A 4.5 to 18 GHz Phase Shifter

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Abstract

This paper describes a wideband phase shifter suitable for hybrid and monolithic phased array modules. The phase shifter employs a 180° digital bit and one or two analog sections to obtain a full 360° phase shift range. The design of the phase shifter and experimental results are presented.

Summary

Phase shifters are required for many microwave systems and are especially required in large numbers for electronic beam steering in phased arrays. The ideal phase shifter is capable of controlling the insertion phase over a 360° range without change in insertion loss and has a flat phase shift versus frequency characteristic throughout the band of interest. Size and cost considerations dictate that the phase shifter be compatible with monolithic microwave integrated circuits (MMIC) manufacturing techniques.

A phase shifter configuration covering the 4.5 to 18 GHz band under development at Westinghouse is shown in Figure 1. This phase shifter consists of a digital 180° bit and one or two analog sections to obtain a full 360° phase shift range. The 180° bit exhibits nearly ideal behavior over the band. The analog sections require some additional logic circuitry to approach ideal characteristics.

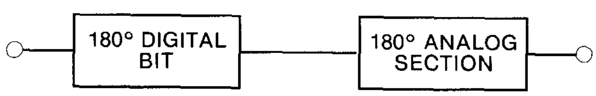

Figure 1. 4.5–18 GHz Phase Shifter Configuration.

The basic building blocks for the wideband 180° phase shifter bit are shown in Figure 2. The network of Figure 2(a) consists of shorted coupled lines. The network of Figure 2(b) is a simple pi network of transmission lines.

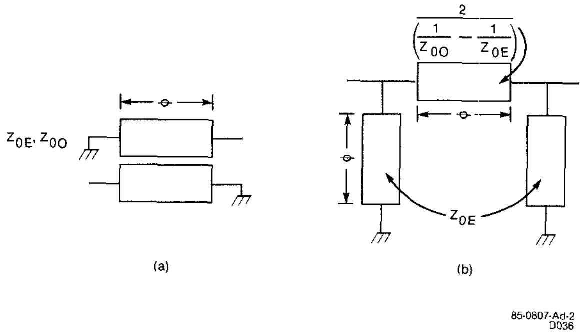

Figure 2. 180° Phase Difference Sections

The two networks are exactly equivalent for all frequencies except that the transmission phase difference between the two circuits is exactly 180 degrees. This can be seen by developing the ABCD matrices for both networks. For the pi network

$$\begin{bmatrix} A & B \\ & pi \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{Yoe}{j\tan\Theta} & 1 \end{bmatrix} \bullet \begin{bmatrix} \cos\Theta & \frac{j2\sin\Theta}{(Yoo-Yoe)} \\ \frac{j\,(Yoo-Yoe)}{2\csc\Theta} & \cos\Theta \end{bmatrix} \bullet \begin{bmatrix} 1 & 0 \\ \frac{Yoe}{j\tan\Theta} & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \frac{(Yoo+Yoe)}{(Yoo-Yoe)}\cos\Theta & \frac{j2\sin\Theta}{(Yoo-Yoe)} \\ \frac{(Yoo+Yoe)^2\cos^2\Theta - (Yoo-Yoe)^2}{j2\,(Yoo-Yoe)\sin\Theta} & \frac{(Yoo+Yoe)}{(Yoo-Yoe)}\cos\Theta \end{bmatrix} \quad (1)$$

The ABCD matrix of the shorted coupled line section is calculated from the y parameters[1] as

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$$\begin{bmatrix} A & B \\ & \text{coupled} \\ C & D \end{bmatrix} =$$

$$\begin{bmatrix} -\dfrac{(Yoo+Yoe)}{(Yoo-Yoe)}\cos\Theta & -\dfrac{j2\ \sin\Theta}{(Yoo-Yoe)} \\ -\dfrac{(Yoo+Yoe)^2\cos^2\Theta-(Yoo-Yoe)^2}{j2\ (Yoo-Yoe)\ \sin\Theta} & -\dfrac{(Yoe+Yoe)}{(Yoe-Yoe)}\cos\Theta \end{bmatrix}$$

(2)

Therefore

$$\begin{bmatrix} A & B \\ & \text{pi} \\ C & D \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \bullet \begin{bmatrix} A & B \\ & \text{coupled} \\ C & D \end{bmatrix}$$

(3)

so that the pi network of transmission lines is equivalent to the shorted coupled section preceded by an ideal phase-reversing transformer. This result is independent of the electrical length Θ of the two networks and thus independent of frequency. The two networks behave identically as bandpass filters.

