Desegmentation Method for Analysis of Two-Dimensional Microwave Circuits

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Abstract—A new method for the analysis of two-dimensional planar circuits called the "desegmentation" method is proposed. This method is applicable to configurations which can be converted into regular shapes (for which Green's functions are known) by adding one or more regular shaped segments to them. Two examples of planar circuits, chosen such that the results could be verified by the previously known segmentation technique, illustrate the validity of the method.

I. Introduction

TWO-DIMENSIONAL planar circuit elements have been proposed [1]–[3] for use in microwave integrated circuits (MIC's) in stripline and microstrip line configurations. The analysis of this type of circuit involves determination of the circuit parameters of its equivalent n-port network as a function of frequency by solving the two-dimensional wave equation subject to the boundary conditions of a magnetic wall around the periphery. When the circuit pattern is of regular shape (i.e., for which Green's function is known as, for example, rectangular, circular, equilateral triangular, etc.), the Green's function technique can be used to solve the problem analytically [1]. Also if the pattern can be divided into segments having regular shapes the segmentation methods [2], [3] can be used for analysis. Sometimes a planar circuit can be extended to a regular shape by adding another segment (or segments) of regular shape to it. Two examples of this kind are shown in Fig. 1. The trapezoidal planar circuit of Fig. 1(a) can be converted into a triangular circuit of Fig. 1(b) by the addition of a triangular segment while the rectangular circuit with a slot (Fig. 1(c)) can be converted into a complete rectangle by the addition of another rectangle as illustrated in Fig. 1(d). In general, in the desegmentation method being proposed here, a regular pattern β is added to a nonregular pattern α (for which Green's function is not available) such that the resulting combination of α- and β-segments is also a regular pattern γ. The characteristics of β- and γ-segments can be computed using Green's function method. The characteristics of the α-circuit can be calculated by the method of "desegmentation" described in this paper.

The desegmentation method can be formulated to evaluate either the S-matrix or Z-matrix for the α-network, in terms of those for the β- and the γ-elements. However,

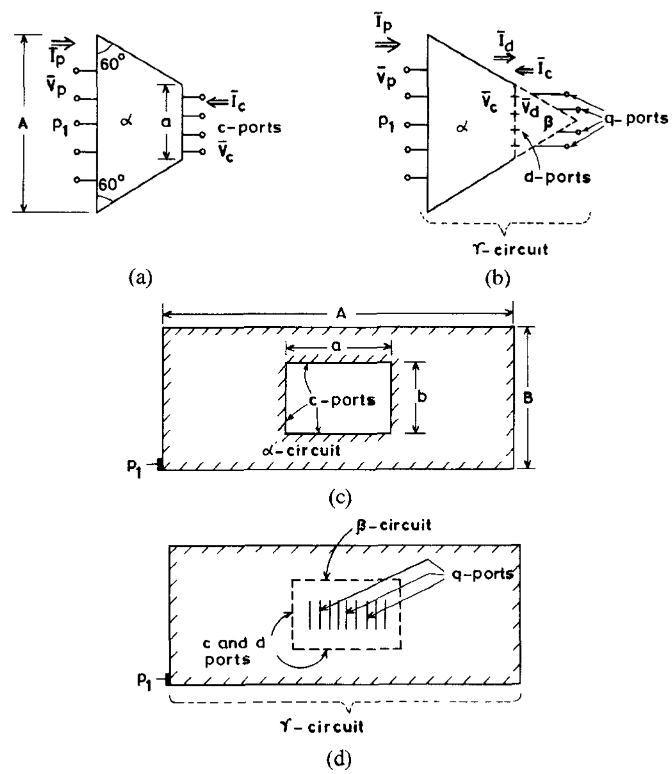

Fig. 1. Examples of planar circuits analyzed by desegmentation method. (a) A trapezoidal planar circuit. (b) Desegmentation method applied to (a). (c) Rectangular ring planar circuit. (d) Desegmentation method applied to (c).

for the segmentation method, it has been shown that the use of Z-matrices is computationally more efficient because Green's function for planar elements yields the Z-matrices directly. Also when this technique is used for analyzing microstrip antennas [4], one is interested in evaluating the equivalent magnetic current or the voltage along the periphery of the antenna. The voltage along the periphery can be calculated by dividing the periphery into a large number of ports and finding the voltage at these ports from the Z-matrix of the multiport network thus formed. Thus the Z-matrix approach is convenient for the antenna analysis also. Consequently, only the Z-matrix formulation is discussed in this paper.

