Excitation of Coupled Slotline Mode in Finite-Ground CPW With Unequal Ground-Plane Widths

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Abstract—**The coupling between the desired coplanar-waveguide (CPW) mode and the unwanted coupled slotline mode is presented for finite-ground CPWs 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 finite-ground coplanar 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 10 dB. Air-bridges are shown to reduce the slotline mode by 15 dB immediately after the air-bridge, but the slotline mode fully reestablishes itself within 2000 μm of the air-bridge. Furthermore, these results are independent of frequency.**

Index Terms—**Coplanar waveguide (CPW), coupling, transmission lines.**

I. INTRODUCTION

FINITE-GROUND coplanar waveguide (CPW) is often used in low-cost monolithic microwave integrated circuits (MMICs) because of its numerous advantages over microstrip and conventional CPW with large ground planes. 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 $\lambda g/5$ wide where λg is the guided wavelength, they reduce the circuit size and the influence of higher order modes [1]. Finite-ground CPWs have been used for a multitude of circuits, some of which are lumped elements [2], [3], Wilkinson power dividers [4]–[7], and phase shifters [8], [9] without any reported problems.

Finite-ground CPWs were developed and are typically modeled as symmetric transmission lines 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 $\lambda g/4$ 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]–[7]. In 90° 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 finite-ground CPW 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 [10]. Right-angle bends and T-junctions are examples of other asymmetric CPW discontinuities that excite the coupled slotline mode [11]. It is for this reason that air-bridges are used to equalize the voltage on the two ground planes of CPW lines at the discontinuity and along the CPW line [10].

The asymmetry of the finite-ground planes in CPW lines in practical circuit layouts is also expected to excite the coupled slotline mode, and air-bridges are used in these 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 air-bridges are placed at the point of the discontinuity, but the asymmetry in asymmetric finite-ground CPW lines is continuous. Therefore, finite-ground CPW lines with uneven ground-plane widths may cause higher loss and noise than in the asymmetry at localized points in CPW circuits.

In this paper, 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 (FDTD) 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 air-bridges on the control of the parasitic mode.

II. CHARACTERIZATION METHODS

The asymmetric finite-ground CPW line is shown schematically in Fig. 1. CPW-type transmission lines are comprised of three separate conductors, and they will support two independent quasi-TEM modes. For symmetric CPWs, 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 finite-ground CPW transmission lines, the two independent modes are a CPW-like mode and slotline-like mode. (*Note*:

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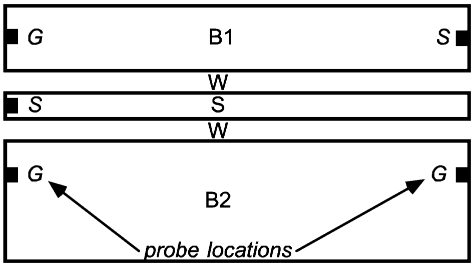


Fig. 1. Schematic of finite-ground CPW with unequal ground-plane widths.

asymmetric CPW transmission lines cannot support two symmetric modes such as the even and odd modes. Instead, the two modes that are supported are typically called the c and the π modes, which are equivalent to the even and odd modes of symmetric transmission lines.) For the problem considered here, a symmetric finite-ground CPW transmission line supporting the CPW and the coupled slotline mode provides the excitation potentials for the asymmetric finite-ground CPW line in the same way that it would in a Wilkinson power divider or other circuit. Likewise, at the far end of the asymmetric finite-ground CPW line, a symmetric finite-ground CPW transmission line is expected to be placed. Thus, we keep the CPW-like mode and coupled slotline-like mode nomenclature throughout the paper and do not refer to the c and π modes.

Determining or measuring the slotline- and CPW-like 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 consider the case when the coupled slotline mode is the excitation signal and the CPW signal is measured, and the case when the CPW mode is the excitation signal and the slotline mode is measured. In other words, a 4×4 scattering matrix would be determined. However, it is very rare that the coupled slotline mode is purposely excited on a CPW line and, in fact, air-bridges are usually used to suppress the slotline mode. Therefore, excitation by the coupled slotline mode 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 in this paper, 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 $\Omega \cdot$ cm and a thickness of 400 μm. The transmission lines are 1.5 μm of electron-beam-deposited Au, which corresponds to three skin depths at approximately 25 GHz, over a 0.02-μm-thick Ti adhesion layer, but the theoretical simulations assume lossless metals. The air-bridges are 3-μm high and 50-μm wide and are constructed of 2.5 μm of plated Au. Two asymmetric finite-ground CPW 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.

