Finite Ground Coplanar (FGC) Waveguide: A Better Transmission Line for Microwave Circuits

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A new version of coplanar waveguide (CPW) with electrically narrow ground strips has been developed for microwave integrated circuits. This transmission line, referred to by Finite Ground Coplanar (FGC) waveguide, has several advantages over conventional coplanar waveguide. Since the ground strips are narrow, parasitic resonances that develop when the CPW is placed on a carrier or in a package are eliminated. In addition, the narrow ground strips permit the integration of lumped and distributed circuit elements in the ground strips as well as in the center strip to reduce the circuit size and improve its performance. Finally, the coupling between adjacent FGC transmission lines is lower than the coupling between CPW lines for the same spacing between the lines. All of these attributes of FGC are presented in this paper.

Key words: Coplanar Waveguide, Finite Ground Coplanar Waveguide, Coupling, and Transmission Lines.

I. Introduction

For Monolithic Microwave and Millimeter-Wave Integrated Circuits (MMICs), microwave Multichip Modules (MCMs), and other microwave circuits, coplanar waveguide (CPW) has been the best transmission line for several reasons that are related to its simple geometry. Unlike most other transmission lines, microstrip and stripline are two examples, the signal strip and the ground plane of CPW are both on top of the substrate as shown in Figure 1a. Thus, it is easy to make both series and shunt connections within the circuit without the need for filled via holes. This simplifies the fabrication process, lowers the fabrication cost of circuits on semiconductor substrates such as GaAs and InP by as much as 30 percent, eliminates the need for wafer thinning which reduces breakage, and reduces the parasitic reactance associated with ground connections. In addition, CPW has lower dispersion than microstrip which makes broadband circuit design easier. In summary, CPW circuits cost less, work better, and are more reliable than circuits made with other commonly used transmission lines.

However, even CPW has problems when it is used in practice. Typically, the substrate is thinned and the circuit is mounted on a metal carrier or package base for improved thermal management. This process introduces a lower ground plane as shown in Figure 1b which, together with the upper ground plane, creates a parallel plate waveguide. Since the parasitic parallel plate waveguide mode has a lower phase velocity over the entire frequency spectrum than the CPW mode, energy leaks from the CPW mode to the parallel plate waveguide mode. Perhaps even worse, since the ground planes and the circuit must be of finite dimensions to be integrated into a larger system or a package, the energy in the parallel plate waveguide mode establishes box type resonances that severely degrade the CPW circuit characteristics [1], [2].

To solve these problems with conventional CPW circuits, filled via holes are often used to short the upper and lower ground plates and thus eliminate the Trans-

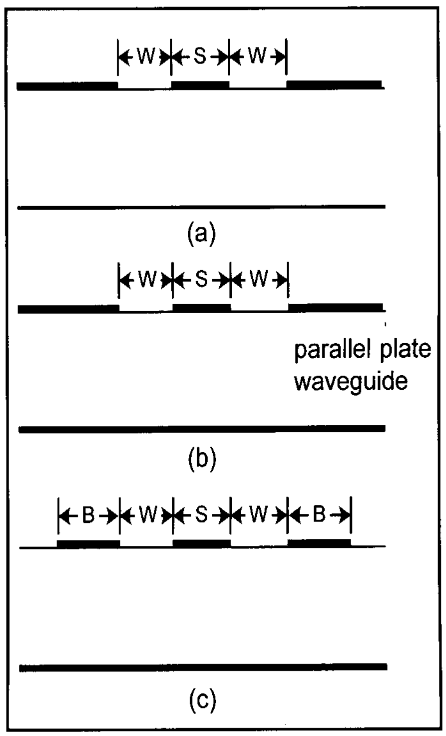

Figure 1. (a) Conventional coplanar waveguide (CPW), (b) Coplanar waveguide with lower ground plane, (c) Finite ground coplanar waveguide (FGC).

