MINIATURE MULTI-KILOWATT PIN DIODE MIC DIGITAL PHASE SHIFTERS

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Abstract

A miniature high power, beryllia substrate, lumped element, PIN diode phase shifter has been developed. Design expressions are presented for two UHF models, which operate at kilowatt powers and exhibit 7% bandwidths with low insertion loss.

Introduction

Multi-kilowatt diode switched digital phase shifters have traditionally been physically large and expensive. The size, particularly at frequencies below 1 GHz, results from the use of designs which employ large numbers of quarter wave sections to reduce diode stresses and maintain impedance matching. Cost has been high because the large metallic sections required by these designs must be precision machined, and piece parts such as the diode holders and bias injection networks have been singularly expensive. These two constraints are overcome with the development of a MIC high power lumped element phase shifter on beryllia substrate which uses few piece parts and eliminates quarter wave coupling sections and impedance transformers. Two classes of phase shifters have been constructed. One, a 45° shifter, uses two series diodes separated by a passive lumped coupling section. The second, a 90° unit, uses three diodes in a pi network.

Analysis

The operation of phase shifters may be understood by considering the insertion phase characteristics of the switched low-pass and high-pass filter networks of Figure 1. The two states of such a phase shifter differ in insertion phase by the amount $\Delta\theta$. The design goal is to realize a constant $\Delta\theta$ over the operating band while maintaining good circuit impedance matches and a low insertion loss. At high power levels these objectives are necessarily compromised by the voltage and current stresses that can be tolerated by the switching diodes.

The analysis proceeds easily with the use of chain matrix techniques. The four complex chain matrix parameters of the general network defined in Figure 2a reduce to one real and two imaginary variables for circuits that are lossless and symmetric. As shown in Figure 2b, the expressions for the network terminal properties are thereby greatly simplified. In a phase shifter, the difference in insertion phase between the two states is made approximately constant over the operating band by forcing the band center phase slopes to be the same for both states of the network. The reflection coefficient slope then remains the one parameter which is available to directly optimize bandwidth.

We now restrict the analysis to the specific case of a two switched series element phase shifter. Such a circuit can be represented by two identical switched reactances which are joined by a symmetric lossless coupling network as shown in Figure 3a. In this type of phase shifter the phase is switched symmetrically about $\pm 90°$, depending upon the coupling section. While a lead network coupling section is seldom used in distributed circuit phase shifters for size and bandwidth reasons, it is preferred here because its use simplifies the diode biasing. Series switching allows operation directly at the 50 ohm system impedance level, eliminating the matching transformers common in high power circuits. It should be noted that by duality, the relations described in Figure 3a for series switched reactances are also valid for shunt switched susceptances if the susceptance variable b is substituted for x and the coupling network parameter γ is replaced by β.

A three diode phase shifter is formed by replacing the passive coupling section of Figure 3a by a third switching element. Such a pi network unit is shown in Figure 3b. A complete analysis is more complex for this network because the insertion phase is now a free parameter, constrained only by the required phase difference between the two states. Although the diode stress distribution is controlled by the value of the mean insertion phase, bandwidth constraints force the mean phase to be near 0° where the series diode experiences twice the VI stress on the shunt diodes.

Models

The models constructed have avoided the limitations of conventional high level phase shifters. The number of piece parts has been kept low through use of photolithographically processed microstrip and the beryllium oxide substrate material has enabled high component packing densities.

The lumped components used in the circuit consist of high-Q porcelain capacitors, saddle mounted diodes and thin film spiral inductors. Commercially available capacitors such as these have been found to tolerate several kilowatts of RF stress. The saddle mount supports the diode at both ends, providing good heat sinking and introducing little parasitic series inductance. The spiral inductors serve to inject bias and are capable of supporting several hundred volts of RF.

The schematic for the lumped constant 90° pi section is illustrated in Figure 4; Figure 5 is a photograph of the actual circuit. The two diode 45° section, designed using a 90° lead network as the coupling section, is pictured in Figure 6. The 45° section shown has been stressed to 7 KW and later generation models have withstood 15 KW without failure.

