Characterization of the Coupling Between Adjacent Finite Ground Coplanar (FGC) Waveguides

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Abstract

Coupling between adjacent Finite Ground Coplanar (FGC) waveguides as a function of the line geometry is presented for the first time. A two Dimension-Finite Difference Time Domain (2D-FDTD) analysis and measurements are used to show that the coupling decreases as the line to line separation and the ground plane width increases. Furthermore, it is shown that for a given spacing between the center lines of two FGC lines, the coupling is lower if the ground plane width is smaller. Lastly, electric field plots generated from the 2D-FDTD technique are presented which demonstrate a strong slotline mode is established in the coupled FGC line.

Key words:

Coplanar Waveguide, Finite Ground Coplanar Waveguide, Coupled Transmission Lines, and Microwave Transmission Lines.

1. Introduction

Coplanar Waveguide (CPW) is often used for microwave and millimeter-wave integrated circuits since both series and shunt circuit elements may be easily integrated without costly via hole and back side wafer processing. However, when CPW is placed in a package, it encounters several problems including the excitation of parallel plate parasitic modes. Specifically, the package introduces a ground plane on the back side of the wafer that establishes a parallel plate waveguide as shown in Figure 1. Since the parallel plate waveguide mode has a lower phase velocity than the CPW mode over the entire frequency spectrum, energy leaks from the CPW mode to the parallel plate waveguide mode. Energy in the parallel plate waveguide mode creates resonances that severely degrade the CPW circuit characteristics when the size of the circuit is greater than $\lambda_d/2$ where λ_d is the wavelength in the dielectric medium[1,2].

Via holes are often used to electrically short the upper to the lower ground planes and eliminate the parallel plate waveguide mode[2], however, this negates the cost advantage of CPW over microstrip. Another alternative is to terminate the semi-infinite ground planes of the CPW so that the total width of the transmission line is less than $\lambda_d/4$ for moderate to wide strip and slot widths and $\lambda_d/2$ for narrow strip and slot widths[3]. This new transmission line is called Finite Ground Coplanar (FGC) waveguide and is shown in Figure 2. If the ground planes of the FGC have approximately the same width as the center strip, FGC may be thought of as a two wire transmission lines. Thus, distributed circuit elements such as series stubs[4,5] and lumped elements such as MIM capaci-

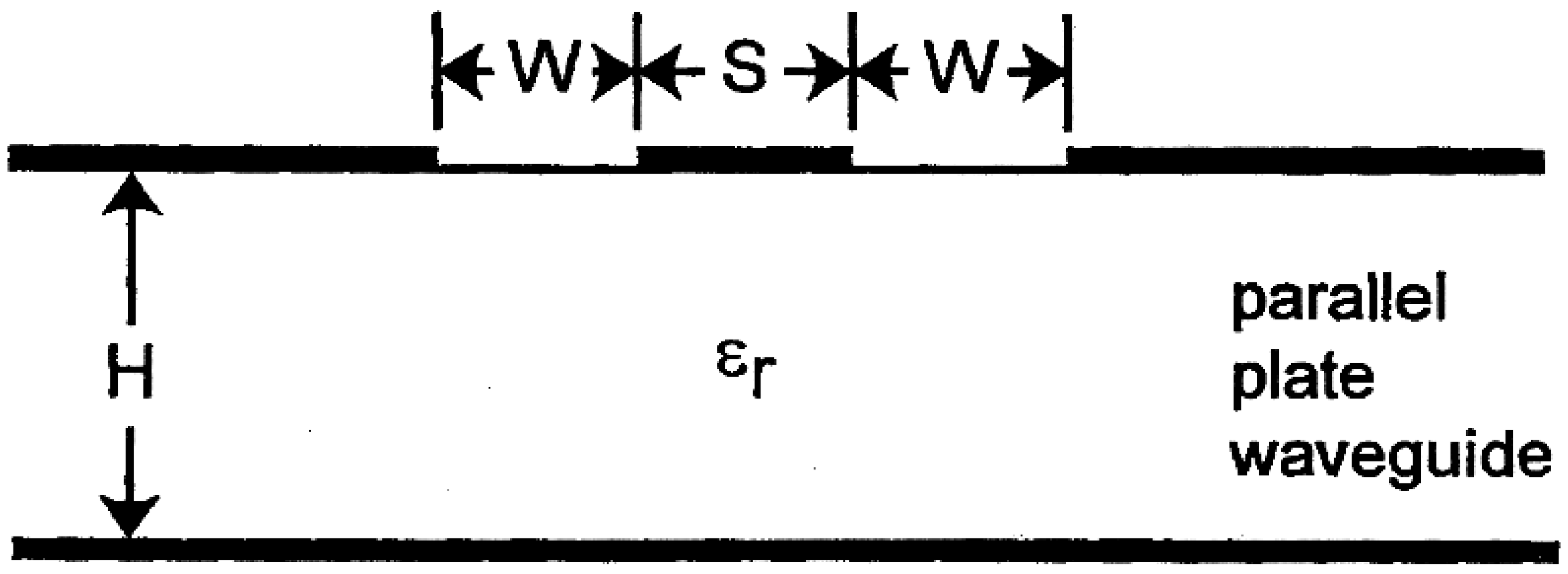

Figure 1. Coplanar waveguide (CPW).