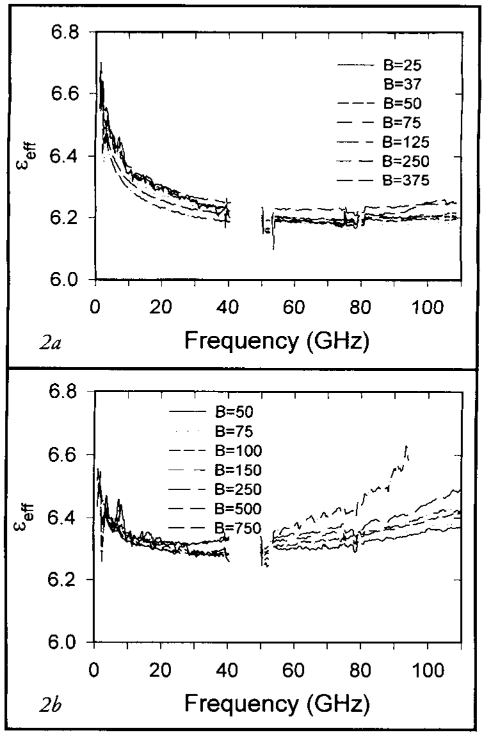

Figure 2. Measured effective dielectric constant of FGC as a function of frequency and ground plane width for (a) S=W=25 μm and (b) S=W=50 μm.

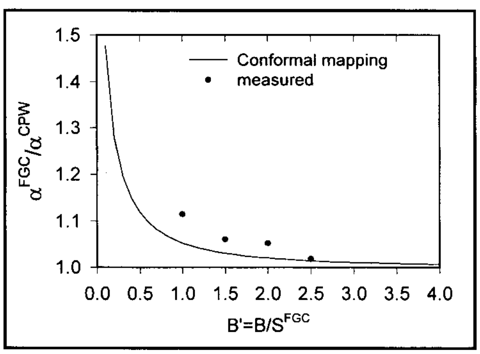

Figure 3. Attenuation of FGC with S=W=25 μm normalized to the attenuation of conventional CPW of the same dimensions.

verse ElectroMagnetic (TEM) mode of the parallel plate waveguide. However, this negates most of the advantages of CPW structure over microstrip. An alternative solution has been developed by the authors that terminates the semi-infinite ground planes on either side of the center conductor of the CPW so that the total width of the transmission line is electrically small. Therefore, the parallel plate waveguide mode is not established and the problem with resonances is eliminated. This new transmission line is called Finite Ground Coplanar (FGC) waveguide and is illustrated in Figure 1c. In this paper, the characteristics of this new transmission line and how it may be used to improve the circuit layout of RF, microwave, and millimeter-wave circuits are presented.

2. Transmission Line Characteristics

Before FGC waveguide can be used, it must be proven that it possesses desirable characteristics. For microwave transmission lines, the requirement means they should have low attenuation and the phase constant should be linearly dependent on frequency or, as it is more often stated, the effective dielectric constant, ε_{eff}, should not be a function of frequency. To investigate the propagation characteristics of FGC lines, two sets of test circuits were fabricated on high resistivity Silicon (Si) substrates with a center conductor and slot width, S and W, respectively, of S=W=25μm and S=W=50 μm, a metal thickness of 1.3 μm, and the ground plane width, B, varied between S and 15 S. These circuits are then measured on a vector network analyzer over the frequency range of 1-110 GHz to determine the propagation characteristics [3], [4].

The measured effective dielectric constant is shown in Figures 2a and 2b for lines with S and W of 25 and 50 μm, respectively. For both sets of lines, ε_{eff} varies by less than one percent as the normalized ground width, B'=B/S, varies from one to fifteen for low frequencies which shows that ε_{eff} is not dependent on B'. Furthermore, ε_{eff} is nearly frequency independent at low frequencies. The two lines behave differently though at higher frequencies. For the line with the narrower strip and slot width, the line is nondispersive until the total line width approaches $\lambda_d/2$ where λ_d is the wavelength in the dielectric, while the lines with wider strip and slot width become dispersive when the total line width approaches $\lambda_d/4$. Generally, dispersion increases when the propagating mode couples to a parasitic mode. Thus, for these two structures, there must be different parasitic modes that are influencing the FGC waveguide. For the wide lines, the parasitic mode is a microstrip mode which is stronger when H/(S+2W) is small [5], while the narrow lines are influenced more by the parallel plate waveguide mode. Further evidence of the parallel plate waveguide mode was seen by the presence of distinct resonances when the total width of the line approaches $\lambda_d/2$. Results for lines above this limit are not presented to maintain clarity in the figures.

