DESIGN OF A NOVEL DIGITAL PHASE SHIFTER AT X-BAND

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ABSTRACT — **A novel digital phase shifter design at X-band is presented. The phase shift is realized by converting a microstrip line to a rectangular waveguide and thus switching the propagation constant of the line. A 3-bit phase shifter has been constructed using passive components in lieu of diode switches for theoretical verification. For this design a maximum insertion loss of 1.4 dB at 11 GHz was achieved. The size of the 3-bit phase shifter is 1.2×0.3 $inch^2$. In addition, a 90 degree phase shifter has been built using PIN diodes as switches, giving an insertion loss of 0.9 dB at 11 GHz with the size of 0.24×0.26 $inch^2$.**

I. INTRODUCTION

The digital phase shifter is a general-purpose microwave component, which is used in a variety of communication and radar systems, microwave instrumentation and measurement systems, and industrial applications [1]. With the rapid growth of microwave integrated-circuit technology, the switched-line type of phase shifter, which uses microstrip or strip lines, has been largely investigated [1]-[2]. This type of phase shifter uses microstrip lines of different lengths to achieve a phase shift, i.e.

$$\Delta\phi = \beta_{ms}\Delta\ell \qquad (1)$$

where,

$\Delta\phi$: phase shift,

β_{ms} : propagation constant of the microstrip line, and

$\Delta\ell$: difference of the two microstrip lengths.

Presented in this paper is a new design which achieves a desired phase shift by switching the propagation mode of a transmission line between microstrip and waveguide, i.e.

$$\Delta\phi = \Delta\beta\ell \qquad (2)$$

where, $\Delta\beta$ is the propagation constant difference between the microstrip and the waveguide, and ℓ is the length of waveguide structure. This approach is similar to loaded transmission line designs in which the propagation constant of the transmission line is changed through the periodically loading with varactor diodes [3]. The proposed work differs from these designs in that a different mode of propagation is formed by switching between the microstrip and waveguide. In Fig. 1, a conceptual view illustrating a transmission line switching between a microstrip and waveguide mode is shown. Note that the waveguide and microstrip lines occupy the same length. The switching is accomplished by shorting the gap between the ground and the microstrip line thereby forming a rectangular waveguide. This transition from microstrip to waveguide is quite similar to a microstrip to waveguide transition that has been previously described in [4].

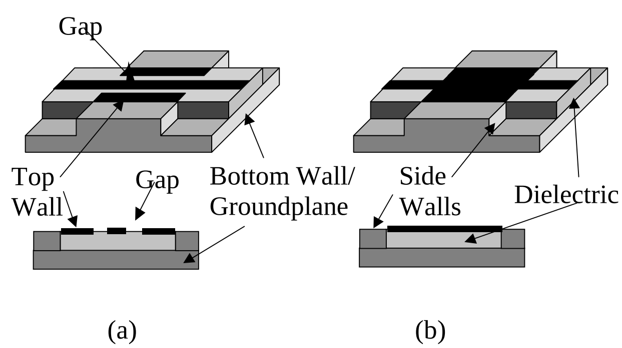


Fig. 1. Perspective and frontal views of the (a) microstrip mode and (b) waveguide mode of the phase shifter.

II. THEORY

A. Propagation mode switching

The structure, including the transition between the microstrip and waveguide, is shown in Fig. 1. Fig. 1a, represents the microstrip mode of operation. In Fig. 1b, the two gaps are closed and the waveguide mode is formed. This transition from microstrip to dielectric filled waveguide serves as the basic principle behind the phase shifter in this work. Closing the gap between the microstrip and the entire top wall of the waveguide can be accomplished by the periodic placement of PIN diodes along this gap as electronic switches, as shown in Fig. 2.

When the diodes of Fig. 2 are switched off, microstrip mode is excited. When they are switched on, a rectangular waveguide is formed, and the dominant mode of the rectangular waveguide, TE_{10} is excited.

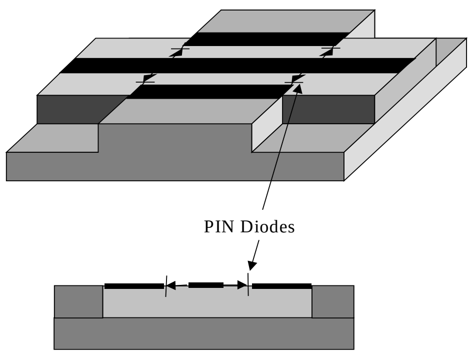


Fig. 2. Perspective and frontal views of the phase shifter with PIN diodes used to switch

The difference between the two propagation constants of the microstrip and waveguide modes is:

$$\Delta\beta = \beta_{ms} - \beta_{wg} \tag{3}$$

where,

$$\beta_{ms} = \frac{2\pi f\sqrt{\varepsilon_{eff}}}{c} \tag{4}$$

$$\beta_{wg} = \frac{2\pi\sqrt{\varepsilon_r}}{c}\sqrt{f^2 - f_c^2} \tag{5}$$

β_{wg} : the propagation constant of the TE_{10} mode in waveguide.

f: operating frequency

fc: cutoff frequency of waveguide TE_{10} mode

c: speed of light

ε_{eff} : effective relative dielectric constant of the microstrip

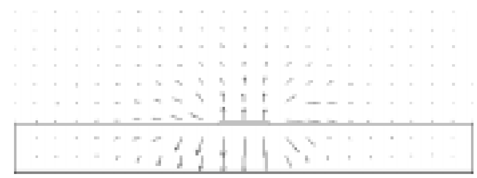
ε_r : relative dielectric constant of the substrate.

