Applications of the Finite Difference Techniques to the Compensated VIP 3 dB Directional Coupler

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Abstract— **A new and simple compensated structure for a vertically installed planar (VIP) 3 dB directional coupler has been studied theoretically as well as experimentally by combining an improved 2-D-general finite difference (2-D-GFD) design procedure with a three-dimensional finite difference time domain (3-D-FDTD) method. The obtained full wave analysis results agree well with the measured ones. The investigations have shown that with this planar compensated structure, a better performance of the VIP coupler in the L-band can be realized by only using the same kind of dielectric substrate for its vertical and horizontal one.**

I. Introduction

IN RECENT years, quite a few research papers on various new planar 3 dB directional couplers or quadrature hybrids have been published [1]–[4]. Good performances can be realized theoretically as well as experimentally by using different structures such as the vertically installed planar (VIP) line [1], slot-coupled line [2], circular disc [3], or rectangular disk [4]. Although these designs were reported to be successfully applied into the L or S-band, the application practice requires that their sizes should be further smaller [5] and the configurations should be more easily calculated and manufactured. Therefore, from these view points, we have set up to start the VIP coupler research.

The VIP directional couplers are new kinds of directional couplers, which have the advantages such as simple structure, small size and good performances. The first research paper about the VIP coupler was reported in 1987 [5]. Since then, there have been several papers reported [1], [6], and [7]. But until now, some special requirements on the design of VIP devices have been existing, which limit their further applications. The permittivity of the vertical substrate should be carefully chosen to be about half of the horizontal one according to the proposed design [1]. Although a three-layer structure for the vertical substrate was taken into consideration [6], it is difficult to be fabricated in practice because of its complicated structure.

Therefore, in order to improve the mass-producibility of a VIP coupler, a new planar compensation structure has been studied experimentally and theoretically in this paper. The results have shown that one can obtain a better frequency response on the S parameters by only adding some simple short microstrip fins and stubs to the VIP coupler circuit.

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Although designs of the VIP coupler can be performed by use of boundary element method (BEM) [1] or finite difference method (FDM) [6] and [8], it is difficult to obtain a good coincidence with experiment for the reflection or isolation of the device by use of those two-dimensional (2-D) methods. A more effective three-dimensional (3-D) calculation method should be considered.

Three-dimensional finite difference time domain (3-D-FDTD) method, which has found very extensive applications in dealing with scattering problems, analyzing distributions of the EM fields and predicting characteristics of various microwave devices of complex structures, will be put into considerations for the design and analysis on the VIP coupler in this paper. The method is very useful to show the characteristics of a device over a very wide frequency spectrum. However, it is usually time consuming and inconvenient when it is used in the device design calculation.

Therefore, in this paper, the investigations based on an improved two-dimensional general finite difference (2-D-GFDM) will be treated as a fundamental or first step for designing and analyzing this compensated VIP directional coupler approximately. The improved three-dimensional finite difference time domain (3-D-FDTD) [9] will be further applied to perform accurate calculations. In this way, we can perform an effective analysis on compensated VIP directional coupler. The measured results in the L-band will be given, which conform well with obtained results from the above mentioned calculation process.

II. The Structure of the Compensated VIP Directional Coupler

A configuration of the proposed compensated VIP directional coupler is illustrated in Fig. 1. The vertically installed line is simply a rectangular cut of a substrate, the permittivity of which can be the same as the horizontal one or greater than it. The structure shown in Fig. 1 allows values of ε_{r1} up to 4, and that of ε_{r2} equal to or less than ε_{r1}. But our study assumes that ε_{r2} is equal to ε_{r1} and the thickness of both substrates is the same hereafter. This restriction is very important for practical ease of fabrication. Fig. 2 is just a top view of this device. The length L between the two pairs of I/O lines is chosen as a quarter wavelength at the center frequency [1] and [6]. But the length of L_v, according to the FDTD calculation results, must be less than L because of the compensation effect of the patterns $W_1 \times L_1$ and $W_2 \times L_2$. The height of the vertical line h_v can be calculated by 2-D-GFDM proposed in this paper. Principally, the compensation fins $(W_1 \times L_1)$ in the

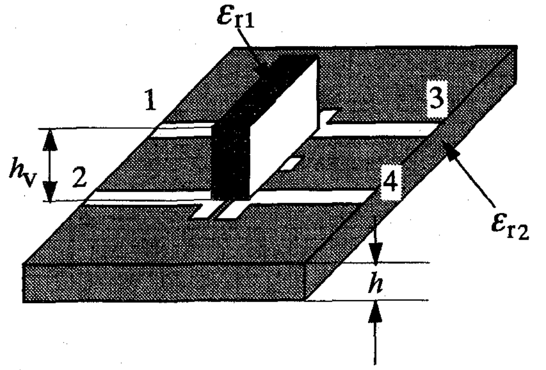


Fig. 1. The compensated VIP directional coupler.