The pi network and its dual of shorted coupled lines can be incorporated into a 180° phase shifter bit as shown in Figure 3. The SPDT switches may be realized as diode or FET switches.

A complete 180° phase shifter bit has been constructed on 0.025" thick alumina, utilizing the phase difference sections and four FETs as switches. A picture of the phase shifter bit is shown in Figure 4. The measured performance is shown in Figure 5. The phase shifter bit provided a measured phase shift of 177 ± 7° from 2 to 17 GHz. The measured insertion loss was 2.3 dB ± 0.8 dB from 4 to 17.5 GHz. The insertion loss difference between he two states was not greater than 1.2 dB and generally less than 0.5 dB from 2 to 17.5 GHz. The return loss was greater than 10 dB from 6 to 18 GHz and greater than 8 dB from 4 to 18 GHz. Some further refinements of the performance of

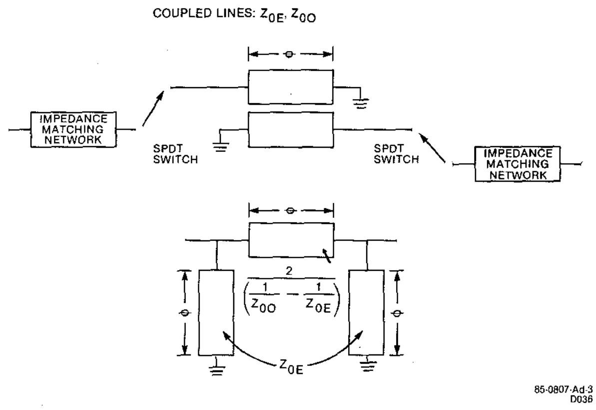

Figure 3. 180° Phase Shifter Bit Configuration.

this bit are possible.

The analog phase shifter section consists of a pair of varactor diode chips in series with a small bond wire inductance as the terminating elements of a 3 dB 90° hybrid coupler. The operation of this type of phase shifter has been previously described in the literature.

Computer aided design techniques were used to design a 4.5 to 18 GHz analog phase shifter section. A four finger interdigitated coupler was utilized on a 0.025 in thick alumina. The two varactor diodes, GaAs hyperabrupt chip tuning varactors manufactured by M/A COM, are mounted off the substrate on a pedestal and connected to the coupler by short bond wires. Voltage bias for the varactors was provided

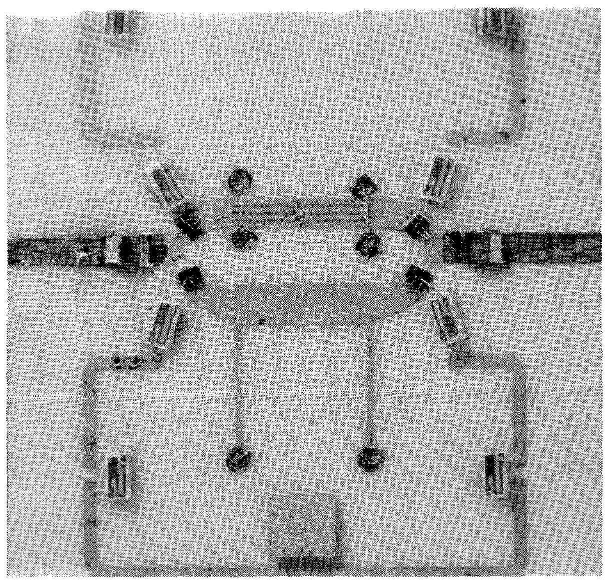

Figure 4. Photograph of Wideband 180° Phase Shifter Bit Utilizing FET Switches.

through chip resistors and DC blocking capacitors are employed at each end of the section. A photograph of the analog phase shifter section is shown in Figure 6.

