# On the Use of Vias in Conductor-Backed Coplanar Circuits

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***Abstract*—Ground planes of conductor-backed coplanar waveguides (CBCPWs) behave like overmoded patch antennas supporting parallel-plate modes and show numerous resonances. For typical monolithic-microwave integrated-circuit chip sizes, these unwanted resonance frequencies lie within the microwave and millimeter-wave frequency region. Due to this feedback mechanism, today's coplanar millimeter-wave amplifiers operating up to 250 GHz require special packaging techniques for stable operation. The use of vias is one method of suppressing parallel-plate modes. The effect of via-holes within a ground plane and the effect of an open or a shorted ground-plane periphery on the parallel-plate modes of CBCPWs were investigated in depth up to 200 GHz for quartz and GaAs substrates. It is shown that the placement of the vias within the coplanar-waveguide structure is crucial for the suppression of parallel-plate modes. If properly placed, vias are an effective means to suppress these unwanted modes over a chosen frequency range.**

***Index Terms*—Conductor-backed CPW, CPW, millimeter wave, modes, vias.**

## I. INTRODUCTION

CONDUCTOR-BACKED coplanar waveguides (CBCPWs) are known to support unwanted bulk modes [1]–[12]. These bulk modes are especially troublesome in monolithic microwave integrated circuits (MMICs), which contain gain stages, because the resulting feedback due to resonances may lead to amplifier instabilities [11]–[17].

In packaging millimeter-wave circuits and components, it is desirable and generally necessary to attach CPW circuits to a metal base for efficient heat removal. Heat removal is more effective if the substrate is thinned, reducing its thermal resistance. However, such a metal base represents an additional ground plane, which, if introduced in close proximity to the coplanar waveguide (CPW) fields, can effectively alter the wave propagating structure, permitting unwanted bulk modes such as surface, parallel-plate, and microstrip-like waves to exist. Thus, as a rule, with reference to Fig. 1(a), $s/h$, as well as $w/h$, should be $<1$, where $h$ is the substrate thickness, isolating the fields of the CPW from the backside metal plane.

Here, we describe a systematic study of the effect of vias in simple CPW circuits, consisting of a single transmission line, not involving active devices, up to the frequency range where modern amplifier MMICs still exhibit useful gain. The insight gained from the study of a transmission line is applicable to MMIC packaging. Packaging coplanar millimeter-wave MMICs is an extremely challenging task, for which, in the past several approaches, have been reported, making use of vias [10], [13], [15], [17], of low dielectric-constant materials [5], [9], [10], of absorbing materials [16], and of flip-chip mounting [18], [19] to suppress unwanted modes.

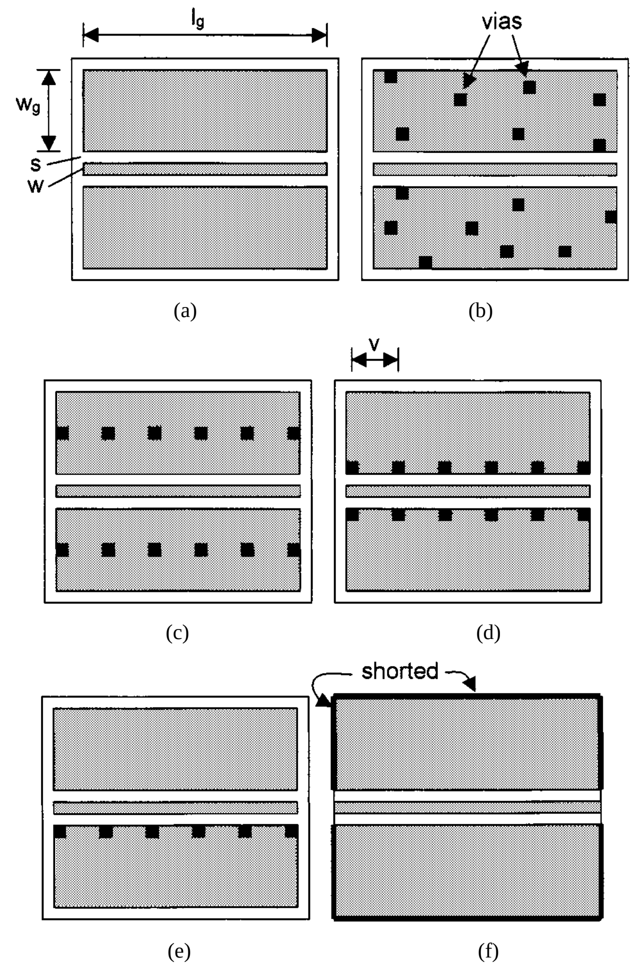


Fig. 1. Symmetric CBCPW structures investigated (not to scale). (b)–(e) The via-holes short the top ground planes with the backside metallization. In (f), the top and bottom ground planes are shorted by a metallized chip periphery.