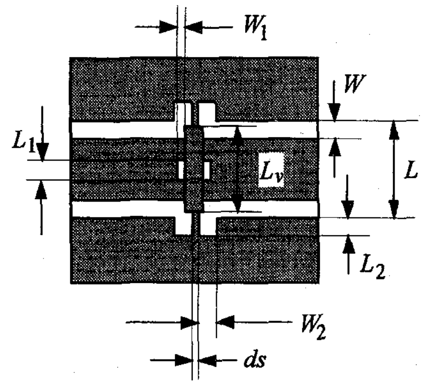


Fig. 2. A top view of the whole planar compensation structure.

center will contribute mainly to reduce the difference between the even and odd mode effective dielectric constants, and the other two pairs of the stubs ($W_2 \times L_2$) at the terminals of the coupling sections will mainly perform the input impedance adjustment of the VIP coupling section.

Although the equivalent circuit analysis method [10] can be applied here to analyze the functions of those compensation lines, we have applied the following new process to simplify the calculations: First to find the basic size of the VIP coupling section by use of an improved FDM; then to compute the whole compensated structure accurately by use of 3-D-FDTD method. Therefore, we can effectively perform a three dimensional design or a full wave analysis on the complex VIP coupler's structure without consuming too much CPU time. This is because some initial values needed in the 3-D-FDTD simulations have been offered by the 2-dimensional approximation analysis and design, which is based on the TEM transmission theory [11]–[13] and easy to be performed.

III. Approximate Design by Use of 2-D-GFDM

A VIP directional coupler can be considered as a quasi-TEM mode device [6], [8], and [11]. Therefore, the well-known formulas for the characteristic impedance Z_c and effective dielectric constant $\varepsilon_{r,eff}$

$$
\begin{aligned}
Z_c &= \sqrt{\frac{\mu_o \varepsilon_o}{C_o C_\varepsilon}} \\
&= \sqrt{\frac{\mu_o \varepsilon_o}{4W_o W_\varepsilon}} \\
\varepsilon_{r,eff} &= \frac{W_\varepsilon}{W_o}
\end{aligned} \tag{1}
$$

can be utilized, where the subscript ε or o represents dielectric material or air filled in the coupling section, respectively. In this paper, the general finite difference method (GFDM) has been developed to perform the approximate design. The computing process includes: first to calculate the potential distribution of the cross section of the coupled line by use of the formula given in [6]; then a new equation shown in (A1) will be applied to calculate the $W_{\varepsilon,o}$. The whole design process by use of the proposed GFDM.

1) Determine h_v, the height of vertical coupling section, which gives a proper even and odd mode impedance $Z_{c,odd}$ and $Z_{c,even}$. According to our investigations, the target values for an ideal 3 dB directional coupler

$$
\begin{aligned}
Z_{c,odd} &\approx 20.71\,\Omega \\
Z_{c,even} &\approx 120.71\,\Omega
\end{aligned} \tag{2}
$$

can not be satisfied at the same time with equality of the effective dielectric constants for the even and odd modes [6]–[8], and [10]–[13]. Since the electric field goes out into the air region for the even mode more than for the odd mode, the $\varepsilon_{re,eff}$ is always smaller than the $\varepsilon_{ro,eff}$. Thus, we choose h_v, which realize (2) approximately, disregarding the effective dielectric constants.

First, the iteration equations shown in [6] is applied to solve the potential distribution across the 2-D plane and, then the obtained potential values are put into (A1) to compute the energy $W_{\varepsilon,o}$. In these calculations, the symmetry principle should be applied along the central line of the half cut cross section of a VIP coupler shown in Fig. 3. Thus, we can find even and odd mode parameters effectively with the Successive Over Relaxation (SOR) method [6] and [8].

2) Determine $W_1 \times L_1$, the size of central compensation fins, which gives the same effective dielectric constants for the even and odd modes as possible. Because $\varepsilon_{re,eff}$ of the even mode increases faster than that of the odd mode by adding W_1 to a VIP coupled lines, we can reduce the difference between them. But this process also reduces the characteristic impedances of both modes, $Z_{c,odd}$ and $Z_{c,even}$ at the same time, thus one has to stop the above process before having $Z_{c,even}$ less than 60% of (2).