Thus, the phase shift becomes:

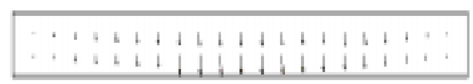
$$\Delta\phi = \frac{2\pi\ell f}{c}\left(\sqrt{\varepsilon_{eff}} - \sqrt{\varepsilon_r}\sqrt{1-\frac{f_c^2}{f^2}}\right) \tag{6}$$

B. Transition design

The most important part of the design process is the transition between the microstrip and the



(a)



(b)

Fig. 3. Electric field distribution for the (a) microstrip and (b) waveguide.

waveguide. An efficient transition requires both a field and impedance match [4]-[5]. When the diodes switch on, the microstrip can excite the dominant mode of the rectangular waveguide as shown in Fig. 3. Although not an ideal transition, the fields match closely enough to cause little reflection from this junction. In addition, the impedance of the microstrip and waveguide must be matched:

$$Zo_{ms} = Zo_{wg} \tag{7}$$

where,

Zo_{ms}: characteristic impedance of the microstrip

Zo_{wg} : equivalent characteristic impedance of the waveguide.

Zo_{wg} is given by:

$$Zo_{wg} = \frac{U^2}{2P} = \frac{2b}{a}\frac{Z_{TEM}}{\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}} \qquad (8)$$

U: the voltage across the center of the top and bottom walls,

P: the power transmitted into the waveguide,

b: height of the waveguide

Z_{TEM} : impedance of TEM wave in free space, which is filled with a dielectric constant equal to ε_r , and

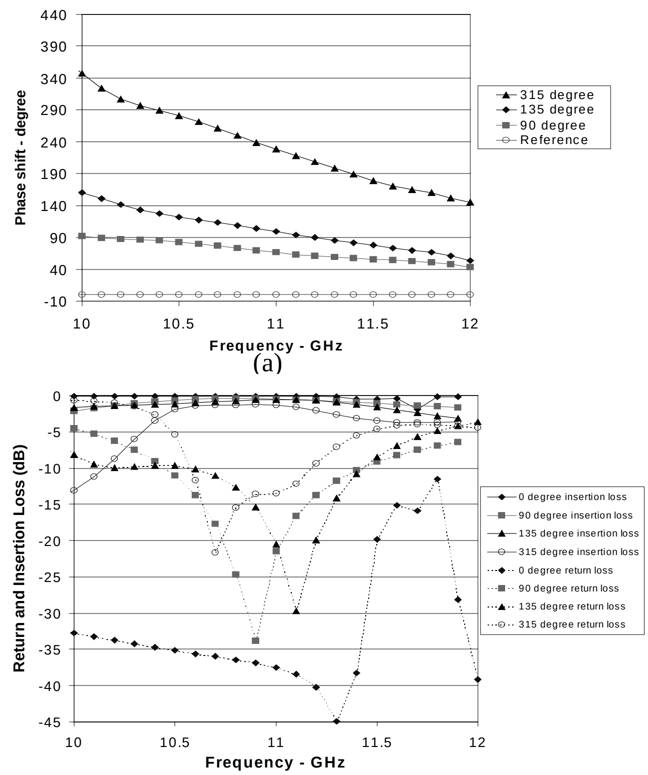
λ: operating wave length.

If Zo_{ms}=50 Ω, then a, the width of the waveguide, can be optimized to achieve $Zo_{ms} = Zo_{wg}$, since the height of the waveguide is dependent on the substrate thickness chosen for the microstrip. Thus, the impedance can be matched for the transition from microstrip to waveguide.

III. EXPERIMENTAL RESULTS

A. Demonstration of a 3-bit phase shifter design

A 3-bit phase shifter was built on *Rogers TMM6™* whose ε_r=6, $tan\delta$=0.0023 and substrate height b=15mil. The ground plane of the microstrip was bonded to a metal test fixture having 3.5 mm connectors. The size of the 3-bit phase shifter is 1.2×0.3 $inch^2$. For this experiment, shorting wires were used to connect the microstrip and top walls of the waveguide for the waveguide mode and no wires for the microstrip mode. The simulated phase shift and losses are shown in Figs. 4a and 4b, respectively. Shown in Figs. 5a and 5b are the measured phase shift and losses, respectively. The phase shift is less than expected from simulation using *Agilent HFSS™.* This may be due to variations in the waveguide width from those simulated. The waveguide width is critical for proper impedance matching. Note that as the frequency decreases, the impedance of the waveguide increases dramatically, causing more reflection loss at the lower frequencies. This is due to the waveguide approaching the cut-off frequency.