II. Theoretical Formulation

Consider the circuit shown in Fig. 1(a) and its extension by desegmentation as shown in Fig. 1(b). As in the segmentation method, the continuous interconnection between

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α- and β-segments is replaced by a discrete number of interconnected ports, named c-ports on α-segment and d-ports on β-segment. Their number $(=C=D)$ depends on the variation of the field along the interconnection and is found by an iterative process in numerical computations. Ports p and q are the external (unconnected) ports of α- and β-segments, respectively.

We define I_p, I_c, I_d, and I_q as the currents, and V_p, V_c, V_d, and V_q as the voltages, at the ports p, c, d, and q, respectively, where $p=1,2,\cdots,P$; $c=1,2,\cdots,C$; $d=1,2,\cdots,D$; and $q=1,2,\cdots,Q$. Since c-ports are connected to respective d-ports, we have $C=D$ and

$$V_c=V_d \qquad I_c=-I_d. \tag{1}$$

The Z-matrices for α, β- and γ-segments, namely $\tilde{Z}_\alpha$, $\tilde{Z}_\beta$, and $\tilde{Z}_\gamma$, respectively, can be partitioned into submatrices corresponding to the external (unconnected) and connected ports as follows:

$$\tilde{Z}_\alpha=\begin{bmatrix}\tilde{Z}_{pp\alpha} & \tilde{Z}_{pc}\\ \tilde{Z}_{cp} & \tilde{Z}_{cc}\end{bmatrix} \tag{2}$$

$$\tilde{Z}_\beta=\begin{bmatrix}\tilde{Z}_{dd} & \tilde{Z}_{dq}\\ \tilde{Z}_{qd} & \tilde{Z}_{qq\beta}\end{bmatrix} \tag{3}$$

$$\tilde{Z}_\gamma=\begin{bmatrix}\tilde{Z}_{pp\gamma} & \tilde{Z}_{pq}\\ \tilde{Z}_{qp} & \tilde{Z}_{qq\gamma}\end{bmatrix}. \tag{4}$$

The third subscript with submatrices in (2)–(4) is used to distinguish the submatrices of the same order in $\tilde{Z}_\alpha$, $\tilde{Z}_\beta$, and $\tilde{Z}_\gamma$. If $\tilde{Z}_\alpha$ and $\tilde{Z}_\beta$ are known, $\tilde{Z}_\gamma$ can be computed using the segmentation method [3]. $\tilde{Z}_\gamma$ thus obtained, by using (1), (2), and (3), is given by

$$\tilde{Z}_\gamma=\begin{bmatrix}\tilde{Z}_{pp\alpha}-\tilde{Z}_{pc}\tilde{Z}'_{dp} & \tilde{Z}_{pc}\tilde{Z}'_{dq}\\ \tilde{Z}_{qd}\tilde{Z}'_{dp} & \tilde{Z}_{qq\beta}-\tilde{Z}_{qd}\tilde{Z}'_{dq}\end{bmatrix} \tag{5}$$

where

$$\tilde{Z}'_{dp}=\left[\tilde{Z}_{cc}+\tilde{Z}_{dd}\right]^{-1}\tilde{Z}_{cp}$$

$$\tilde{Z}'_{dq}=\left[\tilde{Z}_{cc}+\tilde{Z}_{dd}\right]^{-1}\tilde{Z}_{dq}.$$

In the desegmentation method we express $\tilde{Z}_\alpha$ in terms of $\tilde{Z}_\beta$ and $\tilde{Z}_\gamma$ using (4) and (5). This is equivalent to obtaining $\tilde{Z}_\alpha$ in terms of $\tilde{Z}_\beta$ and $\tilde{Z}_\gamma$ employing the interconnection relations given in (1).