The measured circuit performance of the analog phase shifter section is shown in Figure 7. The analog section provided at least 160° of phase shift from 4.5 to 18 GHz for a bias voltage range of +0.5 to -30V. The insertion loss of the section was less than 4.5 dB over the band. Insertion loss variations versus

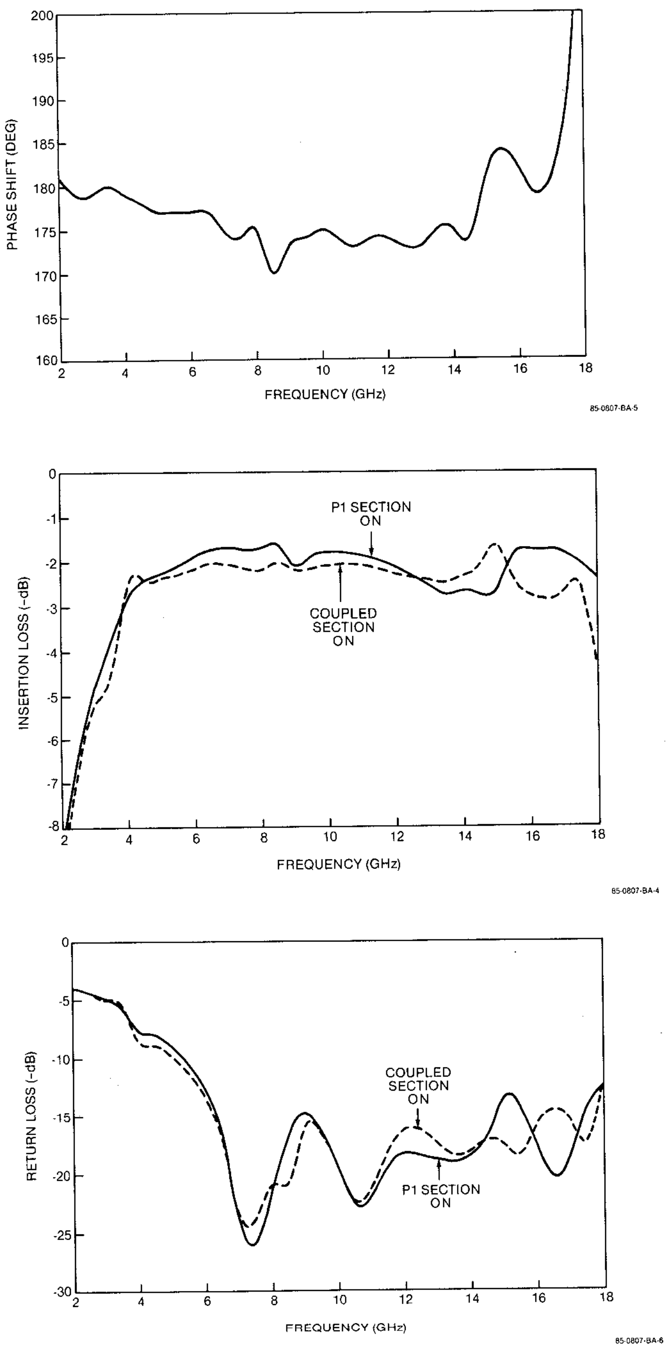

Figure 5. Circuit Performance of 180° Phase Shifter Bit.

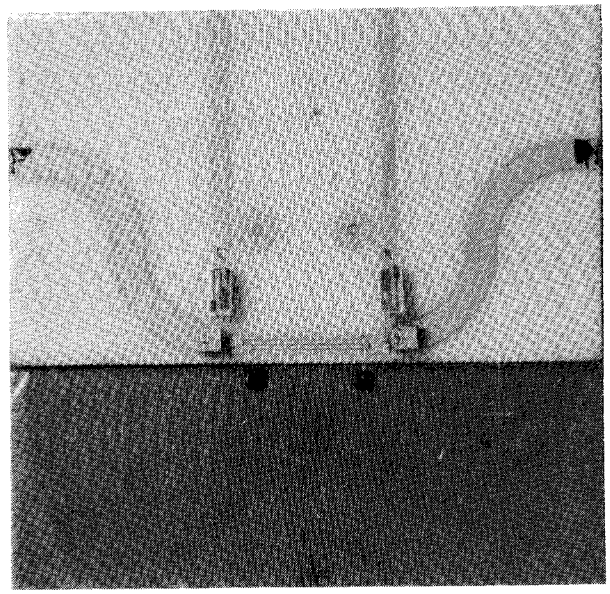

Figure 6. Photograph of Analog Phase Shifter Section.

applied voltage (phase shift) were less than 2.0 dB from 7 to 18 GHz and less than 3.5 dB from 4.5 to 18 GHz.