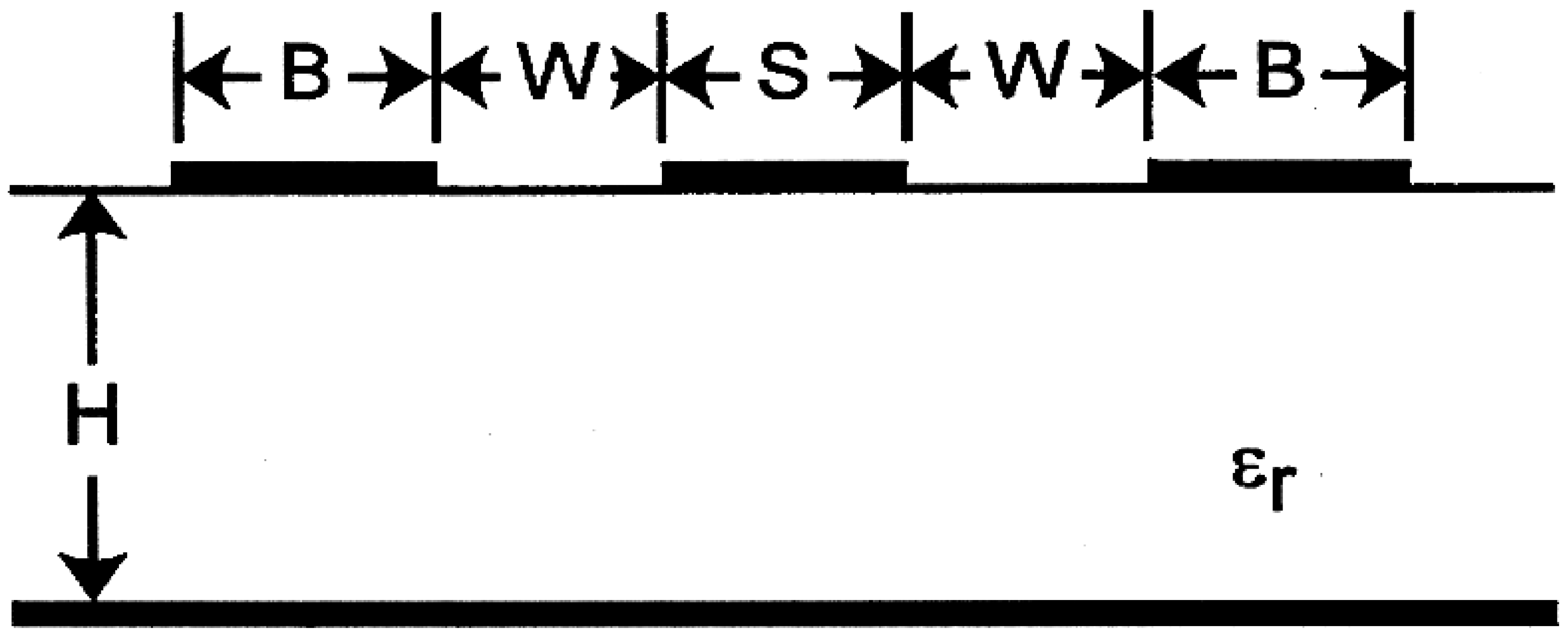

Figure 2. Finite Ground Coplanar (FGC) waveguide.

tors and thin film resistors[6] may be implemented in the ground strips as well as the center strip. Thin ground strips also create surface area on the substrate for integrating chip capacitors, resistors, and other surface mount devices to create a more compact circuit.

If FGC waveguide and the open area it creates on the substrate is to be used to layout more compact circuits, line to line coupling must be understood since coupling increases the noise figure and leads to spurious resonances in microwave circuits. Typically, low coupling is achieved by maintaining a wide separation between transmission lines and circuit elements, but this is not possible when circuit compactness is desired. Thus, other techniques of reducing the coupling between transmission lines is required. Although coupling between adjacent CPW lines has been modeled[7], no characterization of the coupling characteristics of FGC has been reported. In this paper, a two Dimensional-Finite Difference Time Domain (2D-FDTD) analysis and experimental measurements of the coupling between adjacent FGC lines are presented as a function of the ground plane width, B, the line to line separation, D, and the spacing between the center lines of two FGC lines, C, as shown in Figure 3. In addition, field plots generated by the 2D-FDTD method and experimental observations are used to show that a strong parasitic slotline mode is excited in the coupled line.

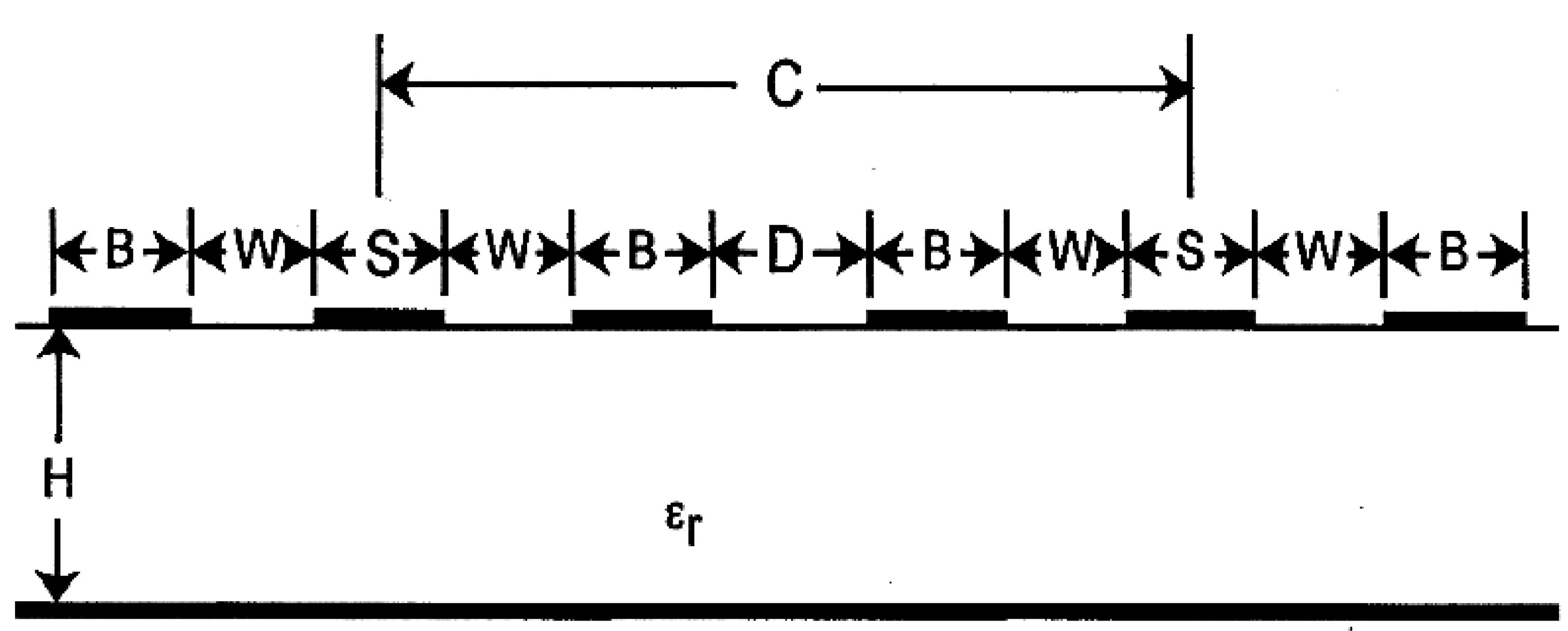

Figure 3. Coupled Finite Ground Coplanar waveguides.

2. Measurement Technique

The FGC circuits are fabricated on double side polished Si wafers with a resistivity of 2500 Ω-cm and a thickness, H, of 411 μm. Two sets of circuits were fabricated. The first set was fabricated with a lift-off process to define the metal lines which consist of 0.02 μm of Ti and 1.5 μm of Au and incorporated no air bridges or via holes to eliminate the slot line mode, a mode with unbalanced ground planes, and a microstrip mode, respectively. The second set of lines was fabricated using a Au plating procedure which results in a final metal thickness of 3 μm. This set of circuits has airbridges spaced 2000 μm apart to suppress the slotline modes. Both sets of lines have a center strip conductor width, S, and a slot width, W, of 25 μm, while the ground plane width, B, and the line separation, D or C, are varied.

Measurements are made using a vector network analyzer and microwave probes with 150 μm pitch. Calibration of the measurement system is accomplished through a full Through-Reflect-Line (TRL) calibration[8] using calibration standards fabricated on the wafer with the FGC test circuits. This calibration procedure places the reference planes at the center of the through line and establishes the reference impedance equal to the characteristic impedance of the delay lines which is approximately 59 Ω for the lines in this paper. The calibration standards consist of a through line, four delay lines, and a short circuit terminated FGC line to cover the measured frequency range of 1-40 GHz. The same probe pad layout is used for the calibration standards and the coupled line circuits so that the mismatch it creates may be accurately removed from the results. Since the slotline mode can couple to the CPW mode at discontinuities such as the probe pads, the second set of circuits have an airbridge immediately after the taper to short out the slotline mode before the microwave probes. Lastly, measurements are made for circuits both with and without a backside ground plane; a quartz spacer is used to isolate the Si substrate from the wafer chuck for the circuits without the backside ground plane.