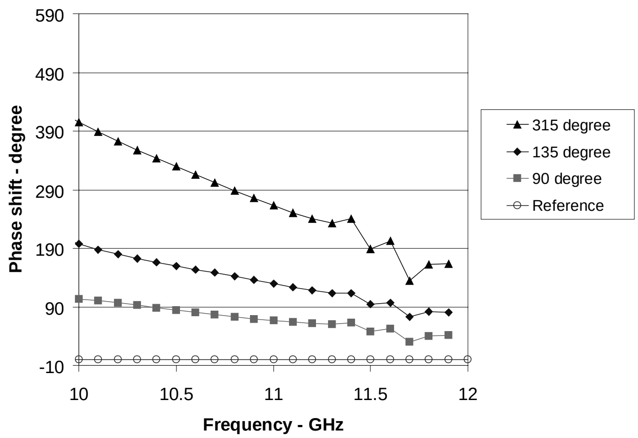
(b)

Fig. 4. Simulated (a) phase shift and (b) insertion loss of the 3-bit phase shifter

B. 90-degree phase shifter using PIN diodes for mode switching

A 90-degree phase shifter using PIN diodes for mode switching was fabricated and tested. The size of the 90-degree phase shifter is 0.24×0.26 $inch^2$. *Agilent HPND-4028* PIN diodes were used for the switching elements. This circuit was simulated using *Agilent HFSS™.* In order to model the devices, an equivalent series resistance was used for the case when the diodes are switched on and an equivalent capacitance was used for the case when the diodes are reverse biased.

The small series resistance of the diodes does not effect the insertion loss since little RF current flows across them at the center of the waveguide. However when the diodes are reverse biased, the capacitance does effect the circuit performance. This effect can be compensated for by adjusting the gap width near the switching diodes. The measured and simulated phase shift and losses for the 90-degree phase shifter are shown in Figs. 6a and 6b, respectively.



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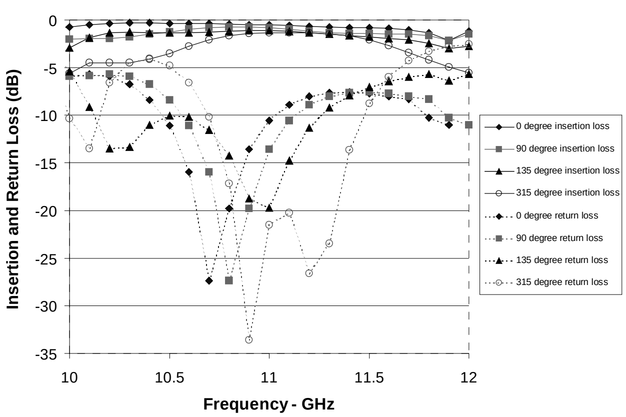
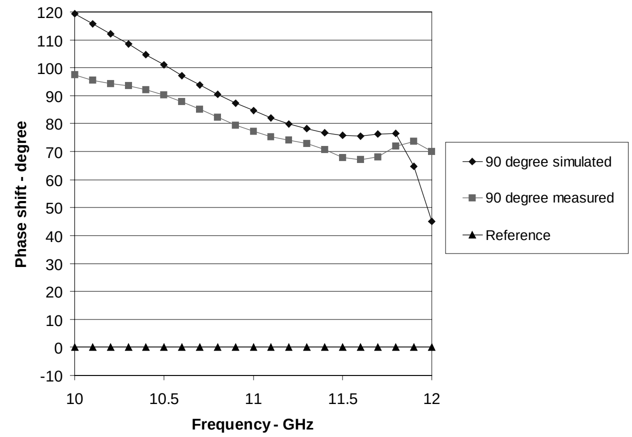


(b)

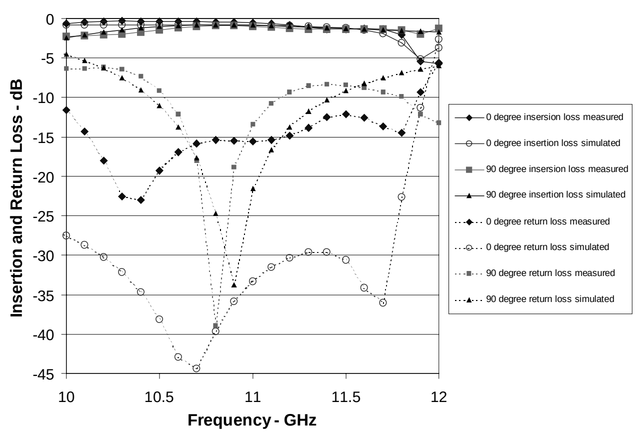
Fig. 5. Measured (a) Phase shift and (b) insertion loss of the 3-bit phase shifter

IV. Conclusion

This paper reports on a novel digital phase shifter design. The phase shift is achieved by switching a transmission line from a microstrip to a waveguide propagating mode. Low insertion loss and significant phase shifting have been achieved.



(a)



(b)

Fig. 6. (a) Phase shift and (b) insertion loss of the 90 degree phase shifter

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