Addition of $W_1 \times L_1$ patterns on both sides of a VIP coupler as shown in Fig. 2 means that the total characteristics for the characteristic impedance of $Z'_{c,odd}$ and $Z'_{c,even}$ are approximated by a certain average of VIP couplers with and without the fins of width W_1. The averaging procedure is described in the Appendix and the empirical formulas on W_1, and L_1 have been obtained as

$$
\begin{aligned}
W_1 &\approx (0.4 \sim 0.6) \times W \\
L_1 &\approx \left(\tfrac{1}{6} \sim \tfrac{1}{8}\right) \times L
\end{aligned} \tag{3}
$$

where W corresponds to a 50 Ω microstrip line impedance and L is the theoretical length of the coupling section. The

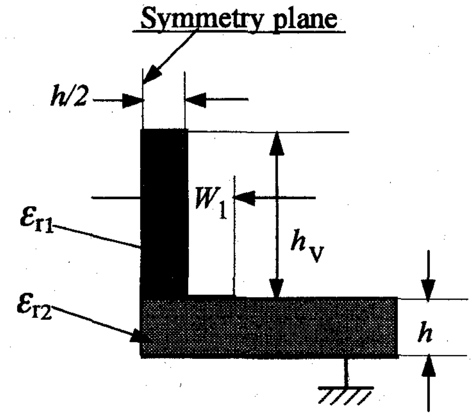
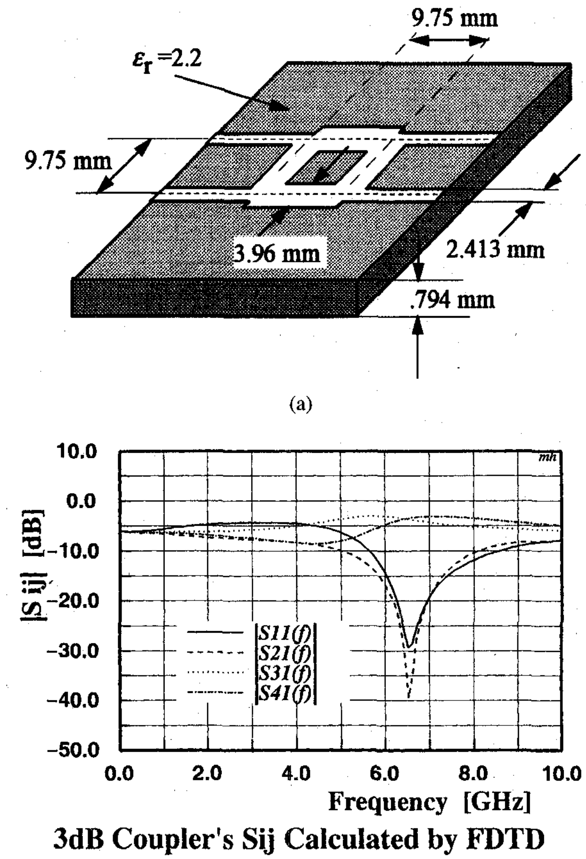


Fig. 3. The cross-sectional views of a compensated VIP directional coupler.

TABLE I
EVEN AND ODD MODE EFFECTIVE DIELECTRIC CONSTANTS OF A MICROSTRIP COUPLER

	this paper (GFDM)	Ref.[14] (Integral method)	Ref.[12] (Green's function)
s/h	$\varepsilon_{re,eff}/\varepsilon_{ro,eff}$	$\varepsilon_{re,eff}/\varepsilon_{ro,eff}$	$\varepsilon_{re,eff}/\varepsilon_{ro,eff}$
.05	7.043/5.541	7.047/5.539	7.054/5.542
.10	7.059/5.561	7.064/5.565	7.071/5.571
.20	7.086/5.667	7.093/5.607	7.100/5.615
.40	7.123/5.667	7.132/5.679	7.140/5.687
.80	7.141/5.798	7.154/5.808	7.161/5.817



(b)

Fig. 4. Simulation results to demonstrate the validity of the method set up in this paper (the circuit is from [15]).

value of $Z'_{c,even}$ or $Z'_{c,odd}$ tends to decrease when W_1 or L_1 is increased.

The values h_v, W_1, and L_1 obtained so far are utilized for the initial condition for the FDTD optimization in the next section. The investigation results on the frequency-dependent scattering parameter formulas [12] have shown us that the amplitude of reflection or isolation is still less than -20 dB in 25% frequency band when the characteristic impedances of even and odd modes are by about 10% smaller than the values given by (2) as long as the ratio $\varepsilon_{re,eff}/\varepsilon_{ro,eff}$ is larger than 0.7.

In Table I, some calculated results on symmetric coupled line by use of the GFDM have been given and compared with those from other methods [12] and [14] to show the correctness of the proposed computing procedure.

