Excitation of coupled slotline mode in finite ground CPW with unequal ground plane widths

George E. Ponchak, John Papapolymerou, and Manos M. Tentzeris

Abstract—The coupling between the desired CPW mode and the unwanted coupled slotline mode is presented for finite ground coplanar waveguides with unequal ground plane widths. Measurements, quasi-static conformal mapping, and Finite-Difference Time-Domain analysis are performed to determine the dependence of the slotline mode excitation on the physical dimensions of the FGC line and on the frequency range of operation. It is shown that the ratio of the slotline mode to the CPW mode can be as high as 18 dB. The use of airbridges is shown to reduce the slotline mode by 15 dB, but that the slotline mode fully reestablishes itself after 2000 μm. Furthermore, these results are independent of frequency.

Index Terms—Coplanar waveguide, coupling, transmission lines

I. INTRODUCTION

Finite ground coplanar waveguide (FGC) is often used in low cost Monolithic Microwave Integrated Circuits (MMICs) because of its numerous advantages over microstrip and conventional coplanar waveguide (CPW). It is uniplanar, which facilitates easy connection of series and shunt elements without via holes, supports a low loss, quasi-TEM mode over a wide frequency band, and since the ground planes are electrically and physically narrow, typically less than $\lambda/5$ wide where λ is the guided wavelength, they reduce the circuit size and the influence of higher order modes [1]. FGC has been used for a multitude of circuits, some of which are lumped elements [2,3], Wilkinson power dividers [4-6], and phase shifters [7,8] without any reported problems.

FGC was developed and is typically modeled as a symmetric transmission line with slot widths and ground planes of equal values. However, in practice, especially in Wilkinson power dividers, rat race dividers, switched line phase shifters, and meander lines, this symmetry is often sacrificed to ease circuit layout. For example, in a Wilkinson power divider, the ground planes between the two $\lambda/4$ sections are often combined, which places a virtual open circuit through the centerline of the circuit and truncates current lines on the ground planes, while the outer ground planes are finite [4-6]. In 90 degree hybrid couplers, there is a virtual short circuit through one axis of symmetry that alters the current on the ground planes. Switched line phase shifters incorporating FGC transmission lines also employ asymmetric ground planes because the area between the transmission lines paths is often a continuous ground plane while the ground plane on the outside of the path is finite.

It is well known that the coupled slotline mode is excited in CPW circuits if there is a discontinuity or an asymmetry in the transmission line. For example, placing a shunt stub on one side of the CPW line excites the coupled slotline mode [9]. Right angle bends and T-junctions are examples of other asymmetric CPW discontinuities that excite the coupled slotline mode [10]. It is for this reason that airbridges are used to equalize the voltage on the two ground planes of CPW lines at the discontinuity and along the CPW line [9].

The asymmetry of the ground planes in FGC lines in practical circuit layouts is also expected to excite the coupled slotline mode, and airbridges are used in FGC circuits in the same manner as they are in CPW circuits to reduce this parasitic mode. The difference is that the asymmetry in CPW circuits is often localized at the point of the discontinuity and the airbridges are placed at the point of the discontinuity, but the asymmetry in asymmetric FGC lines is continuous. Therefore, the FGC lines with uneven ground plane widths may cause higher loss and noise than in the asymmetry at localized points in CPW circuits.

In this letter, the effect of this asymmetry is presented for the first time with an emphasis on the excitation of the unwanted slotline mode by the CPW mode. Quasi-static analysis, Finite-Difference Time-Domain analysis, and experimental measurements are used to determine the coupling between the CPW mode and the slotline mode. These same methods are also used to determine the effect of airbridges on the control of the parasitic mode.

II. CHARACTERIZATION METHODS

The asymmetric FGC line is shown schematically in Fig 1. CPW and FGC are transmission lines comprised of three separate conductors, and they will support two independent quasi-TEM modes. For CPW, these modes are typically called the CPW or even-mode and the coupled slotline or odd-mode. Either of these two modes can propagate along the transmission line independently if they are excited, and they are coupled to each other at discontinuities. For asymmetric transmission lines, the two independent modes are called the *c* and the π modes, which are equivalent to the even and odd modes in a symmetric transmission line. For the problem considered here, a symmetric FGC transmission line supporting the CPW and the coupled slotline mode provides the excitation potentials for the asymmetric FGC line. Likewise, at the far end of the asymmetric FGC line, a symmetric FGC transmission line is expected to be placed.