If the currents at ports p and q are considered as known excitations and other variables, namely, the voltages at p-, c-, d-, and q-ports and the currents at c- and d-ports are determined, the impedance matrix $\tilde{Z}_\alpha$ can be evaluated. In this formulation the unknowns, P voltages at p-ports, Q voltages at q-ports, C voltages and C currents at c-ports, and D voltages and D currents at d-ports, are added to $(P+Q+4D)$. The number of equations available is as follows: $(D+Q)$ equations from the definition of $\tilde{Z}_\beta$, $(P+Q)$ equations from the definition of $\tilde{Z}_\gamma$, and $2D$ equations from (1). These add up to only $(P+2Q+3D)$ equations. In order that $\tilde{Z}_\alpha$ obtained be unique, it is necessary and sufficient that

$$(P+2Q+3D)\geqslant(P+Q+4D) \tag{6}$$

which implies $Q\geqslant D$. Therefore, in the desegmentation method the number of q-ports $(=Q)$ on the periphery common to β- and γ-segments should be at least equal to the number of interconnected ports $(=C=D)$. Since β- and γ-segments are regular shapes, the submatrices of $\tilde{Z}_\beta$ and $\tilde{Z}_\gamma$ can be computed using the corresponding Green's functions. Therefore, the left-hand side of (5) is known. Thus for $Q\geqslant D$, $\tilde{Z}_\alpha$ can be computed from (5) as follows. Comparing submatrices of (4) and (5), we have

$$\begin{aligned}\left[\tilde{Z}_{qq\gamma}-\tilde{Z}_{qq\beta}\right]&=-\tilde{Z}_{qd}\tilde{Z}'_{dq}\\ &=-\tilde{Z}_{qd}\left[\tilde{Z}_{cc}+\tilde{Z}_{dd}\right]^{-1}\tilde{Z}_{dq}.\end{aligned} \tag{7}$$

This equation can be solved for $\tilde{Z}_{cc}$ to give

$$\tilde{Z}_{cc}=-\tilde{Z}_{dd}-\tilde{Z}_1 \tag{8}$$

where

$$\tilde{Z}_1=\tilde{Z}_{dq}\tilde{Z}^t_{dq}\left[\tilde{Z}^t_{qd}\left[\tilde{Z}_{qq\gamma}-\tilde{Z}_{qq\beta}\right]\tilde{Z}^t_{dq}\right]^{-1}\tilde{Z}^t_{qd}\tilde{Z}_{qd} \tag{8a}$$

and the superscript t indicates transpose of a matrix. Employing (5) and (8), other submatrices of $\tilde{Z}_\gamma$ can be expressed as

$$\tilde{Z}_{pq}=-\tilde{Z}_{pc}\tilde{Z}_1^{-1}\tilde{Z}_{dq} \tag{9}$$

$$\tilde{Z}_{qp}=-\tilde{Z}_{qd}\tilde{Z}_1^{-1}\tilde{Z}_{cp} \tag{10}$$

$$\tilde{Z}_{pp\gamma}=\tilde{Z}_{pp\alpha}+\tilde{Z}_{pc}\tilde{Z}_1^{-1}\tilde{Z}_{cp}. \tag{11}$$

Equations (9)–(11) can be rearranged to give submatrices of $\tilde{Z}_\alpha$ as

$$\tilde{Z}_{pc}=-\tilde{Z}_{pq}\tilde{Z}^t_{dq}\left[\tilde{Z}_{dq}\tilde{Z}^t_{dq}\right]^{-1}\tilde{Z}_1 \tag{12}$$

$$\tilde{Z}_{cp}=-\tilde{Z}_1\left[\tilde{Z}^t_{qd}\tilde{Z}_{qd}\right]^{-1}\tilde{Z}^t_{qd}\tilde{Z}_{qp} \tag{13}$$

$$\tilde{Z}_{pp\alpha}=\tilde{Z}_{pp\gamma}-\tilde{Z}_{pc}\tilde{Z}_1^{-1}\tilde{Z}_{cp}. \tag{14}$$

The Z-matrix of α-segment, as partitioned in (2), is thus given by (8), (12), (13), and (14). The procedure for computing $\tilde{Z}_\alpha$ from (8) and (12) to (14) is, therefore, to compute $\tilde{Z}_1$, $\tilde{Z}_{cc}$ from (8), $\tilde{Z}_{pc}$ and $\tilde{Z}_{cp}$ from (12) and (13), and finally $\tilde{Z}_{pp\alpha}$ from (14). As mentioned earlier, the expressions for $\tilde{Z}_\alpha$ obtained above hold good for $Q\geqslant D$. The computations get simplified if D can be made equal to Q. In planar circuits this condition can be met, since the number of interconnected ports can always be made greater than the minimum needed for the convergence of the results or Q can be increased by adding additional ports on the segment β. In this case, when $D=Q$, we have