IV. Practical Considerations on Applications of 3-D-FDTD

A. Validity Demonstration of the Present 3-D-FDTD Algorithm

The Yee's finite difference model set up in the space and time domains has been considered as the most important contribution to the 3-D-FDTD principle, which applies the central difference method to discretize Maxwell's equations not only in the space domain but also in the time domain. In [9], the same process has been performed for space and time parameters, which, however, are further normalized for fast programming considerations.

In practical calculations, we have found that this normalization FDTD algorithm speeds up the iteration procedure effectively in planar circuit analysis. We have executed simulations on the device given in [15] with the present method. The results are shown in Fig. 4. All of the results agreed very well with those shown in [15] (within about 0.5 h CPU time by an IBM-POWER station for 10 000 iteration time steps). Although the double integer mesh arrangement used to satisfy the leap-frog difference step requirement in a 3-D discretized coordinate system, may generate a $\pm\Delta$ difference step error for the vertical substrate with double conductor planes, it will not influence the accuracy of simulation results too much.

B. Excitation Function and Its Optimization

The commonly reported excitation method has been used in the normalization FDTD algorithm. Here we prefer utilizing the Gaussian unit pulse [15] and [16] to a sine wave [9] as the excitation function, because it can easily generate a wider spectrum covering the required frequency band for the S parameters or the frequency response of the device under test. We have found in the VIP coupler simulations that parameters of the excitation function such as Δt, t_o, and T in

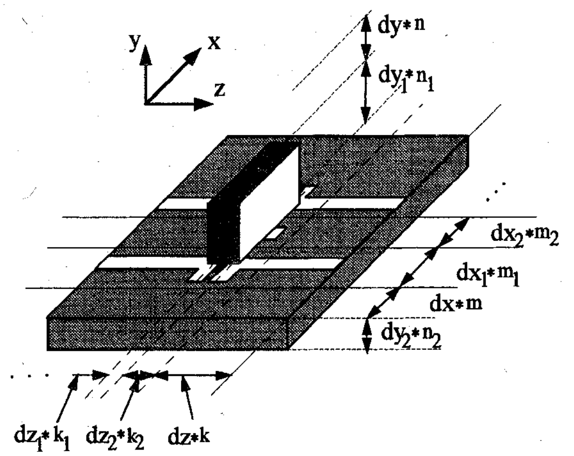


Fig. 5. Mesh arrangement of unequal size for 3-D simulation.

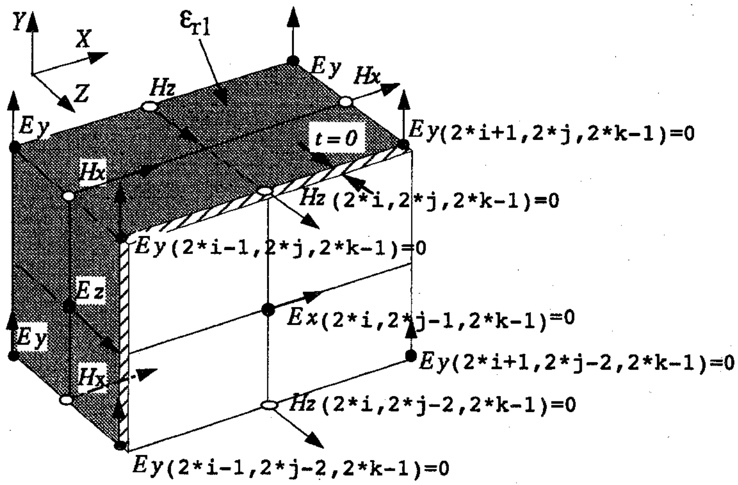


Fig. 6. Three-dimensional Yee mesh arrangements for the analysis of vertical conductors in a VIP directional coupler.

the following equation

$$E_z(n\Delta t) = \exp\left\{\frac{-(n\Delta t - t_o)^2}{T^2}\right\} \tag{4}$$

must be carefully selected. Otherwise, the disperse results will be generated when the device under computation has three-dimensional structure like that of a compensated VIP coupler, in which the Mur's first order boundary condition [17] is no longer easily matched in a wide spectrum. This is because the stability restriction [18] only gives a range of Δt values. Therefore, according to our simulation practice, we propose to make several trial values for parameters such as Δt, t_o, and T in (4), then to observe the incident sampling wave form and to make sure that the nondistorted wave form is obtained. It looks like doing a "time-domain observation" in advance to reduce errors in the time domain iteration computing.

