid and the terminations. Also isolation and the return loss of the coupler influence the phase shifter performance Lange couplers can provide a large bandwidth, while terminations used limit the bandwidth [3].

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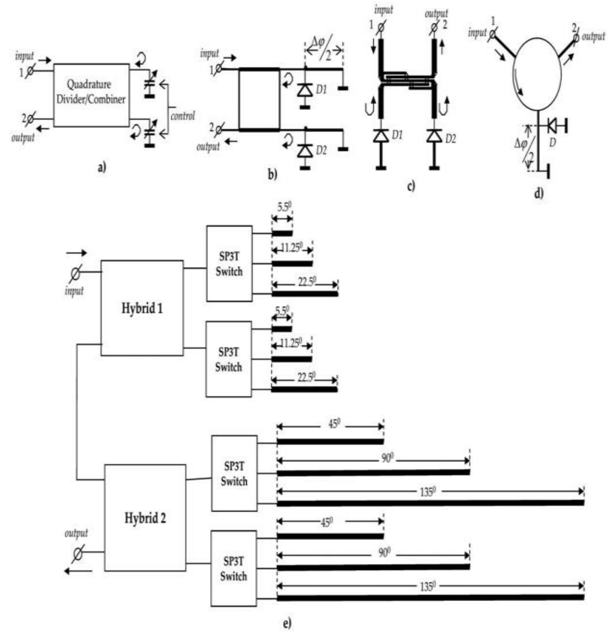

Fig. 9 Various configurations of reflection type phase shifter (a) with quadrature hybrid and capacitors, (b) with two branch hybrid and diodes, (c) with Lange coupler and diodes, (d) with circulator, (e) with reflect stubs

Fig 9 shows various combinations of reflection type phase shifter. In phase shifter shown in fig 9(a) 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 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 D_1 and D_2 is shown in fig 9(b). n 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 $\Delta\varphi$ 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. Fig 9(c) illustrates a reflection-type phase shifter which uses a divider/combiner based on the Lange coupler and varactor diode D_1 and D_2 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 D_1 and D_2, 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 provided 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. Fig 9(d) illustrates the reflection-type phase shifter of the circulator type. The phase shift of this phase shifter is given in equation 4, where ΔL is transmission line length [1].

$$\Delta\varphi = \frac{2\Pi\Delta L}{\lambda} \qquad (4)$$

The switched-line reflection phase shifter shown in fig 9(e) 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 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. 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 [1].

VI. SWITCHED NETWORK PHASE SHIFTER

The switched network phase shifter is another type of transmission phase shifter. The development in this type of phase shifter is very active because the number of network combination is numerous. Common switched network phase shifters switch between different passbands of different networks to obtain the phase difference as shown in fig 10. It has two topologies high-pass/ low-pass phase shifter and all-pass phase shifter which include Schiffman phase shifter [9].

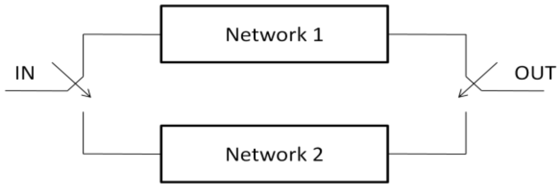

Fig. 10 Basic schematic of switched network phase shifter

A. High-pass/Low-pass (HP/LP) Phase Shifter
The HP/LP phase shifter switches between high-pass filters and low-pass filters. A typical third order HP/LP phase shift bit is shown in fig 11. The T-network is chosen for the HP filter and the π-network is chosen for the LP filter to minimize the number of inductors used [10].

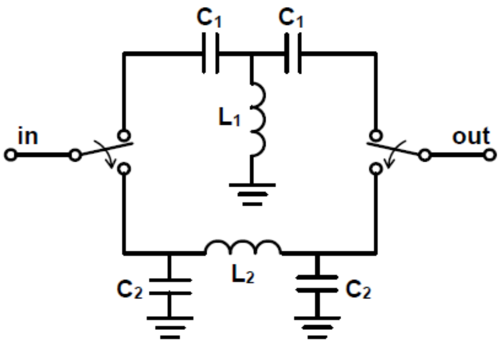

Fig. 11 third order HP/LP phase shifter

Design parameters for the T-network and π-network for a given center frequency ω_o and desired phase shift ΔØ at ω_o. For smaller phase shifters, larger inductors are needed for the high-pass filter using this topology. The insertion loss is affected by the parasitic the matching from the adjacent phase bits and the two SPDT switches. FETs can also be used as switching elements [4].

B. All-pass Phase Shifter
The two topologies of the all-pass networks shown in fig 12 have same performance when the values satisfy equation 5. The phase shift can be obtained by changing ω_o of two all-pass networks and a phase shift peak will be obtained for each setting. The advantage of the all-pass network is that the insertion phase can be treated separately due to the very high return loss. Therefore, when two stages are cascaded, two peaks in the phase response can be obtained to get a phase shift ripple and the bandwidth can be significantly improved. For the two-section phase shifter, the bandwidth ratio increases to 4:1 for the same performance of the single-section phase shifter. Besides the large bandwidth applications, the all-pass network is also used in compact integrated circuit designs. Like the HP/LP topologies, FETs can be integrated into the circuits to minimize the circuit area. Furthermore, the capacitors in both the HP/LP phase shifters and the lumped all-pass network phase shifters can be changed to varactors to realize continuous phase tuning [4].

$$LC = \frac{1}{\omega_o^2}, \frac{L}{C} = Z_o^2 \qquad (5)$$

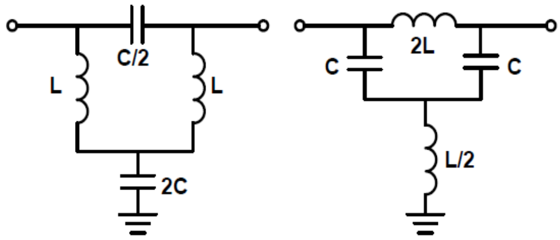

Fig. 12 All-Pass network phase shifter

VII. CONCLUSION

An overview of principle of phase shifter, its fundamental types depending on nature of input signal, its sub-types depending on different configurations is presented in this paper. If PIN diodes, FETs which provide discrete phase shift are used as switching elements then it is digital phase shifter and if varactor or schottky diodes which provide continuous tuning are used then it is analog phase shifter. Further phase shifters can be of transmission type or reflection type depending on its operation. Rather than phase shift insertion loss, return loss and bandwidth are important parameters which are influenced by transmission line length, lumped components used and switching elements. Dielectric materials used in microstrip line also have an effect on these parameters. Thus choosing appropriate values and types of elements is very tedious. For minimum cost phase shifters they are designed using microstrip line. For lower cost strip line and slotted strip line can also be designed.

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