The measured attenuation for these two lines decreases as the normalized ground width increases until it exceeds two, at which point the attenuation as a function of B' saturates. This is demonstrated by plotting the attenuation of finite ground lines normalized to the attenuation of conventional CPW with the same strip and slot width as shown in Figure 3. Notice that the attenuation is high for very narrow ground plane strips but it quickly becomes comparable to the attenuation of CPW as B' increases. Furthermore, it is found that at low frequencies, there is no measurable difference in attenuation as a function of the ground plane width.

Therefore, FGC waveguide does have low attenuation, low dispersion, and no parasitic resonances if the ground plane width is at least twice the center conductor width and the total line width is less than $\lambda_d/4$. Since the width of the center conductor of CPW is typically less than $\lambda_d/10$ to maintain a quasi-TEM mode, it follows that the ground planes for FGC are also electrically narrow if B=2S. Thus, the ground planes of FGC may be thought of as two strips in parallel on either side of the center strip of the CPW. With this view in mind, the ground strips may be used to implement circuit elements in the same way as they are currently implemented in the center conductor of CPW.

3. Passive Circuit Elements in FGC

For the purpose of understanding the role of using the ground strips of FGC waveguide, the researchers consider in this section the integration of a NiCr thin film resistor and a Si_3N_4 Metal-Insulator-Metal (MIM) capacitor [6]. As discussed in the prior section, these circuit elements may be placed in either the center conductor or the ground strips as shown in Figures 4 and 5. Notice that the symmetry has been maintained when the elements in the ground strips are placed to avoid exciting the parasitic slotline mode. Both of the elements were characterized over the frequency band of 1 to 40 GHz using a vector network analyzer and microwave probes, and from the measured data, the equivalent circuits shown in Figures 6 and 7 are developed.

To model the thin film resistors, the parasitic reactance is modeled by a pair of equivalent shunt capacitors to ground and a series inductance as shown in Figure 6. The equivalent circuit resistance as a function of the resistor length is shown in Fig-

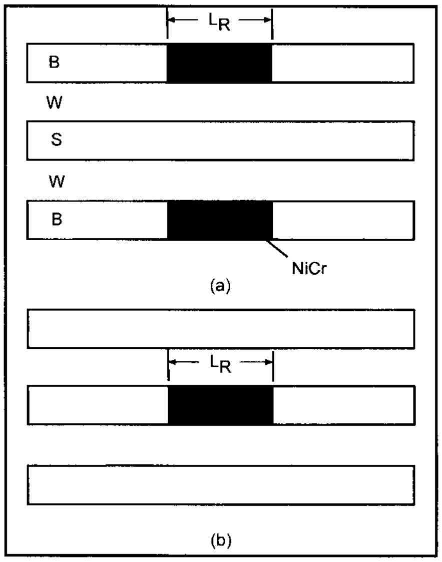

Figure 4. Schematic of thin film resistor in the (a) ground planes and (b) center conductor of FGC.

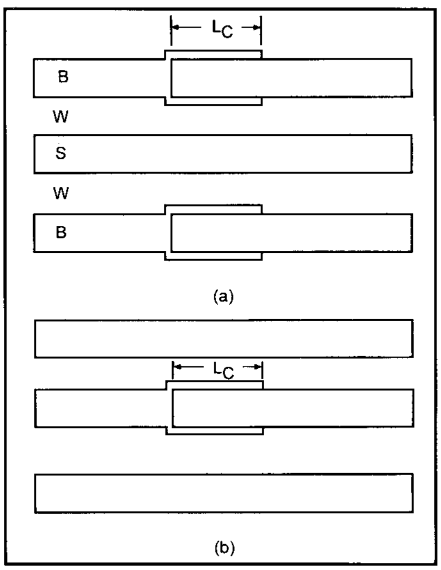

Figure 5. Schematic of MIM capacitor in the (a) ground planes and (b) center conductor of FGC.

ure 8, where it is seen that the DC measured resistance of the resistor placed in the center strip is twice as large as the same length resistor placed in the ground planes, while the RF determined resistance of the center strip resistor is approximately three times larger than the ground resistor. Furthermore, it is found that the parasitic reactances are independent of the placement of the resistor which is interesting since the associated inductance is expected to vary the same as the resistance values.