$$\tilde{Z}_1=\tilde{Z}_{dq}\left[\tilde{Z}_{qq\gamma}-\tilde{Z}_{qq\beta}\right]^{-1}\tilde{Z}_{qd} \tag{8b}$$

and $\tilde{Z}_\alpha$ can be expressed as

$$\tilde{Z}_\alpha=\begin{bmatrix}\tilde{Z}_{pp\gamma}-\tilde{Z}_{pq}\tilde{Z}'_{qp} & -\tilde{Z}_{pq}\tilde{Z}'_{qd}\\ -\tilde{Z}_{dq}\tilde{Z}'_{qp} & -\tilde{Z}_{dd}-\tilde{Z}_{dq}\tilde{Z}'_{qd}\end{bmatrix} \tag{15}$$

where

$$\tilde{Z}'_{qp} = \left[\tilde{Z}_{qq\gamma} - \tilde{Z}_{qq\beta}\right]^{-1} \tilde{Z}_{qp}$$

$$\tilde{Z}'_{qd} = \left[\tilde{Z}_{qq\gamma} - \tilde{Z}_{qq\beta}\right]^{-1} \tilde{Z}_{qd}.$$

It can be seen from (15) that it is not necessary to follow any sequence, as is required in the general case, for computing the submatrices of $\tilde{Z}_\alpha$ when $D=Q$.

The $\tilde{Z}_\alpha$, obtained in both the cases discussed above, is the Z-matrix of the α-segment to which several c-ports have been added at the interface between α- and β-segments. Some of these c-ports may be the original c-ports, of the α-segment, for which the Z-parameters are required, and others are the ports added for computations in the desegmentation method outlined above. The Z-matrix pertaining to the original ports only, of α circuit, can be written by discarding the rows and columns corresponding to the c-ports added during computations of $\tilde{Z}_\alpha$ from (15).

One of the methods, of selecting the number of Q-ports, which has been used successfully in several cases is as follows. Consider a special case with $P=1$. Starting with an assumed value of $Q=1$, evaluate $\tilde{Z}_{pp\alpha}$ by using a part of (15) which may be rewritten as

$$\tilde{Z}_{pp\alpha} = \tilde{Z}_{pp\gamma} - \tilde{Z}_{pq}\left[\tilde{Z}_{qq\gamma} - \tilde{Z}_{qq\beta}\right]^{-1} \tilde{Z}_{qp}. \tag{16}$$

It may be noted that for computing $\tilde{Z}_{pp\alpha}$ we do not need to evaluate $\tilde{Z}_{dd}$, $\tilde{Z}_{dq}$, and $\tilde{Z}_{qd}$. Only the evaluations of $\tilde{Z}_\gamma$ and $\tilde{Z}_{qq\beta}$ are required which do not involve the Z-parameters corresponding to c- and d-ports. The value of the number Q is increased iteratively until the value of $\tilde{Z}_{pp\alpha}$, calculated from (16), converges. This gives the value of Q, that is, the minimum number of q-ports needed for computations. The number of c- and d-ports should be at least equal to this value. In the number of examples that have been studied, it is found that this is also the sufficient number of c-ports required for convergence of $\tilde{Z}_\alpha$.

It may be noted that, if $\tilde{Z}_{qq\gamma} = \tilde{Z}_{qq\beta}$, both (8a) and (8b) become indeterminate and the desegmentation method cannot be used. However, such a situation is rare in the case of two-dimensional planar circuits.

III. Examples and Discussion

For illustrating the validity and applications of the desegmentation method, two examples of the analysis of planar circuits are discussed in this section. The circuits chosen are such that the results could be verified by the previously used segmentation method also.

A. Example 1

Consider the trapezoidal planar circuit configuration shown in Fig. 1(a). It is desired to evaluate the input impedance, for this one port circuit, at port p_1. This impedance has been evaluated using both the desegmentation method proposed in this paper and the segmentation method known earlier [3].