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Thus, we keep the CPW and coupled slotline mode nomenclature throughout the paper and do not refer to the *c* and π modes. Determining or measuring the slotline and CPW modes is difficult and involves measuring the current on each ground plane and then separating it into even and odd modes. A full, two mode analysis of the problem would also consider the case when the coupled slotline mode is the excitation signal and the CPW signal is measured. In other words, a 4 by 4 scattering matrix would be determined. However, it is very rare that the coupled slotline mode is purposely excited on a FGC or CPW line. Therefore, this particular case is not being considered here, but measurements do show that the results are symmetric if that case is of interest. Thus, for each characterization method, the CPW mode is excited at the left hand side port as shown in Fig. 1 and the coupled slotline mode is measured at the right hand side.

The circuits are fabricated for the measurements and simulations on silicon wafers with a resistivity of 2500 Ω cm and a thickness of 400 μm. The asymmetric FGC lines are 1.5 μm of electron beam deposited Au over a 0.02 μm thick Ti adhesion layer, but the theoretical simulations assume lossless metals. The airbridges are 3 μm high and 50 μm wide and are constructed of 2.5 μm of plated Au. Two asymmetric FGC line geometries are characterized; the first is S, W, and B1 of 15, 10, and 45 μm respectively and the second is S, W, and B1 of 50, 28, and 150 μm respectively. The parameter k=S/(S+2W) for each case is 0.43 and 0.47 respectively, which yields a characteristic impedance of 50 Ω. The ground width B2 is varied to yield a range of values for B2/B1 from 0.2 to 2.0.

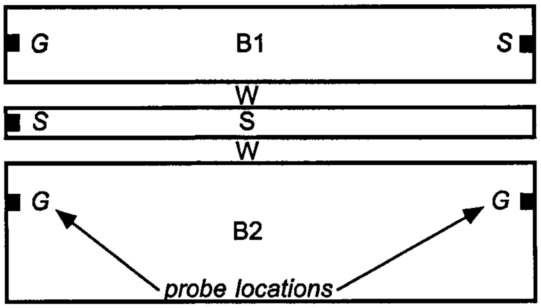


Fig. 1: Schematic of finite ground coplanar waveguide with unequal ground plane widths.

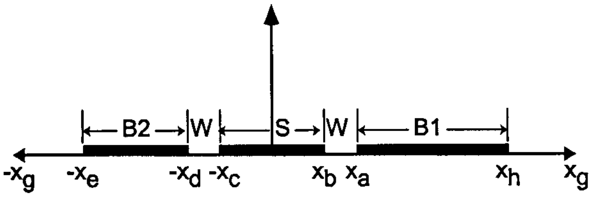
A. *Finite-Difference Time-Domain*

To understand the physics behind the moding of the asymmetric FGC lines, cross-sectional field plots are generated with the ATHENA FDTD simulator in 2.5D and 3D [11,12]. The first step involves two, 2.5D simulations for even and odd excitation to derive the E- and H-field distributions for even ("quasi-CPW") and odd excitation ("quasi-slotline") mode in a plane perpendicular to the propagation direction. Various values of propagation constant, β, (from 100 to 1,000) are utilized to verify the quasi-TEM nature of both modes and also justify the almost frequency-invariant effective permittivity. The magnitude of the fields are renormalized for the same transferred power (ExH*) for both modes. The 2.5D simulations are critical for the accurate simulation of the full-3D cases since they model the non-symmetric current and voltage distributions due to the uneven grounds and also allow for the mode decomposition. The full 3D geometry is excited with even excitation and the E-field distribution is recorded at different distances from the airbridges. Using the 2.5D derived mode patterns for the E-fields, the relative amplitudes of the two modes are identified for various ratios of ground sizes by performing numerical integration along the cross-sections of interest. For each asymmetric FGC line, the left and right metal ground planes are connected with 50 μm air-bridges that are spaced every 2500 μm.