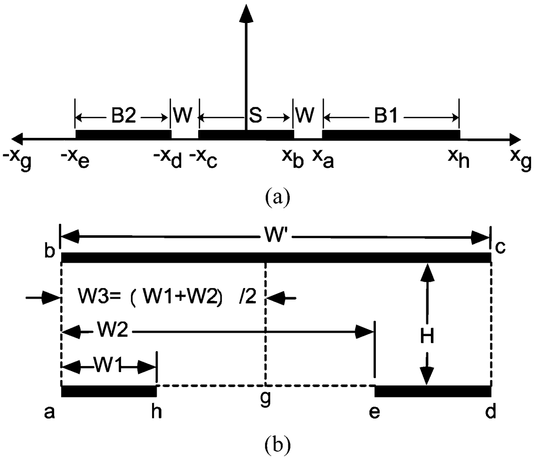
A. FDTD

To understand the physics behind the moding of the asymmetric finite-ground CPW lines, cross-sectional field plots are generated with the ATHENA FDTD simulator as two-and-one-half-dimensional (2.5-D) and three-dimensional (3-D) [12], [13]. The first step involves two 2.5-D simulations for even and odd excitation to derive the E- and H-field distributions for even ("quasi-CPW-like") and odd excitation ("quasi-slotline-like") mode in a plane perpendicular to the propagation direction. Various values of propagation constant β (from 100 to 1000) are utilized to verify the quasi-TEM nature of both modes and also justify the almost frequency-invariant effective permittivity from 10 to 60 GHz. The 2.5-D simulations are critical for the accurate simulation of the full 3-D cases since they model the nonsymmetric current and voltage distributions due to the unequal ground-plane widths and also allow for the mode decomposition. The full 3-D geometry is excited with even excitation and the E-field distribution is recorded at different distances from the air-bridges. Using the 2.5-D 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 sampling of the 3-D field values with the respective 2.5 mode distributions along the cross sections of interest. It has to be noted that the 2.5-D mode pattern amplitudes have been normalized in such a way that they express the same total transferred power by division with the value of the numerical surface integral of $(E \times H^*)$ over the transverse cross section. For each asymmetric finite-ground CPW line, the left- and right-hand-side metal ground planes are connected with 50-μm air-bridges that are spaced every 2500 μm, and the no air-bridge results are analyzed at 2500 μm from an air-bridge.

B. Conformal Mapping

While FDTD analysis can yield a very accurate frequency-dependent solution, it is time consuming and computationally extensive. Quasi-static solutions employing conformal mapping are widely used to determine the characteristic impedance of CPW and finite-ground CPW lines [14]. Here, conformal mapping is employed to determine the ratio of the slotline-like mode to the CPW-like mode from a calculation of the capacitance between each ground plane and center conductor.

Fig. 2 illustrates the asymmetric finite-ground CPW line and its transformation into an equivalent structure. The structure shown in Fig. 2(b) is equivalent to the structure in [15, Fig. 2]. 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. Due to the quasi-static equivalence between Fig. 2(a) and (b), $C1$ 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-like mode to the CPW-like mode is found from $|(C1 - C2)/(C1 + C2)|$.



(a)

(b)

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

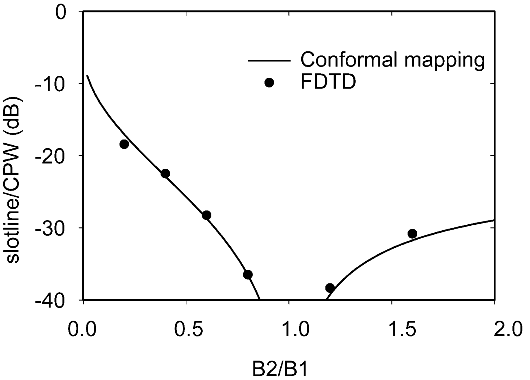


Fig. 3. Ratio of slotline mode to CPW mode at the end of an asymmetric finite ground coplanar line with $S = 15$ μm, $W = 10$ μm, and $B1 = 45$ μm.