## II. RESULTS

The effect of vias on CPWs with large ground planes was investigated for two substrate materials of sufficiently different dielectric constant, GaAs with $\varepsilon_r = 12.9$ and quartz with $\varepsilon_r = 3.8$, to obtain additional insight and to cover the range of dielectrics used not only for MMICs, but also for packaging components. We investigated CPW substrates with dimensions close to those

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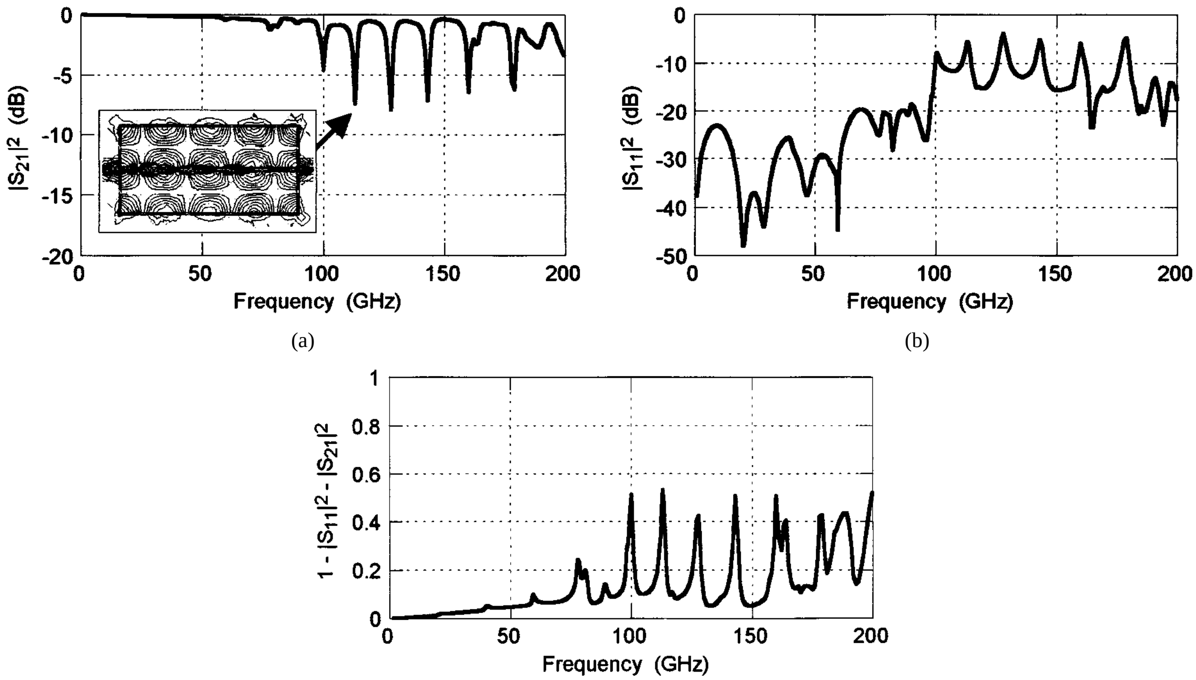



(c)

Fig. 2. Simulated: (a) power transmitted, (b) power reflected, and (c) power radiated for a CBCPW on quartz, as shown in Fig. 1(a) without vias. The inset in (a) shows the $E_z$ electric-field mode pattern of the $m = 1, n = 4$ resonance at 113 GHz.

commonly used in actual millimeter-wave MMICs and connecting structures, typically ranging from 1 to 4 mm in size with a thickness of 0.1 mm. The CPW configurations studied were those illustrated in Fig. 1. They have two large-area ground planes to either side of the center conductor. The substrates were placed on 0.525-mm-thick metal blocks of similar dimensions. This ensemble was then placed on an infinite ground plane. The coplanar line dimensions used in the simulations were $w$=40 $\mu$m, $s = 30$ $\mu$m. The substrate lateral dimensions were 2 mm $\times$ 4 mm and its height was $h$=100 $\mu$m. The CPW top ground-plane dimensions were $w_g = 0.90$ mm and $l_g = 3.9$ mm, and the via-holes were 100 $\mu$m $\times$ 100 $\mu$m. The ground-plane dimensions for the case illustrated in Fig. 1(f), where the outer narrow faces of the substrate were conducting as shown, were 0.95 mm $\times$ 4 mm. All simulations were performed with lossless metals and dielectrics. The metallization thickness was chosen to be zero. The samples were surrounded by a radiation surface, allowing the CPW configuration to be simulated as an antenna. Simulations with lossy materials and finite metal thickness showed no significant differences in the resonance phenomena studied. In the simulation, the CPWs were contacted by small coplanar probes of the same material as the substrate of the CPW under study. The probes were kept small such that mode-free propagation was possible up to 200 GHz. This was verified by separate simulations of the probes.