C. Mesh Arrangement and 3-D Conductor Boundary Considerations

The practical mesh design for 3-D-FDTD is shown in Fig. 5. In order to accurately simulate the complicated structure of the coupler, the nonuniform mesh dividing method have been utilized. The smallest one among the different mesh sizes in each direction ($\Delta_{x\ \min}$, $\Delta_{y\ \min}$, $\Delta_{z\ \min}$) must be used in the initial time step Δt computation [15] and [16] or optimization. As mentioned earlier, we propose to carry out a further adjustment on Δt by checking the time domain wave form to make sure that there is a least distortion generated in the incident one. In this way, the disperse problems in the Mur's first order boundary expression [17] and [18] will be greatly overcome or at least become tolerable for the engineering applications.

There are two important points in designing the difference mesh sizes: One is the width W of 50 Ω microstrip line [15] and another is the space ds between the terminals of the two stubs ($W_2 \times L_2$), which are the most sensitive parameters for deciding the suitable mutual capacitance of the coupling line [10]. The size of ds will be from about 0.2–0.4 mm for the case when the selected substrate's permittivity is from about 2–4. The other sizes in the circuit can also be simulated by using a multimesh-dividing method.

In the compensated VIP directional coupler simulations, conductors situated along the different coordinate axes have to be dealt with. On the conductors of the vertical substrate, the boundary condition requires

$$\begin{aligned} E_y &= E_x \\ &= H_z \\ &= 0. \end{aligned} \tag{5}$$

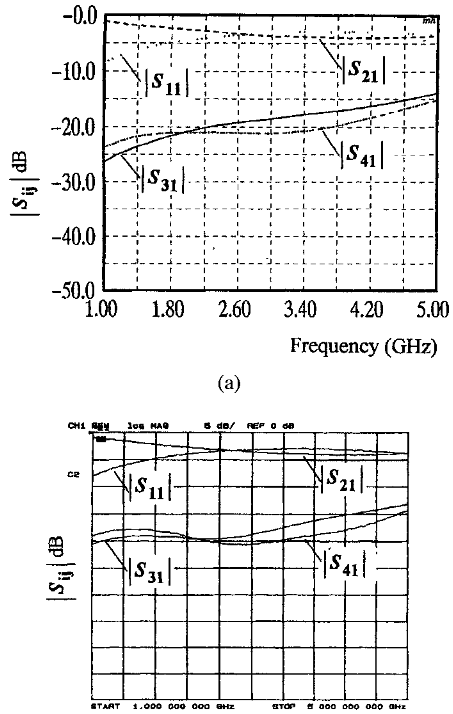
It means that three components on the conductors of the vertical coupling section must be zero. Fig. 6 gives these distributions utilizing the Yee's mesh principle. Although the above condition is simple, the programming should be carefully designed to satisfy the leap-frog difference space step condition at the same time. After considering the above points, the first order absorbing boundary condition has been found to be good enough to simulate the experimental devices under investigation.

D. DFT Improved from Fourier Series Approximation

An effective DFT algorithm has been designed to perform the digitally sampled signal transformation from the time domain to the frequency one [19]. Although a fast Fourier transform (FFT) algorithm can also be used for this procedure, we propose to use a DFT in the practical computation, which can save the time to perform a 3-D simulations when one needs to optimize the parameters of the excitation function and use a few time steps to check the parameters in it.

V. Numerical and Experimental Results

Lots of simulation as well as experimental works have been done on these VIP coupler devices. We will give some of numerical results to demonstrate the effectiveness of the proposed compensation design for the couplers by utilizing the two step methods mentioned in Section III; and also show the relating experimental results by comparing them with the 3-D-FDTD results.



(b)

Fig. 7. S_{ij} for an uncompensated VIP directional coupler. (a) Simulation result by 3-D-FDTD ($\varepsilon_r = 2.68$, $h_v = 4$ mm, $h = 0\ 8$ mm) and (b) measured result with the same size as shown in (a).

TABLE II
COMPUTED RESULTS BY 2-D-GFDM
($f_o = 3.0$ GHz; $h = 0.8$ mm)

ε_{r1} ($=\varepsilon_{r2}$)	h_v mm	L mm	$Z_{c,even}$ (Ω)	$Z_{c,odd}$ (Ω)	$\varepsilon_{re,eff}$	$\varepsilon_{ro,eff}$
2.68*	3.9	18.4	115.9	18.4	1.58	2.18

* Measured by straight resonator method(SRM) [12]

TABLE III
RESULTS CALCULATED BY 2-D-GFDM ($f_o = 3.0$ GHz; $h = 0.8$ mm)