C. Measurement Procedure

Measuring circuits with noninsertable probe pads (ground–signal–ground (GSG) on the left-hand side and ground–signal (GS) on the right-hand side) is a difficult task. Various methods were tried, including a two-tier deembedding process, but the most consistent 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 150-μm-long linear taper to facilitate the symmetric GSG probes. During the measurements, a quartz wafer was placed between the silicon wafer and the metal wafer chuck. Due to 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

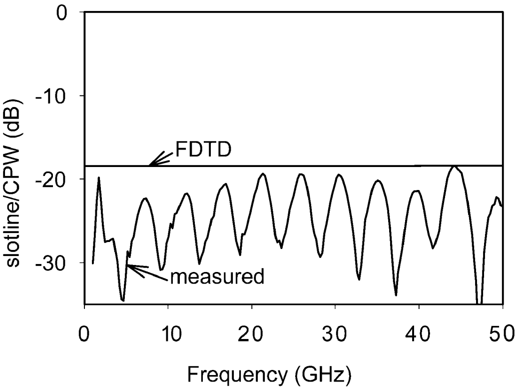


Fig. 4. Ratio of slotline mode to CPW mode measured and determined by FDTD analysis of an asymmetric line with $S = 15$ μm, $W = 10$ μm, $B1 = 45$ μm, and $B2/B1 = 0.2$.

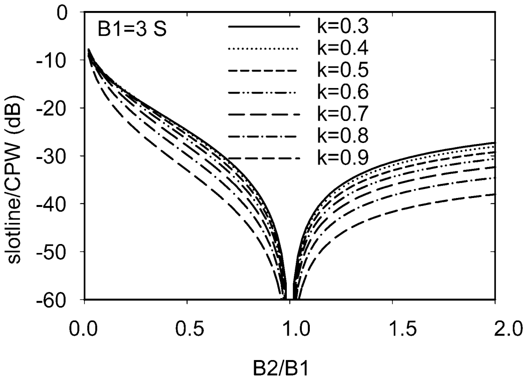


Fig. 5. Ratio of slotline mode to CPW mode as a function of k and $B2/B1$ determined by conformal mapping.

First, to demonstrate the accuracy of the two theoretical methods, Fig. 3 shows the ratio of the slotline-like mode to the CPW-like mode at the end of a 12 000-μm-long asymmetric finite-ground CPW line with no air-bridges, or the test port far from the air-bridges, 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 measured results indicate that the characteristics shown in Fig. 3 are independent of the frequency from 1 to 50 GHz, which is shown in Fig. 4. Fig. 4 shows only one case ($S = 15$ μm, $B1 = 3S$, and $B2/B1 = 0.2$) of measured and FDTD analysis, but it is representative of the other cases. This demonstrates that the excitation of the slotline-like mode is due to quasi-static effects, which further confirms the appropriateness of using the conformal mapping.

Fig. 5 shows the ratio of the slotline-like mode to CPW-like mode determined by conformal mapping as a function of the ratio of the ground planes. It is seen that the slotline-like mode is large, i.e., -10 dB, when $B2/B1$ is small and theoretically decreases to zero when $B2/B1 = 1$. Although the slotline-like mode increases for large ratios of $B2/B1$, it does not reach values above -25 dB. Furthermore, the slotline-like mode is stronger for smaller values of k, which corresponds to higher characteristic impedance values. The slotline-like mode excitation is inversely dependent on the ground-plane width $B1$, as shown in Fig. 6, 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 $3S$ to $4S$ of the slots.

Fig. 7 shows the measured ratio of the slotline-like mode to the CPW-like mode for asymmetric finite-ground CPW lines without air-bridges and a length of 13 000 μm. It is seen that

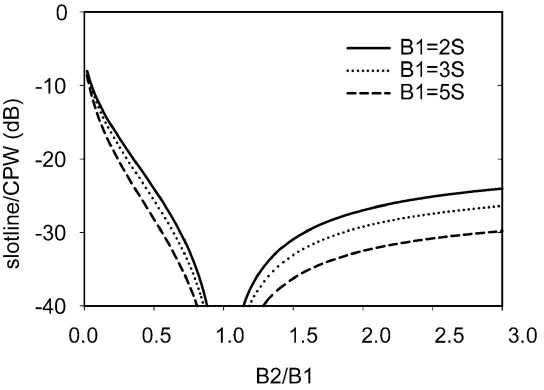


Fig. 6. Ratio of slotline mode to CPW mode as a function of ground-plane width $B1$ for $k = 0.5$.