The model of the MIM capacitor is shown in Figure 7, and its equivalent circuit

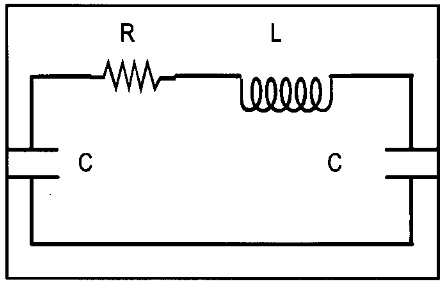

Figure 6. Equivalent circuit model of thin film resistor in FGC.

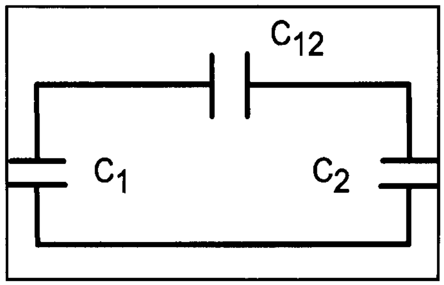

Figure 7. Equivalent circuit model of MIM capacitor in FGC.

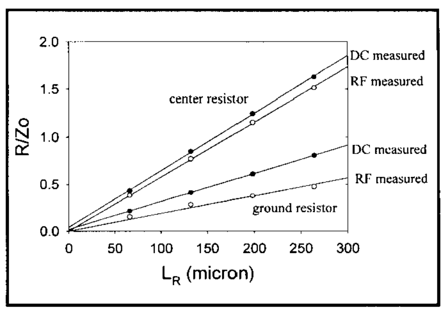

Figure 8. Measured resistance values of thin film resistor in FGC as a function of the resistor length.

element values as a function of the length L_C are shown in Figures 9 and 10. The capacitance C_{12} is approximately two and a half times larger when the capacitor is placed in the ground planes, while the parasitic shunt capacitances are independent of the capacitor placement as shown in Figure 10. In Figure 9, the self resonant frequency of the capacitors is also plotted where it is seen that for the same value of capacitance, the resonant frequency is higher when the capacitor is placed in the ground plane. If it is assumed that the resonance is due to a series inductance, it is found that the value of this parasitic inductance is dependent only on the length of the capacitor and not on its placement.

While the researchers have only reported in this paper on the characteristics of the

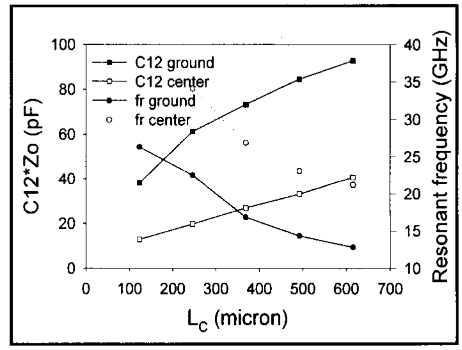

Figure 9. Measured series capacitance and self resonant frequency of MIM capacitors in FGC as a function of the capacitor length.

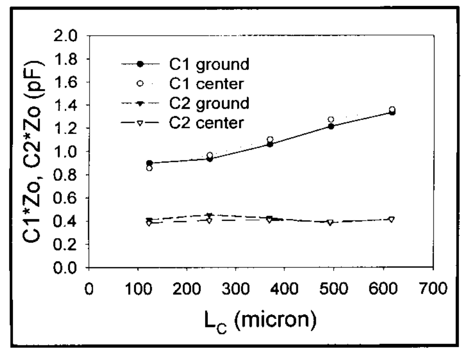

Figure 10. Measured shunt capacitance values of MIM capacitors in FGC as a function of the capacitor length.

integration of thin film resistors and MIM capacitors, the results are typical of those found for the integration of spiral inductors and series connected open and short circuit terminated stubs [7]. In all cases, the characteristics indicate that circuit elements may be placed in the ground strips of FGC waveguide and that they behave to a first order as two elements connected in parallel. Furthermore, the parasitic reactances do not appear to be dependent on the placement of the elements. Thus, it is possible to obtain better electrical characteristics for some circuit elements when they are placed in the ground strips. In particular, capacitive elements are best placed in the ground strips since it is possible to obtain twice the capacitance per unit length and a higher self resonant frequency compared to capacitors placed in the center strip.