For employing the desegmentation method, an equilateral triangle β is added to the trapezoid (α-segment) so that the combination of α and β is also an equilateral triangle γ as shown in Fig. 1(b). The Z-matrices for β- and γ-segments are computed using Green's function [6]. The number of the q-ports is decided by following the procedure outlined in the previous section and is found to be 4. The width of the q-ports is chosen small enough so that the field variation, over a port width, can be assumed to be negligible. As there is no specified port of the initial α-circuit corresponding to the c-ports, (16) yields the value of the input impedance needed. Fig. 2 shows the variation of this input impedance with frequency for the case when $A=3.1711$ cm, $a=0.25$ A, $\epsilon_r=2.55$, and the thickness of the dielectric substrate $d=1.6$ mm.

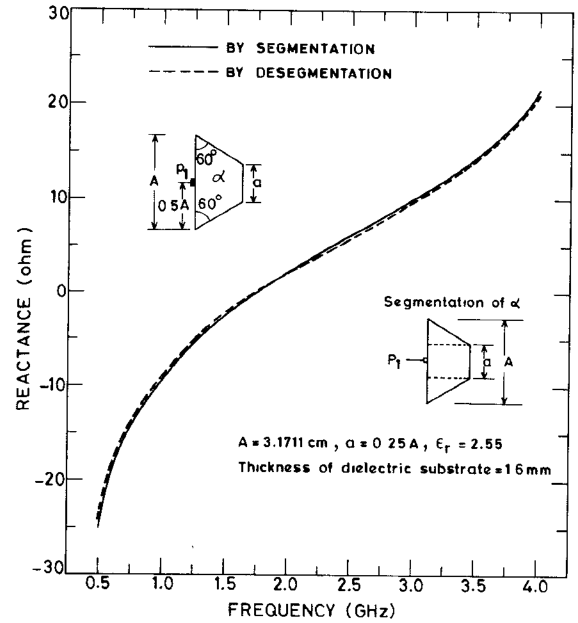

Fig. 2. Variations of input impedance of trapezoidal circuit as calculated by the segmentation and the desegmentation methods.

For the analysis using the segmentation method, the trapezoidal circuit is divided in three segments, i.e., two 30°–60° right triangles and one rectangle as illustrated in Fig. 2 (inset). The Z-matrices for these segments are computed using Green's functions [1], [6]. $\tilde{Z}_{pp\alpha}$ is then computed using the segmentation method for Z-matrices [3]. It is found that the number of interconnecting ports (between the rectangle and two 30°–60° triangles) required for convergence of $\tilde{Z}_{pp\alpha}$ is 16. The results obtained by this method are also plotted in Fig. 2 and agree very well with those obtained by the desegmentation method.

B. Example 2

Another example considered is a rectangular ring type planar circuit shown in Fig. 1(c). In this case also it is required to find out the input impedance at the port p_1 of the α-circuit. In this case β-segment is a rectangular element of length "a" and width "b" which when added to α-pattern of Fig. 1(c) results in a complete rectangular planar circuit γ as shown in Fig. 1(d). The characteristics of the small rectangle β and the outer (filled) rectangle γ, of dimensions $A \times B$, are computed using Green's function [1]. In this case the total periphery of the β-segment is common

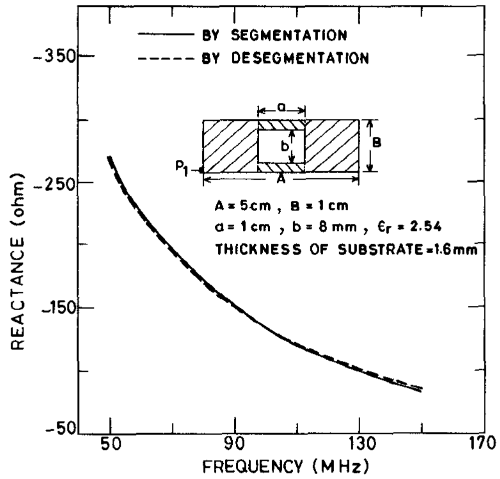

Fig. 3. Variation of input impedance of rectangular ring circuit, as calculated by segmentation and desegmentation methods.