The phase shift versus frequency characteristic of the analog phase shifter section deviates from the desired flat response significantly over the bias range of +0.5 to -30V. This characteristic is unavoidable in this type of phase shifter. The phase flatness versus frequency characteristics can be improved by operating only in the most linear portion of the characteristic and accepting less total phase shift per section; i.e., using two analog sections of 90° each.

Another approach to the nonlinear phase shift versus frequency characteristics is to employ a "smart" silicon driver chip incorporating a "look up table" to determine to determine the appropriate voltage to obtain the desired phase shift at any particular frequency. This approach minimizes the size and cost of the more critical RF circuits (the GaAs chip in the case of an MMIC embodiment) of a phased array at the expense of the simpler driver circuits (a silicon chip).

Small insertion loss variations versus applied voltage (phase shift) in the analog phase shifter section of about 2 dB can be compensated in the 180° digital bit by changing the FET switch bias to make the "on" state resistance slightly higher. Experiments on the 180° digital bit indicate the 180° phase shift characteristic is affected negligibly with the introduction of small "on" state FET resistances.

Both the 180° digital bit and the analog phase shifter section are amenable to MMIC technology. Because the 180° phase shift of the digital bit was obtained independent of the

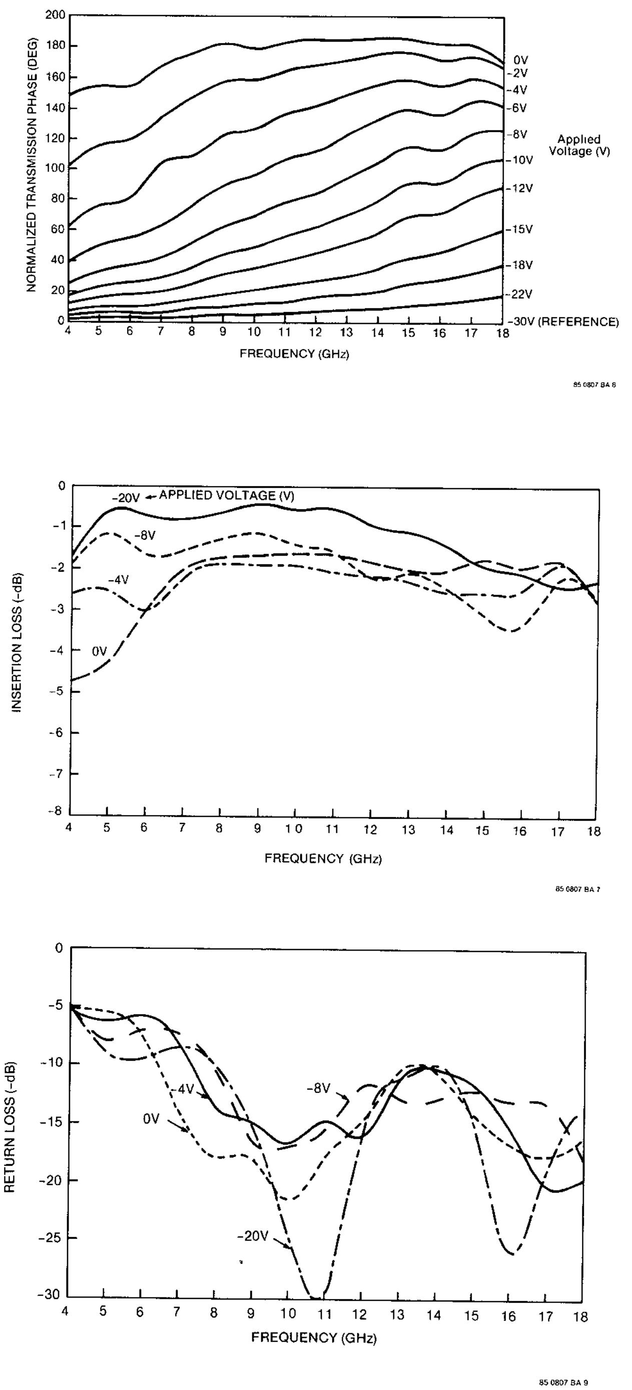

Figure 7. Measured Circuit Performance of Analog Phase Shifter Section.

electrical length of the phase difference sections, it could be made smaller and tuned at the low end of the band for insertion loss by lumped elements. By using only one analog phase shifter section and employing smart driver circuitry the phase shifter could be constructed with excellent performance over the 4.5 to 18 GHz band while minimizing its size and cost.

References

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