4. Coupling Between Adjacent FGC Waveguides

The researchers have shown that FGC has electrical properties similar to those of CPW while being electrically narrow and that circuit elements may be implemented

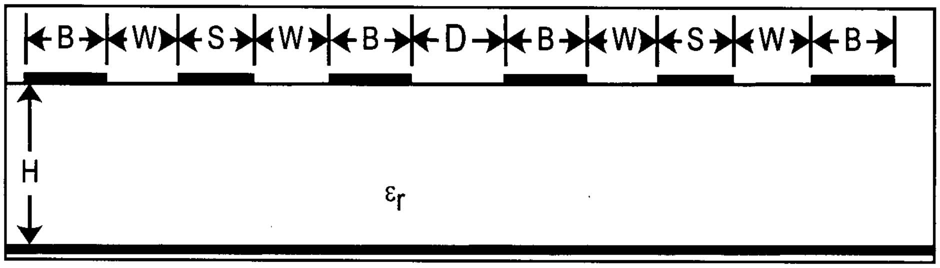

Figure 11. Coupled FGC waveguides.

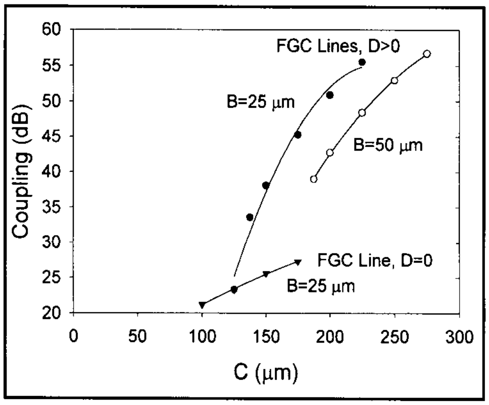

Figure 12. Coupling between FGC lines as a function of B and C determined by 2D-FDTD method.

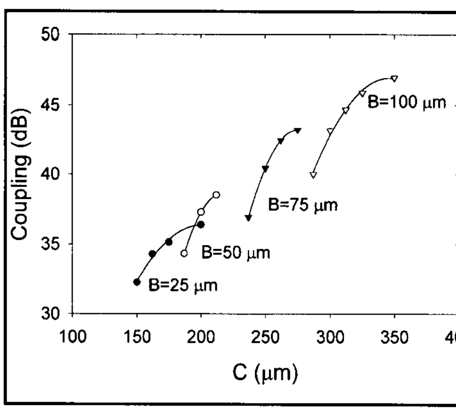

Figure 13. Measured coupling between FGC lines as a function of B and C.

in novel ways to reduce the circuit size. However, these advantages are lost if coupling between adjacent transmission lines forces the circuit designer to separate the lines further than they would be for conventional CPW. Therefore, the researchers investigated the coupling between adjacent FGC lines as shown in Figure 11 and compared it to the coupling between CPW lines [8], [9]. Two methods for measuring the coupling are used: direct measurement using a vector network analyzer and theoretically through a 2-Dimensional Finite Difference Time Domain (2D-FDTD).

The results are summarized in Figures 12 and 13 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. Therefore, to minimize coupling between FGC lines, it is advantageous to have a narrower ground plane width and larger D for a specified center to center spacing. Also, shown in Figure 12 is the coupling for FGC lines with a continuous ground plane between the lines, D=0. 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 by using finite ground planes between the coupled lines, and even a small value of D greatly reduces the coupling.

5. Conclusions

In this paper, the authors have reviewed the development of finite ground coplanar waveguide and the desirable attributes that make this transmission line better than conventional CPW. In particular, the researchers have shown that the attenuation of FGC is comparable to the attenuation of CPW, dispersion is minimal, circuit elements may be implemented in novel ways using the ground strips, in addition to the center strip to obtain better circuit performance, and that the coupling between lines is even smaller when the ground plane width is reduced. Since this requirement is accomplished without via holes, FGC is evaluated as a better transmission line than CPW.

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