Principle	h_v mm	L mm	L_v mm	L_1 mm	$Z_{c,even}$ (Ω)	$Z_{c,odd}$ (Ω)	$\varepsilon_{re,eff}$	$\varepsilon_{ro,eff}$
Fig.3(W_1=0.0 mm)	3.9	18.4	*	*	115.9	18.4	1.58	2 18
Fig.3(W_1=1 1 mm)	3.9	17.2	*	*	72.3	16 6	2.01	2.2
eq (A-3)(W_1=1 1 mm)	3.9	18.1	14.8	2.36	115.8	18.2	1.66	2.19

TABLE IV
RESULTS FROM 3-D-FDTD CALCULATION AND EXPERIMENT

Principle	h_v	L_v	L_1	L_2	W_1	W_2	W
FD-TD	3.92	14.86	2.4	2.8	1.2	2.5	2.08
Exp.	3.9	15.9	2.5	2 8	1 1	2.6	2.08

A. The Analysis Results on Uncompensated VIP Couplers

Before discussing compensated VIP couplers, we would like to show some results on uncompensated ones simulated by FDTD method. Those research began from the idea that one may design a VIP directional coupler by using different combinations of dielectric substrates [7]. As we mentioned before, the GFDM could be applied so as to offer a good initial values for fast and effective calculations when carrying out FDTD simulations. In Table II, an example calculated by 2-D-GFDM is listed. The even and odd modes' parameters computed by a 2-D-GFDM were put into the equations in [12] to find the frequency-dependent $S_{ij}(f)$ parameters. Since the obtained results were quite different from the experimental ones, we have then applied FDTD method to carry out the full wave analysis. The S parameters of the VIP coupler shown in Fig. 7(a) agree well with experimental ones shown in Fig. 7(b). The thickness of the substrate is 0.8 mm.

B. The Analysis Results on Compensated VIP Couplers

By using the above mentioned 3-D-FDTD method, we can easily perform a full wave analysis on a compensated VIP coupler. This research has been done for several kinds of substrates, the permittivity of which ranges from 2–4. Table III gives one of the calculated results by 2-D-GFDM. In Table IV, the dimensions for a compensated VIP coupler calculated by 3-D-FDTD are given, which are also compared with the experimental ones.

Now the full wave analysis results about small variations on sizes of L_1 and L_2 of a compensated VIP coupler shown in Table IV are given in Figs. 8 and 9. It is found that the size L_1 influences mainly on the central frequency of the reflection and isolation, and the size L_2 mainly on their amplitudes. A good balance between two 3 dB output signals can be obtained by use of those compensation structures.

C. Experimental Results on a Compensated VIP Directional Coupler

In Fig. 10, the experimental result for Fig. 9(b) is given. It is found that it agrees very well with the theoretical one. In Fig. 11, the full wave simulation results on a compensated VIP 3 dB directional coupler are given. The measured results are given in Fig. 12, the dimensions of which were shown in Table IV with the fabricating errors about $\pm 0.05 \sim 0.1$ (mm). In order to evaluate the reflection coefficient at all ports $S_{ii}(i = 1, \cdots, 4)$, the experimental results are given in Fig. 12(b) for the design parameters shown in Table IV.

VI. CONCLUSION

The performance of a VIP directional coupler made of lower permittivity substrates can be effectively improved by introducing compensation planar patterns into its design. The horizontal and vertical substrates have the same dielectric constant and thickness, which is of great practical importance. The dimensions of this coupler can be computed quickly and correctly by use of the 2-D-GFDM program for calculating the basic sizes approximately, and also the 3-D-FDTD method for simulating this device or performing a full wave analysis

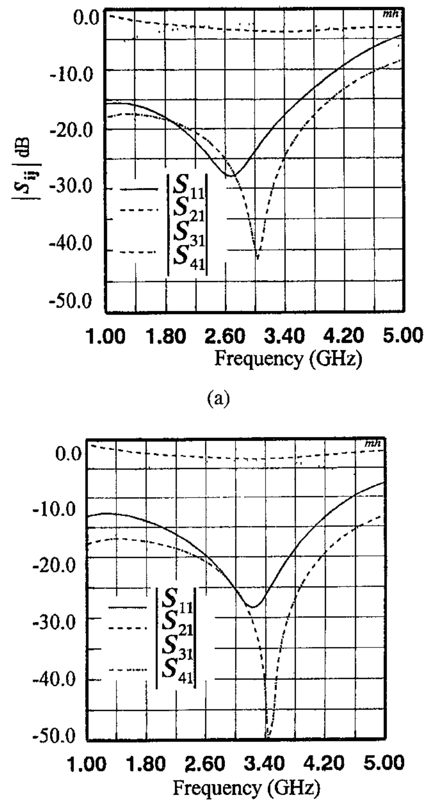


Fig. 8. Compensation effects of $L_1(\Delta L_1 = 0.246$ mm). (a) Decrease of L_1 by $2\Delta L_1$ and (b) increase of L_1 by $2\Delta L_1$.