B. *Conformal Mapping*

While FDTD analysis can yield a very accurate, frequency dependent solution, it is time consuming and computationally extensive. Quasi-static solutions based employing conformal mapping are widely used to determine the characteristic impedance of CPW and FGC lines [13]. Here, conformal mapping is employed to determine the ratio of the slotline mode to the CPW mode from a calculation of the capacitance between each ground plane and the center conductor.

Fig. 2 illustrates the asymmetric FGC line and its transformation into an equivalent structure. The structure shown in Fig. 2b is equivalent to the structure in Fig. 2 of [14]. Therefore, the same analysis can be performed to determine the capacitance between line segment *ah* and the portion of the segment *bc* above it and the capacitance between line segment *ed* and the portion of the line segment *bc* above it, which are capacitances C1 and C2 respectively. Because of the quasi-static equivalence between Fig. 2a and Fig. 2b, C1 and C2 are the capacitances between ground planes of width B1 and B2 and the center conductor respectively. The broken line from point *g* to the line segment *bc* is a perfect magnetic wall that is an estimation of the exact location of the nonlinear magnetic wall. The ratio of the slotline mode to the CPW mode is found from $|(C1-C2)/(C1+C2)|$.



(a)

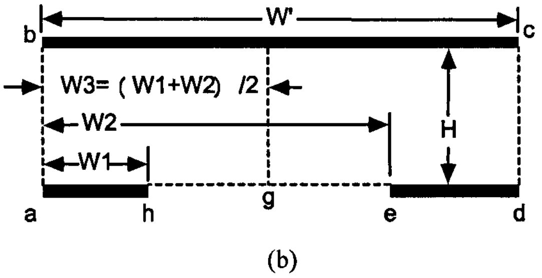


Figure 2: (a) Asymmetric finite ground coplanar waveguide and its transformation into the W-plane (b). In (b), the broken lines are perfect magnetic walls.

C. *Measurement Procedure*

Measuring circuits with non-insertable probe pads (Ground-Signal-Ground (GSG) on the left side and Ground-Signal (GS) on the right side) is a difficult task. Various methods were tried, including a two-tier deembedding process, but the best results are obtained by performing a Thru-Reflect-Line (TRL) calibration with symmetric GSG probes at both ends of the line using standards fabricated on wafer and substituting a GS probe for the right hand side GSG probe. For the measurements, the asymmetric transmission line is transitioned to symmetric probe pads by a simple taper to facilitate the symmetric GSG probes. During the measurements, a quartz wafer was placed between the silicon wafer and the metal wafer chuck. Because of these difficulties and the fact that GS probes are not accurate when unbalanced currents are present at the probe tips, the measurements shall be considered approximate.

III. RESULTS

First, to demonstrate the accuracy of the two theoretical methods, Fig. 3 shows the ratio of the slotline mode to the CPW mode at the end of a 12,000 μm long asymmetric FGC line with no airbridges, or the test port far from the airbridges, and a center conductor width of 15 μm. It is seen that there is excellent agreement, which indicates that either method may be used. Both the FDTD analysis and the measured results indicate that the characteristics shown in Fig. 3 are independent of the frequency from 1 to 50 GHz. This demonstrates that the excitation of the slotline mode is due to quasi-static effects, which further confirms the appropriateness of using the conformal mapping.