Typically, to measure coupling between transmission lines, two of the four ports need to be matched to the characteristic impedance of the transmission lines, but in practice, this is difficult since the impedance of each line is not known exactly. Therefore, an alternative technique is used in this work and the coupling is measured between two FGC lines with one port of each line terminated in a short circuit as shown in Figure 4. Because the short circuit termina-

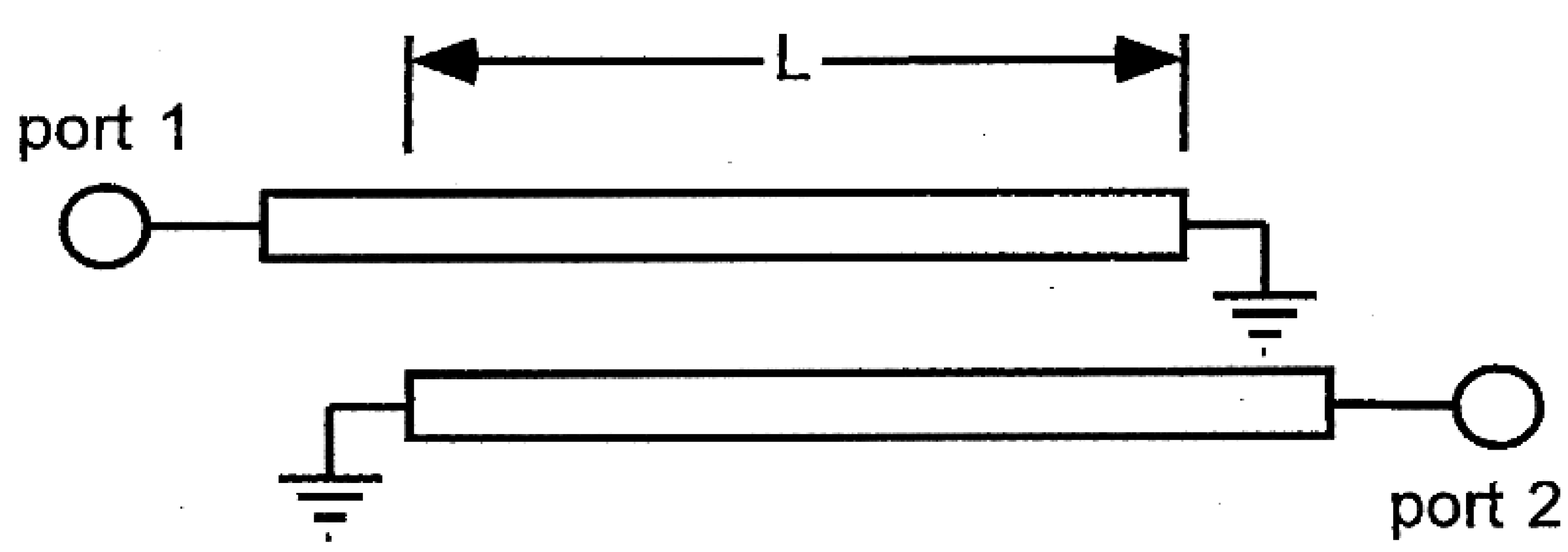

Figure 4. Schematic of Coupled Finite Ground Coplanar waveguides used in measurements.

tion establishes a standing wave on both the excited and the coupled lines, the measured coupling is determined from the peaks of the resulting standing wave pattern. It can be shown that the coupling measured by this technique is 3 dB higher than the coupling between match terminated lines if the lines are sufficiently long and do not have high attenuation. This is assured by characterizing circuits with coupling lengths, L, of 2000 and 12000 μm and comparing the results. Measured coupling presented in this paper is corrected for this 3 dB and the attenuation through the coupled line length which is mathematically removed using attenuation data from prior work[3]. As an example, if the maximum measured S_{21} value is -27 dB at 20 GHz for a coupled line length of 12000 μm, the actual coupling is -27.36 dB since 3 dB is subtracted and (1.2 cm)*(2.2 dB/cm) = 2.64 dB is added to the measured value. Finally, throughout this paper, the absolute value of the coupling is presented; thus, the reported coupling for this example is 27.36 dB.

3. Application of FDTD Method

For the theoretical analysis of the coupled FGC waveguides with S=W=25 μm and H=411 μm, the 2D-FDTD method Reference[9] is employed as outlined in Reference[3]. In all simulations, the discretization cell has dimensions of 2.5 μm in the horizontal direction and 25 μm in the vertical dimension, see Figure 3, and the time step takes the value of the Courant limit. The propagation constant, β, has values of 100 and 500 which correspond to frequencies of 1.883 and 9.417 GHz, respectively. The computational domain is terminated to the left, to the right, and to the top (see Figure 3) by eight cells of Perfectly Matched Layer (PML) absorber, yielding a maximum theoretical reflection coefficient, ρ_{max}, of 10^{-5}. Without loss of generality, the CPW mode is excited in the left FGC line by applying a horizontal odd electric field across the two gaps between the ground planes and the center conductor. The horizontal, parallel to the dielectric interface, electric field is probed at symmetrical observation points across the two gaps of the coupled (right) FGC line. It is preferable to choose the observation points close to the middle of the gaps so that the horizontal electric field component is much larger than the vertical one, thus making the probed electric energy approximately equal to the total electric energy at the probe points. The probed values at the coupled (right) FGC line are a superposition of two modes: the CPW mode and the parasitic slotline mode. By decomposing the two sampled values of the horizontal electric field into even (slotline) and odd (CPW) coefficients, the coupling coefficients for both of these modes can be calculated by taking their ratio to the horizontal electric field along the excitation line.

4. Results

The coupling between two FGC lines as a function of the ground plane width, B, and the line separation, D, determined by the 2D-FDTD method and experimentally measured are shown in Figures 5 and 6, respectively. Note that the 2D-FDTD analysis is for a FGC line with a lower ground plane while the experimentally measured coupling is for FGC lines with airbridges and without a lower ground plane. It is seen that the coupling decreases as B and D increases, and the coupling saturates when B and D become large. This is simply showing the expected results that coupling decreases as two transmission lines are moved farther away from each other.