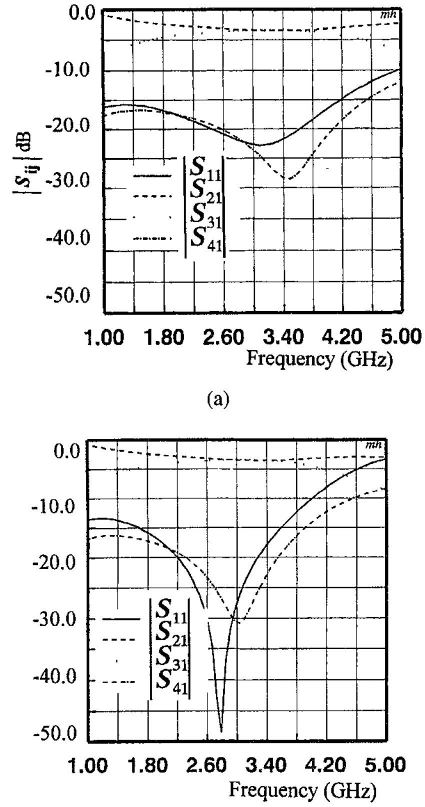


Fig. 9. Compensation effects of $L_2(\Delta L_2 = 0.240$ mm). (a) Decrease of L_2 by $2\Delta L_2$ and (b) increase of L_2 by $2\Delta L_2$.

on it. The obtained frequency band width was about 25% with its reflection and isolation of less than −20 dB. The outputs of its two 3 dB channels are very uniform and the reflection coefficients of each ports are at the same level with slight variations of their central frequencies. The experimental results are in a good agreement with the numerical ones. As the compensation process has been done totally in the planar substrate, those kinds of directional couplers' designs will be simple and easy to be carried out in the practical engineering by utilizing a 3-D-FDTD process. The advantages of this compensated VIP directional coupler are a relatively smaller size and also easy fabrication. It is expected that a substrate of higher dielectric constant is utilized in the same manner to reduce the total size further in the future.

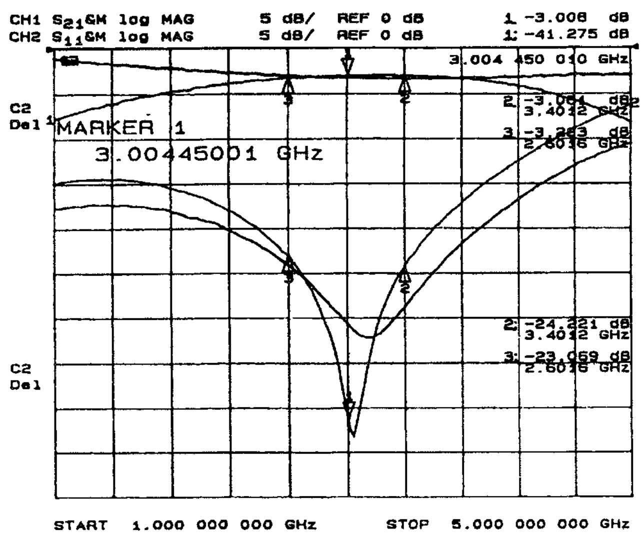


Fig. 10. Experimental demonstration of compensation effect for the VIP coupler shown in Fig. 9(b).

APPENDIX

The electric energy across a 2-D surface can be computed via potential differences utilizing 2-D Laplace's principle. The geometrical size and the relative dielectric constants in each elements are

$$h_i,\, h_j; \quad \varepsilon_{ij} \quad i = 1, 2, \cdots, M; \quad j = 1, 2, \cdots, N.$$

Then, the stored energy can be simply expressed by

$$W_{\varepsilon,o} = \tfrac{1}{2} \iint_S \varepsilon_{ij}(|E_x|^2 + |E_y|^2)\, ds$$

$$= \frac{1}{8}\left(\sum_{j=1}^{N}\sum_{i=1}^{M} \varepsilon_{ij}|\phi_i - \phi_0 + \phi_{0'} - \phi_j|^2 \frac{h_j}{h_i} + \sum_{j=1}^{N}\sum_{i=1}^{M} \varepsilon_{ij}|\phi_{0'} - \phi_i + \phi_j - \phi_0|^2 \frac{h_i}{h_j}\right) \quad \text{(A1)}$$