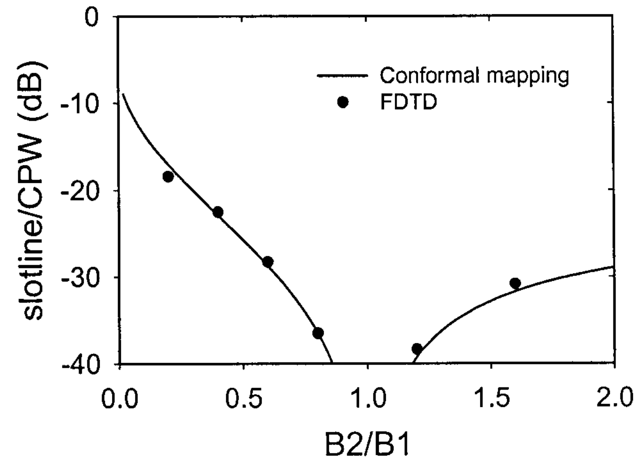


Figure 3: Ratio of slotline mode to CPW mode at the end of an asymmetric FGC line with S=15 μm, W=10 μm, and B1=45 μm.

Fig. 4 shows the ratio of the slotline mode to CPW mode determined by conformal mapping as a function of the ratio of the ground planes. It is seen that the slotline mode is large, -10 dB, when B2/B1 is small and theoretically decreases to zero when B2/B1=1. Although the slotline mode increases for large ratios of B2/B1, it does not reach values above -25 dB. Furthermore, the slotline mode is stronger for smaller values of k. The slotline mode excitation is inversely dependent on the ground plane width B1, as shown in Fig. 5, and decreases approximately by 6 dB as B1 in increased from 2S to 5S. Larger ground sizes decrease the effect of the asymmetry because the majority of current in the ground planes is within 3 to 4S of the slots.

Fig. 6 shows the measured ratio of the slotline mode to the CPW mode for asymmetric FGC lines without airbridges and a length of 13,000 μm. It is seen that the measured results qualitatively and quantitatively agree with the theoretical results in Fig. 3 except for the absence of a null at B2/B1=1 and S=50 μm. For all of the measurements taken, the GS probe characteristics have less scatter and error for the narrower transmission lines than the wider lines. Thus, the lack of the null at B2/B1=1 is believed due to a higher noise floor for the S=50 μm measurements. The maximum slotline mode magnitude is -18 dB for B2/B1≥0.2. Characterization of asymmetric FGC lines of different lengths further shows that the ratio of the slotline mode to the CPW mode is independent of line length.

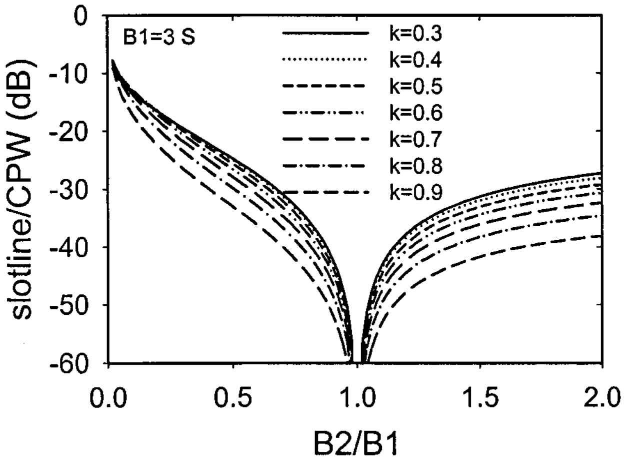


Figure 4: Ratio of slotline mode to CPW mode as a function of k and B2/B1 determined by conformal mapping.

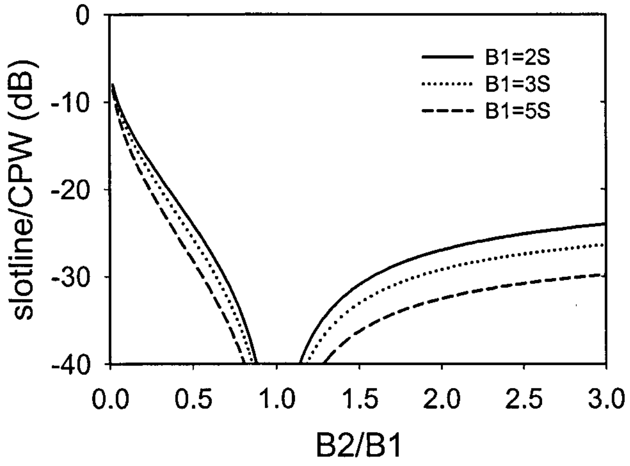


Figure 5: Ratio of slotline mode to CPW mode as a function of ground plane width B1 for k=0.5.