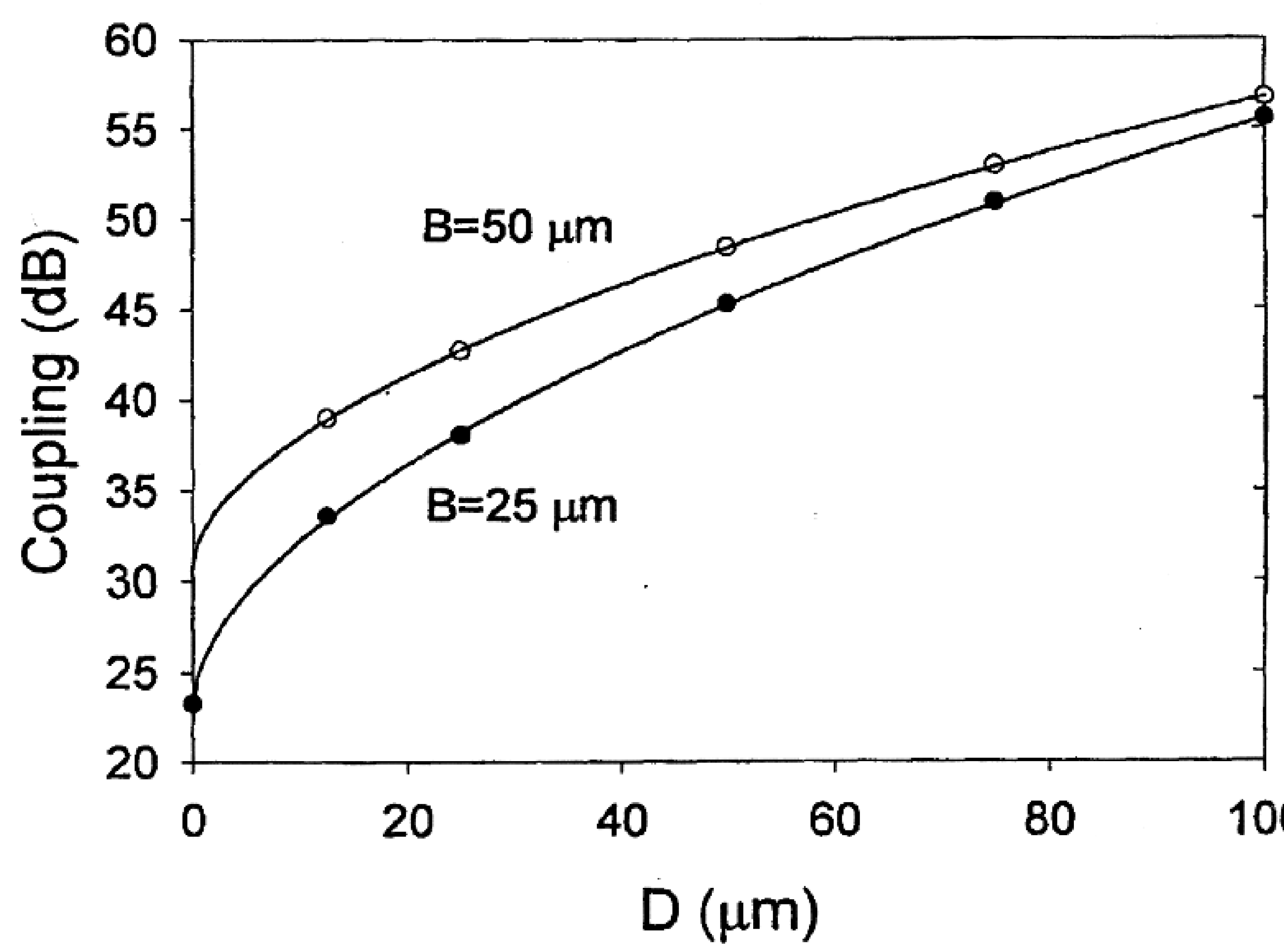

Figure 5. Coupling between Finite Ground Coplanar waveguides as a function of B and D determined by the 2D-FDTD method (S=W=25 μm).

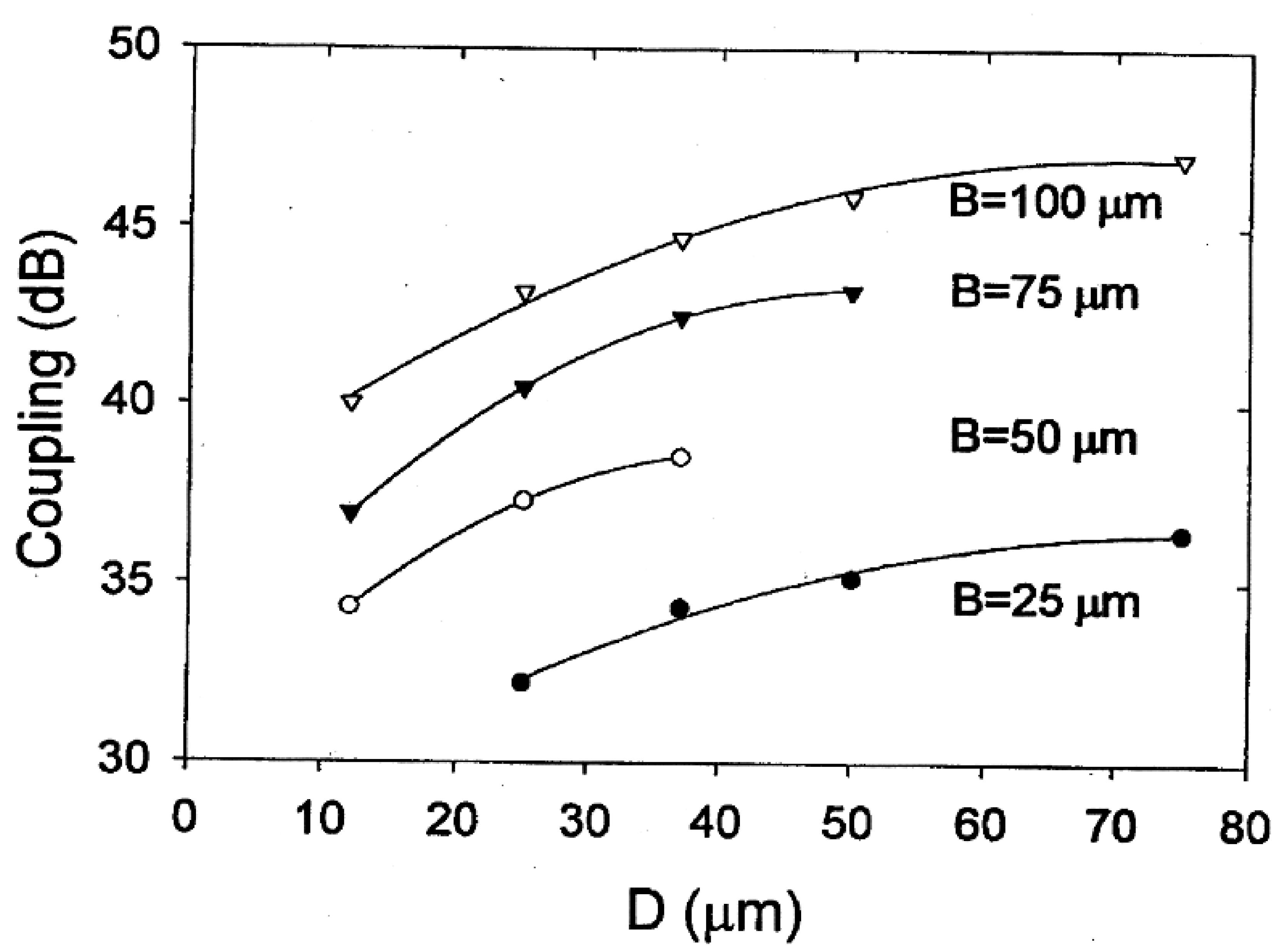

Figure 6. Measured coupling between Finite Ground Coplanar Waveguides as a function of B and D (S=W=25 μm).