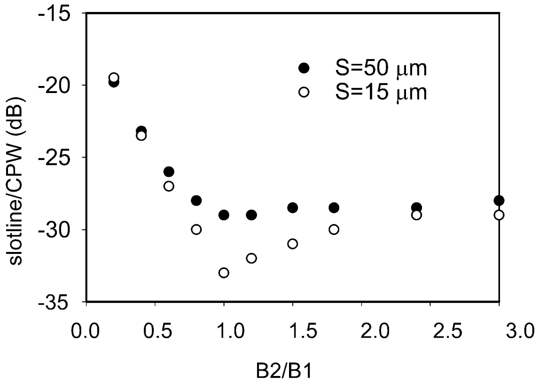
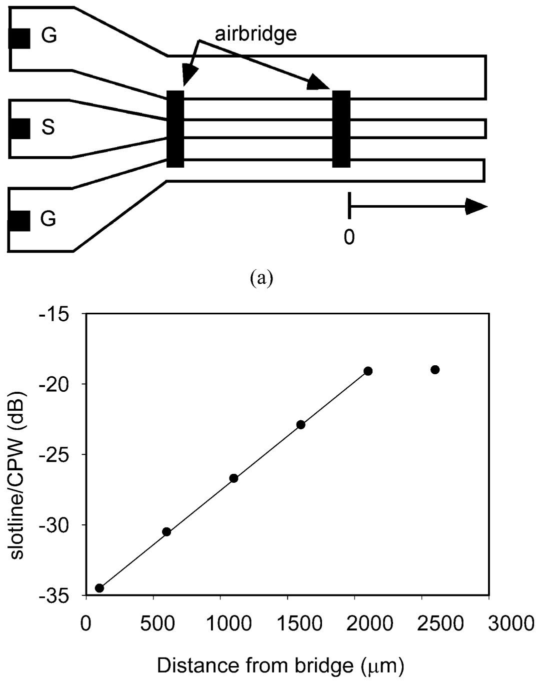


Fig. 7. Measured ratio of slotline mode to CPW mode on asymmetric finite-ground coplanar lines without air-bridges. ($B1 = 3S$).



(a)

(b)

Fig. 8. Ratio of slotline mode to CPW mode as a function of distance from an air-bridge determined by FDTD. (a) Drawing of the circuit analyzed.

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-like mode magnitude is -18 dB for $B2/B1 \geq 0.2$ Characterization of asymmetric finite-ground CPW lines of different lengths further shows that the ratio of the slotline-like mode to the CPW-like mode is independent of line length.

The typical method of eliminating the parasitic slotline mode is to place air-bridges between the two ground planes periodically along CPW lines. An FDTD analysis of asymmetric finite-ground CPW lines with air-bridges spaced every 2500 μm was performed. The ratio of the slotline-like mode to the CPW-like mode as a function of the distance from an air-bridge is shown in Fig. 8. It is seen that the ratio is small immediately after the air-bridge, but that the slotline-like mode grows linearly for 2000 μm, after which the slotline-like mode magnitude saturates to the value without air-bridges. This characteristic is also found to be independent of frequency over the range of 1–50 GHz. Note that 2000 μm is approximately $\lambda g/4$ at 15 GHz and, for lower frequencies, air-bridges must be placed at very small electrical lengths to suppress this mode. A set of asymmetric finite-ground CPW lines was fabricated with air-bridges placed every 1000 μm and the last air-bridge between 1000–4000 μm from the right-hand-side port. The maximum measured decrease in the slotline-like mode is 5 dB, which occurs when the air-bridge is 1000 μm from the measurement port. At the air-bridge, it is expected that the slotline-like mode is eliminated, but as shown in Fig. 8, the mode still exists. Since the numerical noise floor of the FDTD analysis is lower than -50 dB, the slotline-like mode measured at the air-bridge is probably due to higher order evanescent modes in the near field of the air-bridge discontinuity and to the fact that the actual modes supported on the asymmetric finite-ground CPW are c and π modes that are not strictly equivalent to the CPW and slotline modes.

IV. CONCLUSIONS

The layout of circuits with CPW lines with unequal finite-ground-plane widths is demonstrated to cause a significant slotline-like mode to be excited. It is shown that the use of air-bridges does not eliminate the slotline mode, but it reduces the mode within short distances of the air-bridge. Lastly, these results are independent of frequency. Thus, air-bridges must be placed at short distances in asymmetric finite-ground CPW lines, even for low-frequency circuits.

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