### *A. Open Ground-Plane Periphery*

For the case of ground planes with an open (nonconducting) periphery, as illustrated in Fig. 1(a), the CBCPW can be treated as two patch antennas with a coplanar feed running along one side of each patch [12]. Energy is coupled into the two ground-plane patches on either side of the center conductor through the electric field in the gap $s$ of the CPW along the entire length $l_g$. For the simple case of a rectangular patch, the resonant frequencies are given by the expression [20], [21]

$$f_{mn} = \frac{c}{2\sqrt{\varepsilon_r}} \left[ \left( \frac{m}{w_g} \right)^2 + \left( \frac{n}{l_g} \right)^2 \right]^{0.5} \tag{1}$$

where $c$ is the velocity of light, $\varepsilon_r$ is the relative dielectric constant, $w_g$ and $l_g$ are the width and the length of the ground patch, respectively, and $m$ and $n$ are integers, the mode indexes. In the above equation, the thickness $h$ of the substrate and, thus, electric-field fringing effects, are neglected. The coordinate system chosen is $x$ along the CPW, $y$ normal to it in the plane of the CPW, and $z$ normal to and out of the plane of the CPW. The $E_z$-field distribution across the plane of the patch varies as a cosine function in both $x$ and $y$ over the patch. For patch dimensions of a few millimeters and millimeter-wave frequencies, the ground patch represents an overmoded parallel-plate resonator. The effect of electric-field fringing [20], [21] was not observable in the simulated or measurement data. At the frequencies $f_{mn}$, the incoming signal is: 1) partly reflected due to a strong decrease in the impedance; 2) partly radiated due to the antenna properties; and 3) partly transmitted. At resonance, the impedance of the CPW as determined from the simulated $S$-parameters is considerably below that of the input line characteristic impedance, which is 50 $\Omega$ for GaAs and 85 $\Omega$ for quartz, resulting in a large reflective component of the incoming signal [12]. From the above equation, a small $w_g$ can result in $f_{mn}$ higher than the operating frequency, yielding mode-free operation. This phenomena, the "finite ground" CPW, which exhibits no resonances and no power loss over a large frequency range, has been observed and utilized in the past [22], [23]. However,