A more interesting result is presented in Figures 7 and 8 which show the coupling as a function of the ground plane width and the center to center line spacing, C, determined theoretically and experimentally, respectively. It is seen that for a given spacing between the center lines of two FGC lines, the coupling is lower when B is smaller. There-

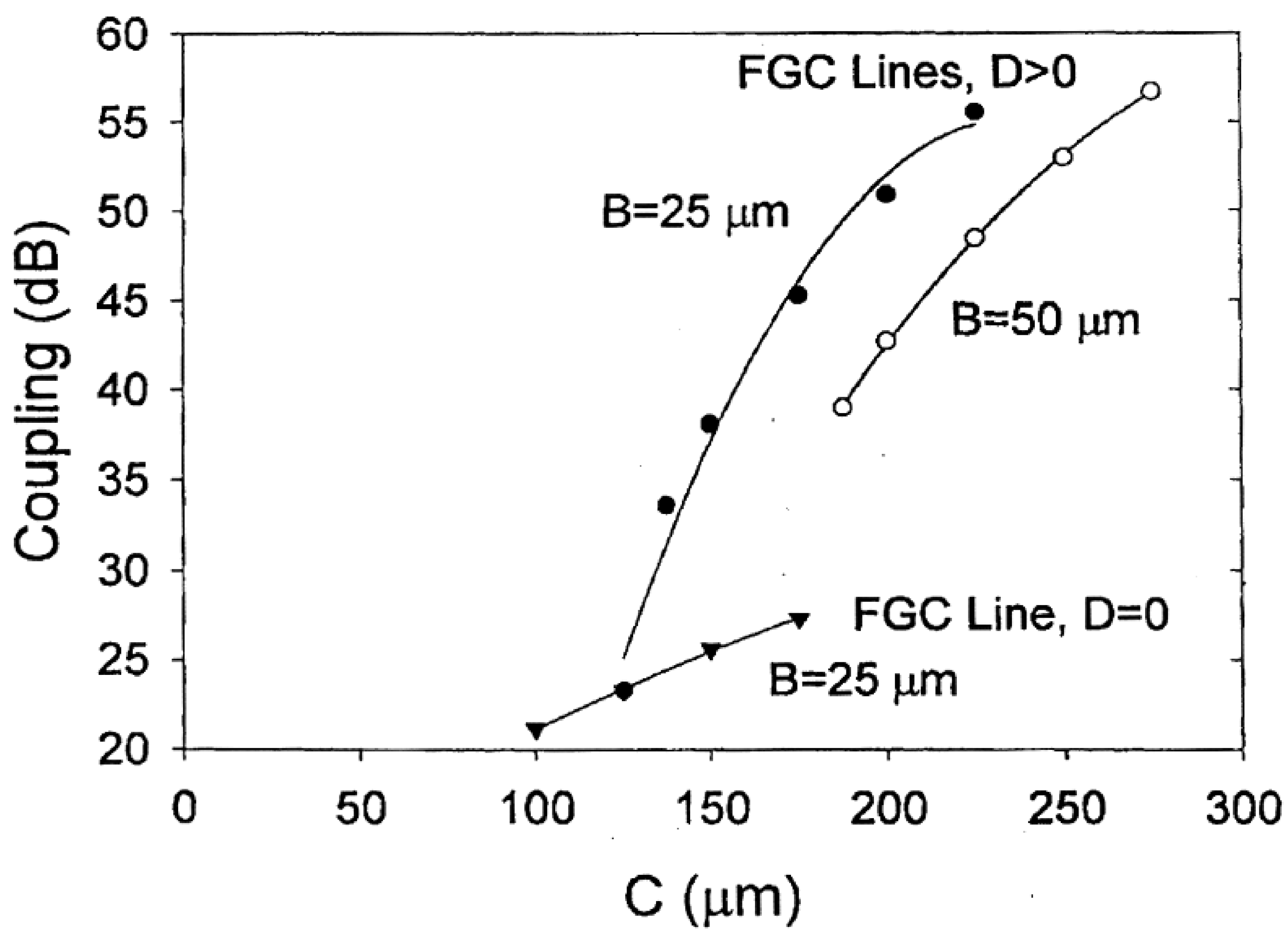

Figure 7. Coupling between Finite Ground Coplanar Waveguides with D>0 and between Finite Ground Coplanar waveguides with a continuous ground plane as a function of B and C determined by the 2D-FDTD method (S=W=25 μm).

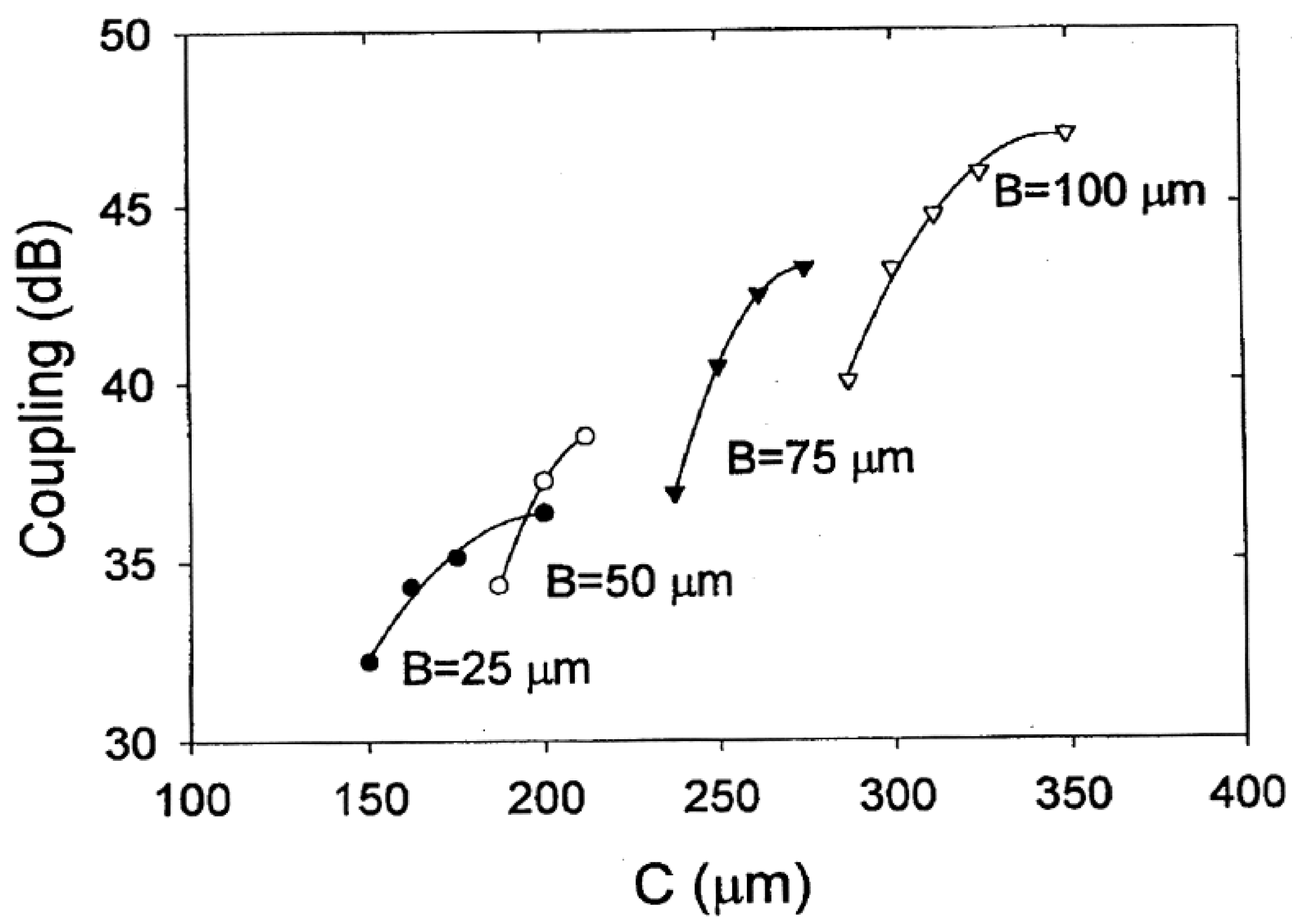

Figure 8. Measured coupling between Finite Ground Coplanar waveguides as a function of B and C (S=W=25 μm).

fore, to minimize coupling between the FGC lines, it is advantageous to have a narrower ground plane width and a larger D for a specified center to center spacing. Also, shown in Figure 7 is the coupling for FGC lines with a continuous ground plane between the lines, see Figure 9. Note that the ground plane dimension, B, given for this data is only for the ground plane on the outside of the coupled lines. The 2D-FDTD results show that FGC lines with a continuous ground plane have greater coupling than the conventional FGC lines; coupling is reduced by as much as 15 dB using finite ground planes between the coupled lines, and even a small value of D greatly reduces the coupling.