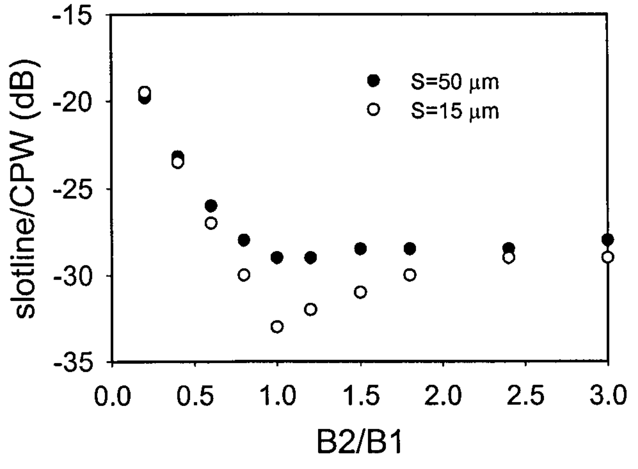


Figure 6: Measured ratio of slotline mode to CPW mode on asymmetric FGC lines without airbridges.

The typical method of eliminating the parasitic slotline mode is to place airbridges between the two ground planes periodically along the FGC line. An FDTD analysis of asymmetric FGC lines with airbridges spaced every 2500 μm was performed. The ratio of the slotline mode to the CPW mode as a function of the distance from an airbridge is shown in Fig. 7. It is seen that the ratio is small immediately after the airbridge, but that the slotline mode grows linearly for 2000 μm, after which the slotline mode magnitude saturates to the value without airbridges. This characteristic is also found to be independent of frequency over the range of 1 to 50 GHz. Note that 2000 μm is approximately $\lambda/4$ at 10 GHz, and for lower frequencies, airbridges must be placed at very small electrical lengths to suppress the slotline mode. A set of asymmetric FGC lines was fabricated with multiple airbridges placed every 1000 μm, with the last airbridge between 1000 and 4000 μm from the right hand port. The maximum measured decrease in the slotline mode is 5 dB, which occurs when the airbridge is 1000 μm from the measurement port. At the airbridge, it is expected that the slotline mode is eliminated, but as shown in Fig. 7, the mode still exists. Because the numerical noise floor of the FDTD analysis is lower than -50 dB, the slotline mode measured at the airbridge is probably due to higher-order evanescent modes in the near field of the airbridge discontinuity.

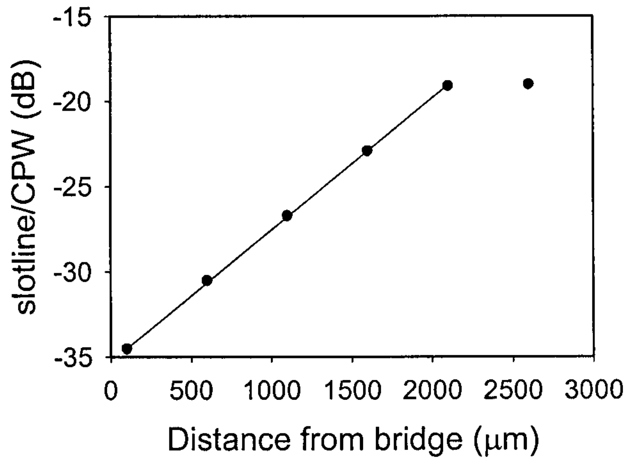


Figure 7: Ratio of slotline mode to CPW mode as a function of distance from an airbridge determined by FDTD.

IV. CONCLUSIONS

The layout of FGC line circuits with unequal ground planes is demonstrated to cause a significant slotline mode to be excited. It is shown that the use of airbridges does not eliminate the slotline modes, but it reduces the slotline mode within short distances of the airbridge. Lastly, these results are independent of frequency. Thus, airbridges must be placed at short distances in asymmetric FGC lines, even for low frequency circuits.

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