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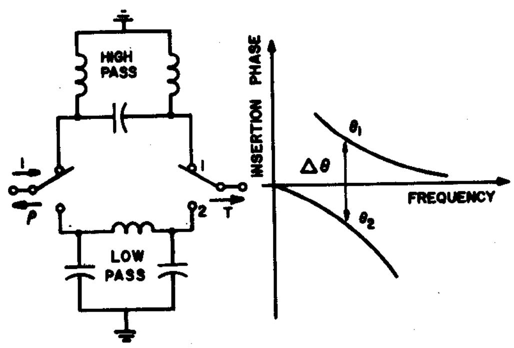
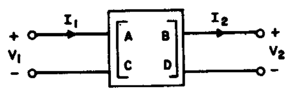
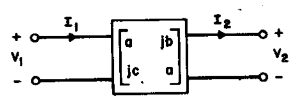


FIGURE 1



GENERAL NETWORK

FIGURE 2a



LOSSLESS SYMMETRIC NETWORK

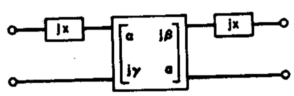
TRANSMISSION

$$T = \frac{2}{2a + j(b+c)} = |T| e^{j\theta}$$

REFLECTION

$$\rho = \frac{j(b-c)}{2a + j(b+c)}$$

FIGURE 2b



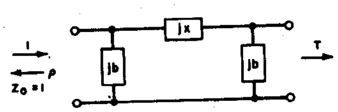
MODEL FOR TWO SERIES SWITCHED ELEMENT PHASE SHIFTER

MATCH $x_{\frac{1}{2}} = \frac{\alpha \pm \sqrt{1-\gamma^2}}{\gamma}$

PHASE SHIFT $x_1 - x_2 = 2 \tan \frac{\Delta\theta}{2}$; $\gamma = \pm \cos \frac{\Delta\theta}{2}$

CONSTANT PHASE SLOPE $\gamma(\dot{x}_1 - \dot{x}_2) + \dot{\gamma}(x_1 - x_2) = 0$

FIGURE 3a



MODEL FOR THREE SWITCHED ELEMENT PHASE SHIFTER

MATCH CONDITION

$$b = -\tan \frac{\theta}{2} \; ; \quad x = -\sin\theta$$

$$|\dot{\rho}| = \left| \frac{\dot{x}}{1+\cos\theta} - \dot{b}\cos\theta \right|$$

PHASE SLOPE

$$\dot{\theta} = -\left(\dot{b} + \frac{\dot{x}}{1+\cos\theta}\right)$$

FIGURE 3b

LUMPED CONSTANT 90° BIT

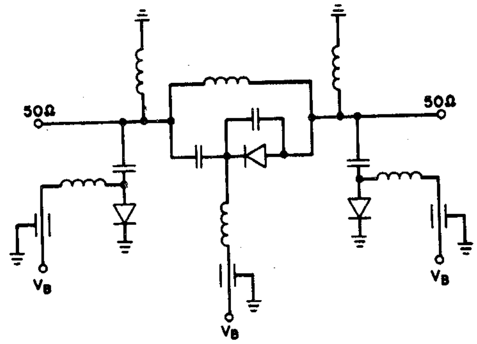


FIGURE 4

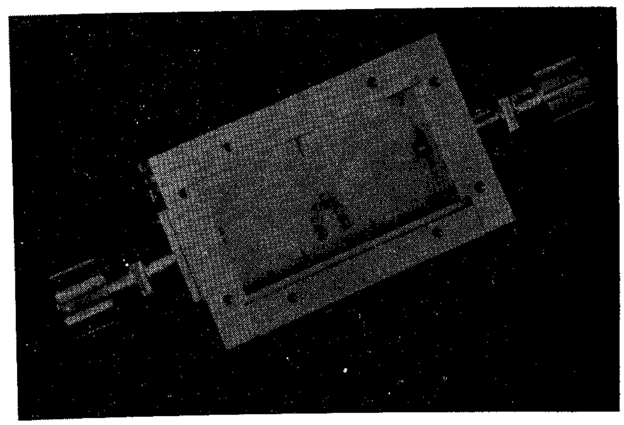


Figure 5. Lumped Constant 90° Model.

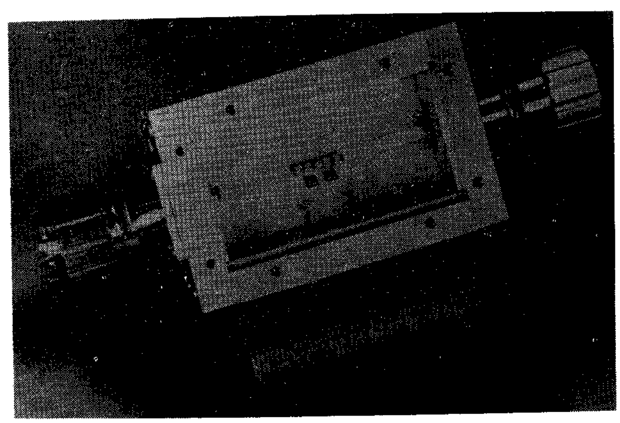


Figure 6. Lumped Constant 45° Model.