The nature of the coupling may be understood by examining the horizontal electric field magnitudes for an isolated FGC line shown in Figure 10 and two coupled FGC lines as shown in Figures 11 and 12. Each of these lines has the same values for

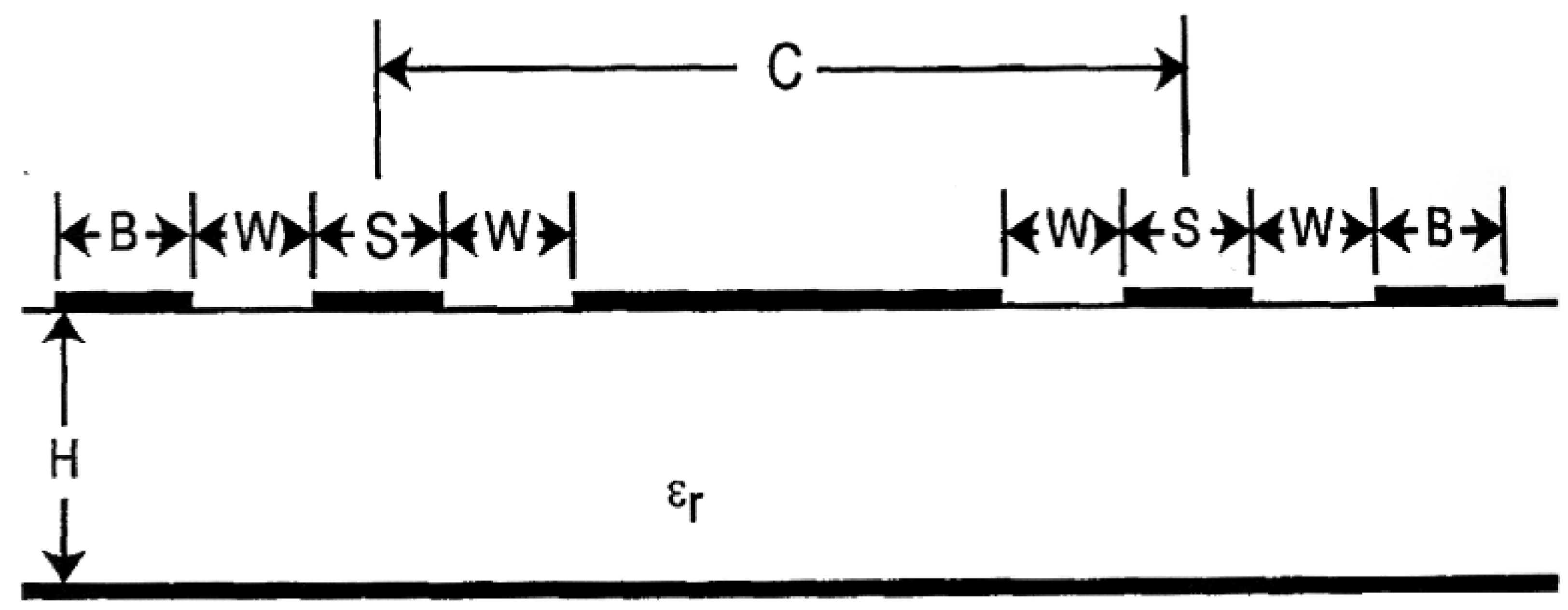

Figure 9. Coupled Finite Ground Coplanar waveguides with a continuous ground plane between the lines.

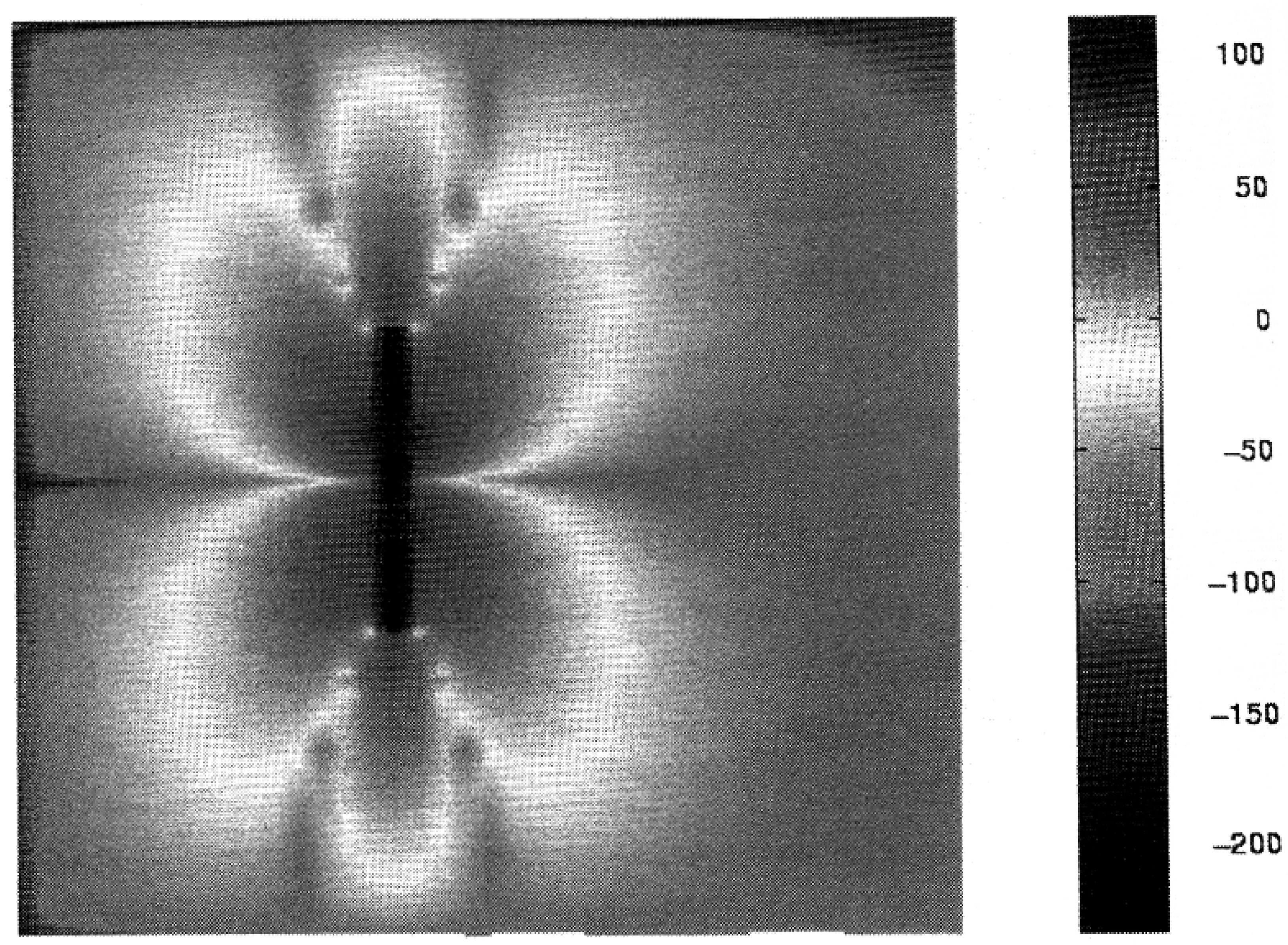

Figure 10. Horizontal electric field component of isolated Finite Ground Coplanar waveguide (S=W= 25 μm, B=50 μm).