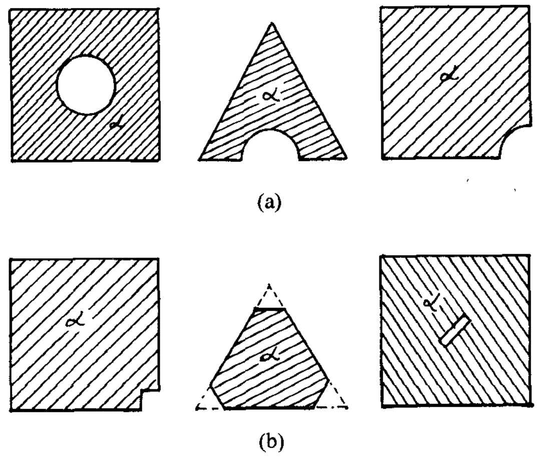

Fig. 4. (a) Examples of circuit patterns which can be analyzed only by desegmentation. (b) Examples of circuits for which desegmentation is more efficient.

with the inner periphery of the α-segment. The ports c and d are located along this interconnection. Thus there is no part of the periphery, of the β-segment, left for locating the q-ports. Since Q (the number of q-ports) cannot be made zero, these ports are located inside the β-segment (i.e., inside the small rectangle). These are the fictitious ports, with port voltages measured between the port locations and the ground plane. As in the case of the ports on periphery, in this case also the voltages are averaged over each port width. The port current is considered to flow in the direction normal to the plane of the paper. The formulation presented in the previous section holds good for such a case also. The minimum number of q-ports is decided by following the same procedure as used in Example 1 and is found to be 9. These q-ports are indicated by vertical bars in Fig. 1(d). The widths of these ports have also been selected iteratively for fast convergence of numerical computations. The values of the input impedance obtained are plotted in Fig. 3, as a function of frequency, for the case when $A = 5$ cm, $B = 1$ cm, $a = 1$ cm, $b = 8$ mm, $\epsilon_r = 2.54$, and thickness of substrate is 1.6 mm.

This circuit is analyzed using the segmentation method also. The α-circuit is divided into four segments as shown in Fig. 3 (inset). In this example, the number of interconnected ports required, between the various segments, is found to be 4. The results agree very well with those obtained from the desegmentation method as shown in Fig. 3.

The two examples discussed above illustrate the validity and the applications of the desegmentation method proposed in this paper. Of course, the examples chosen are such that the segmentation method is possible, so that comparisons can be made. There are several situations where the segmentation is not possible and the desegmentation method can be used. Some examples of this type are shown in Fig. 4(a). Also there could be situations where the desegmentation method is more efficient. This is likely to happen when the size of the β-segment (needed to convert the α-segment into a regular shape γ) is small compared to the α- and the γ-segments. Some examples of this type are shown in Fig. 4(b).

IV. Concluding Remarks

The desegmentation method is also applicable to transmission line circuits and lumped element circuits. This method can be considered a generalization of the "de-embedding" problem discussed in [7] for eliminating the effects of connectors, etc., from the measured data. In this case, the total system can be treated as the γ-segment whose characteristics are measured. The embedding network (connectors etc.) becomes the β-segment (characterized by previous calibration) and the device or the network under test is the α-segment whose characteristics are to be found.

The desegmentation method, as presented in this paper, extends the applicability of the Green's function technique for analysis of two-dimensional planar circuits. It is expected to find applications in the analysis of microstrip and stripline circuits and also for studying two-dimensional microstrip antenna configurations.

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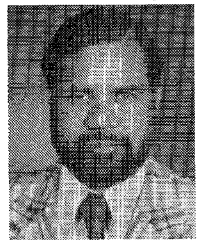

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Short Papers

Broad-Band Active Phase Shifter Using Dual-Gate MESFET

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***Abstract*— This paper describes a broad-band, dual-gate MESFET phase shifter (vector generator), operating over the 4–8-GHz frequency band and capable of a continuous phase shift and multiplicity of modulations including digital phase shift and amplitude modulation directly, and indirectly (with additional information processing circuits), single sideband modulation, frequency modulation, and phase modulation, etc. A dual-gate FET is used as a variable gain amplifier and phase shift is obtained by complex addition of two orthogonal variable vectors. The principle of the phase shifter and the experimental results are presented.**

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I. Introduction

In the past, ferrite phase shifters have been used in the phased array radar systems. The p-i-n diode phase shifters are being considered because of their lighter weight, higher speed, and transmission reciprocity as compared to the ferrites [1]–[4]. The ferrite and p-i-n diode phase shifters, however, still suffer from a relatively slow response time. The recent interest in fully active phased array radars as well as progress in the monolithic GaAs integrated circuits has opened the possibility of realizing active phase shifting subassemblies based upon GaAs field-effect transistors (FET's).