where ϕ_i, ϕ_j, ϕ_0, and $\phi_{0'}$ are the potentials distributed on

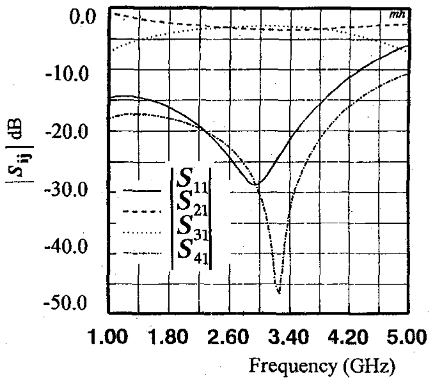
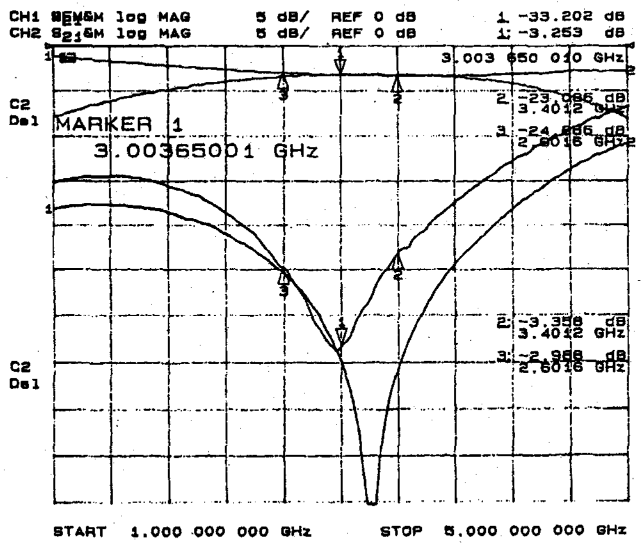
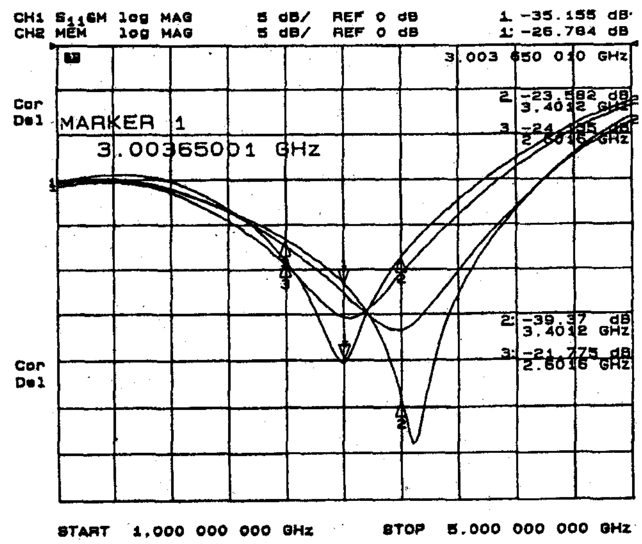


Fig. 11. S_{ij} simulation results of the compensated VIP directional coupler.



(a)



(b)

Fig. 12. Measured S_{ij} for the coupler shown in Fig. 11. (a) S_{ij} parameters for excitation from port 1 and (b) whole reflection parameters S_{ii} ($i = 1, 2, 3, 4$).

the four difference nodes of the rectangular mesh under consideration.

The approximation for the characteristic impedance and effective dielectric constants of the compensated coupling section will also be found by utilizing (1). If the fins are narrow enough, the total energy in (1) can be defined as a linear combination of these two uniform quasi-TEM lines

$$W_o'W_\varepsilon' \approx \frac{(L-L_1)W_oW_\varepsilon}{L} + \frac{L_1W_{o1}W_{\varepsilon1}}{L}. \tag{A2}$$

In (A2), the geometric averaging operation on the length of L and L_1 have been carried out. Therefore, we can derive the following formulas

$$Z_c' \equiv \frac{1}{\sqrt{\frac{L-L_1}{LZ_c^2} + \frac{L_1}{LZ_{c1}^2}}}$$

$$\varepsilon_{r,eff}' \equiv \frac{L-L_1}{L}\varepsilon_{r,eff} + \frac{L_1}{L}\varepsilon_{r1,eff}, \tag{A3}$$

where, Z_c or Z_{c1} is the characteristic impedance with or without W_1, L_1 section respectively and $\varepsilon_{r,eff}$ and $\varepsilon_{r1,eff}$ are the corresponding effective dielectric constants. The above formulas will be applied into the evaluations for approximate designs on the compensated VIP directional couplers.

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