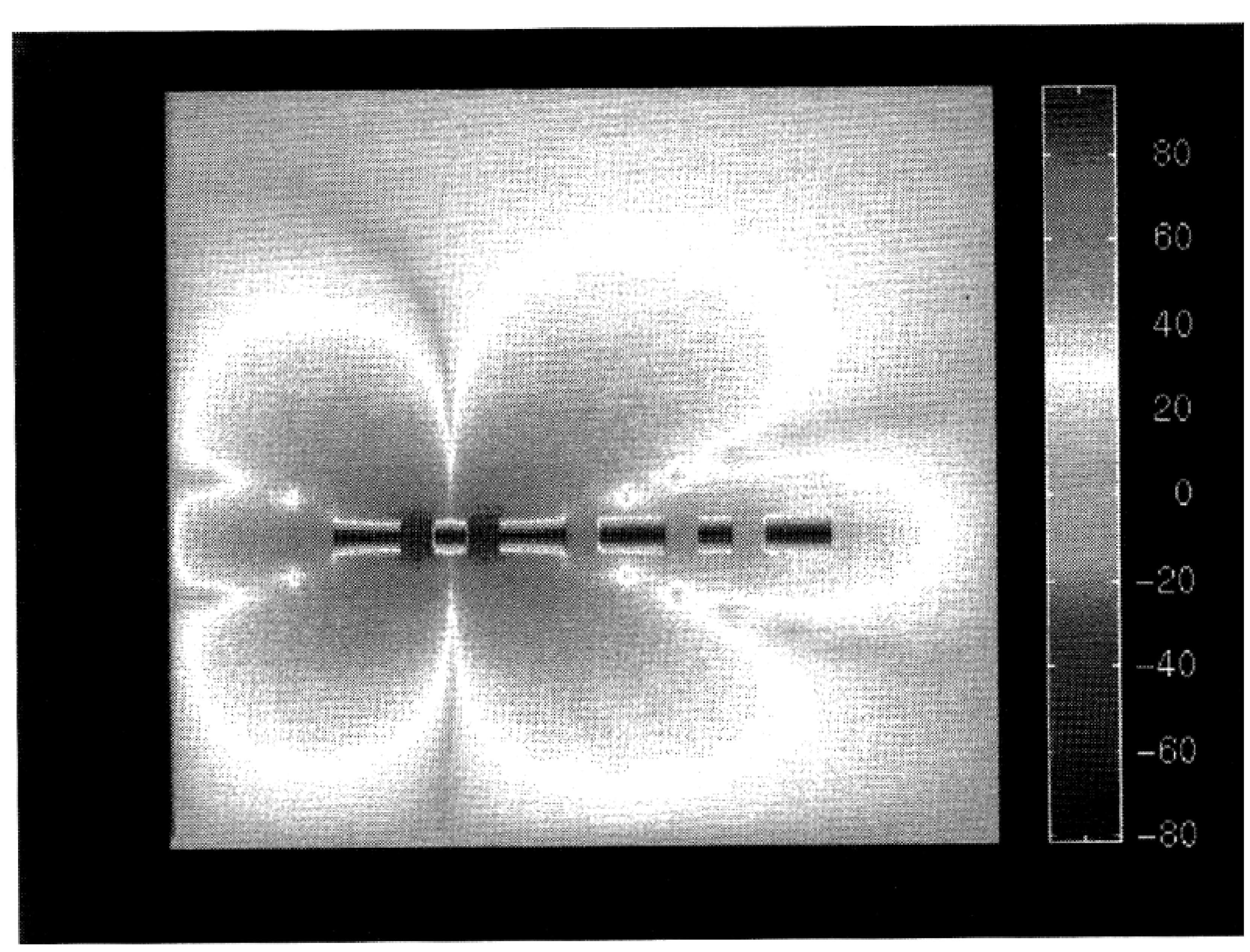

Figure 11. Horizontal electric field component of Coupled Finite Ground Coplanar waveguides (S=W= 25 μm, B=50 μm, D=25 μm).

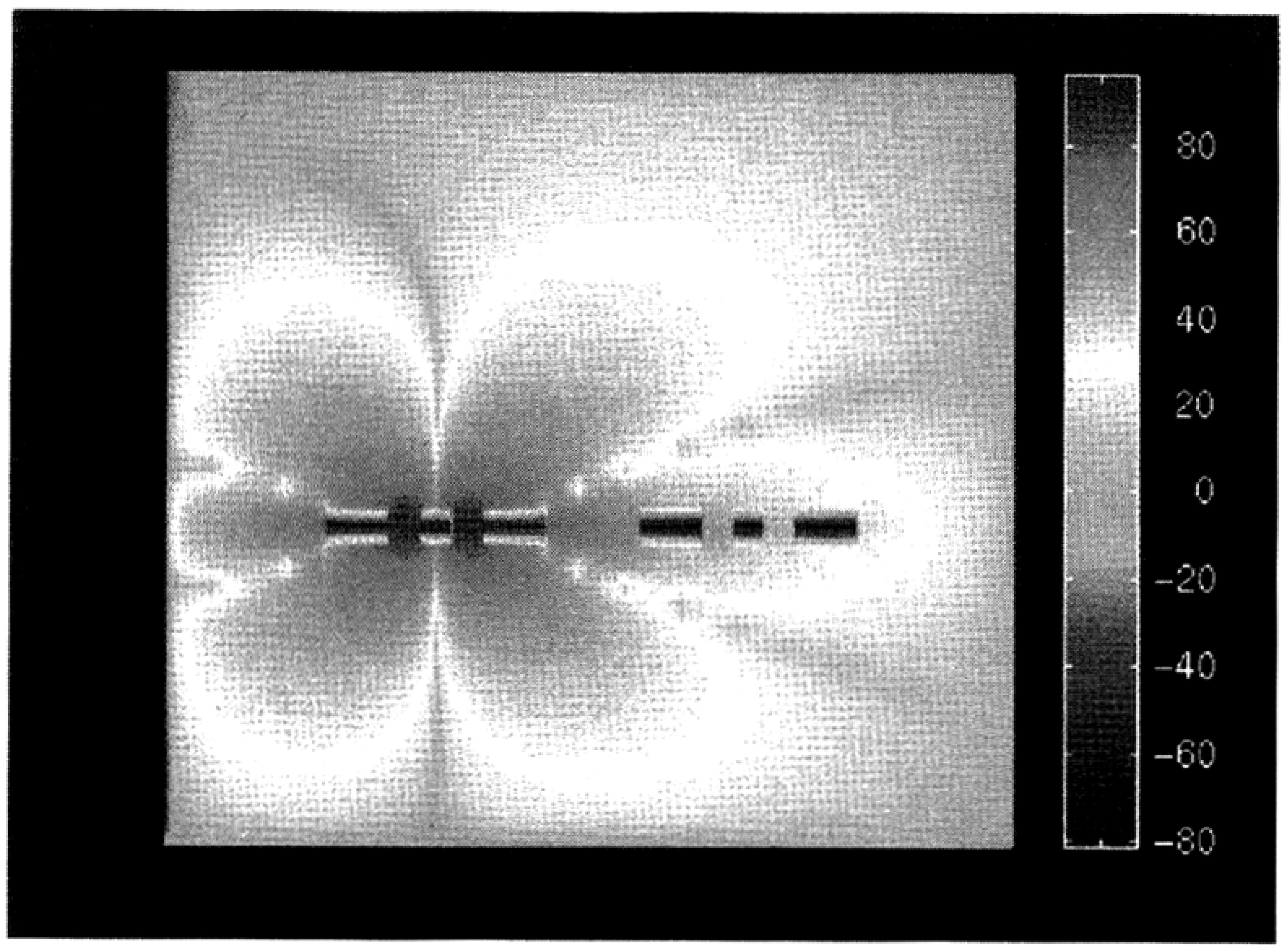

Figure 12. Horizontal electric field component of Coupled Finite Ground Coplanar waveguides (S=W= 25 μm, B=50 μm, D=75 μm).

S, W, and B and the coupling is shown for two separation distances, D. For the isolated FGC line shown in Figure 10, there exists a strong horizontal electric field component at the air/dielectric interface on both sides of the FGC line. This electric field envelops the coupled FGC line as shown in Figures 11 and 12 and is responsible for the coupling. Further examination of Figures 11 and 12 shows a strong non-symmetry of the electric fields across the slots of the coupled FGC line, indicating a strong slotline mode. In fact, the slotline mode is approximately 10 dB greater than the CPW mode in the coupled line. For FGC lines with a continuous ground plane as shown in Figure 9, the slotline mode is approximately 5 dB weaker than the CPW mode. Thus, while FGC lines with D>0 have substantially lower coupling than the same lines with a continuous ground plane, they have a stronger slotline mode which requires airbridges to eliminate.

Although the measured and theoretically determined coupling lead to the same qualitative conclusions, they do not quantitatively agree with each other. There are several factors that may be causing this discrepancy. First, the strong slotline mode excited in the coupled FGC line may couple to the CPW mode at discontinuities such as at the FGC to microwave probe contact. Evidence of this effect is seen by comparing the results of the FGC lines fabricated with and without the airbridges. The lines presented in this work with the airbridges agree with the 2D-FDTD method much better than the lines without the airbridges[10]. Second, discontinuities in the FGC lines excite surface wave modes in the Si substrate that may couple to the second FGC line. The surface wave mode coupling increases the noise floor and thus causes the measured coupling to saturate at a lower level than it otherwise would. This is observed in the measurements made on substrates with a backside ground plane. They had a higher noise floor and more variation in the measured coupling than the measurements made of circuits without a backside ground plane. Finally, the 2D-FDTD method does not account for the finite metal thickness of the lines; it is expected that coupling between the ground planes of the FGC lines would be greater as the metal thickness increases.

5. Conclusions

The coupling between adjacent finite ground coplanar waveguides has been characterized for the first time through a two dimensional-finite difference Time Domain method and also verified experimentally. The results show that the coupling decreases as the ground plane width and the separation between lines increases until a point where the coupling saturates. Furthermore, it is shown that for a given center to center line spacing, the coupling between two FGC lines is lower when the ground plane width is smaller. Thus, FGC with narrow ground planes have lower coupling than FGC with wide ground planes and conventional CPW lines. Finally, a strong slotline mode is established in the coupled line which must be suppressed by airbridges.

Acknowledgments

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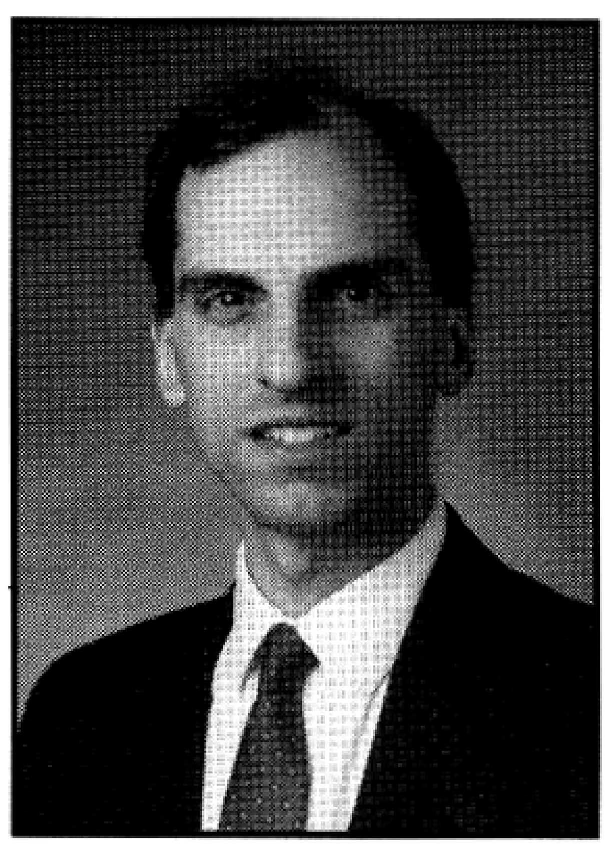
About the authors



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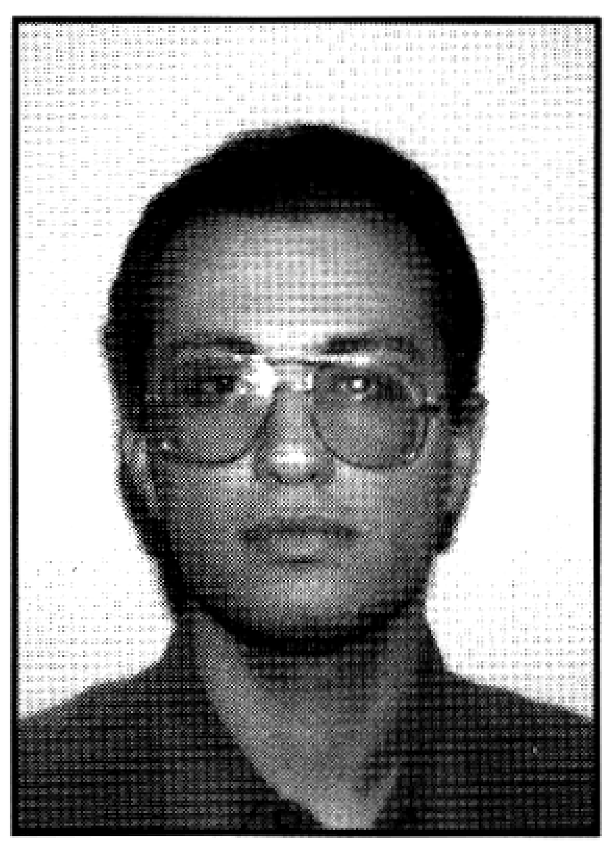

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