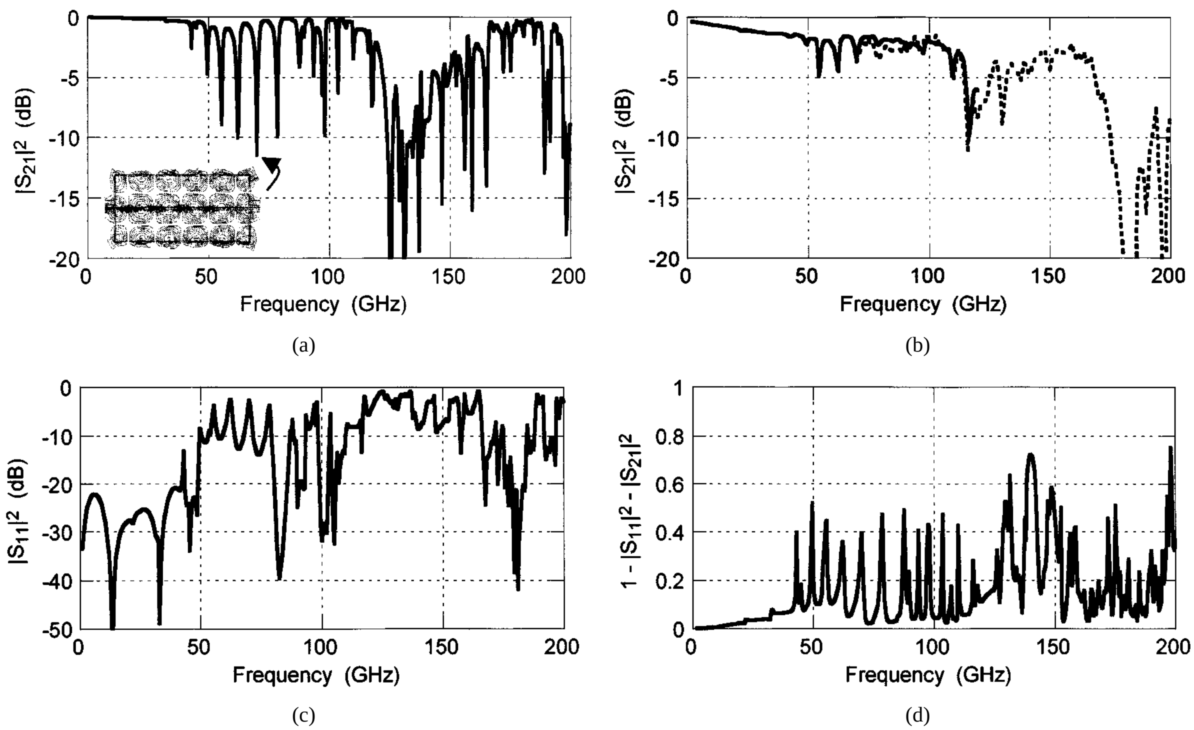



Fig. 3. Simulated: (a) power transmitted, (c) power reflected, and (d) power radiated for a CBCPW on GaAs, as shown in Fig. 1(a) without vias. The inset in (a) shows the $E_z$ electric-field mode pattern of the $m = 1, n = 5$ resonance at 70 GHz. The measured power transmitted is shown in (b) over a 200-GHz range employing two network analyzer systems (solid and dotted lines).

for complex coplanar MMICs on substrates with high dielectric constants and with numerous stubs and bias lines, the approach based on "finite ground" CPWs is not a practical one, except for very simple circuits [24], since the surface of an MMIC will be a mesh of ground conductors, still resulting in resonances.

Fig. 2 illustrates the simulation results for a CBCPW of the type shown in Fig. 1(a). We chose a quartz substrate with $\varepsilon_r$=3.8 in order to clearly demonstrate the discrete frequencies $f_{mn}$ of the resonance phenomena over a 200-GHz frequency range, which is the range of today's millimeter-wave integrated circuits (ICs) [15]. The effect of a low dielectric constant is similar to that of a small patch dimension, a shift of $f_{mn}$ to higher frequencies. The simulated frequencies $f_{mn}$ in Fig. 2(a) indicated by the dips in transmission ($|S_{21}|^2$), are for $m = 1$ and $n = 3$ at 100 GHz, $n = 4$ at 113 GHz, $n = 5$ at 128 GHz, $n = 6$ at 143 GHz, $n = 7$ at 160 GHz, and $n = 8$ at 178.5 GHz. They agree well with the values of 100.3, 113.1, 127.6, 143.4, 160.1, and 177.4 GHz calculated from (1).

A contour representation of the electric-field magnitude of the $E_z$ component (across a plane 50 $\mu$m below the chip surface) of the $f_{14}$ mode at 113 GHz is shown as an inset. $E_z$ varies over one patch along the $x$- and $y$-directions according to cosine functions, by $\pi$ along $w_g$, and by $4\pi$ along $l_g$. High reflection losses ($|S_{11}|^2$) occur at the above frequencies as observable from Fig. 2(b). Due to the excitation and boundary conditions for the $E_z$-field mode pattern, which dictates the field maxima to lie along the slot and on the patch periphery, the $m = 0$ modes below approximately 100 GHz are not excited.

It should be noted that the spacing of the $E_z$-field maxima does not correspond to the value $c/(\varepsilon_r^{0.5} f_{mn})$, but is given by the eigenfunctions of the patch antenna, and is different in the $x$- and $y$-directions according to the values of $m$ and $n$. For example, at the frequencies $f_{mn}$ with $m = 1$ and $n = 2$–6, the distance between the peaks of the $E_z$-field on one ground plane remains constant and equal to $w_g$ in the $y$-direction, and varies from $l_g/2$–$l_g/6$ in the $x$-direction. The simulated power lost $[1-(|S_{21}|^2)-(|S_{21}|^2)]$ by radiation is shown in Fig. 2(c), as calculated from the $S$-parameters. Power leakage may also occur in the form of surface waves propagating on the surrounding unmetallized substrate [11], [18]. No such power leakage is possible for our CBCPWs since their top surface is metallized.

Simulated and measured data for the case of a GaAs substrate with $\varepsilon_r = 12.9$ are shown in Fig. 3. As predicted from (1), the resonant frequencies $f_{mn}$ are lower. Three groups for $m = 1, 2$, and 3 are visible. Due to the numerous number of possible modes, they are not well defined above approximately 110 GHz. Again, transmitted [see Fig. 3(a)], reflected [see Fig. 3(c)], and radiated [see Fig. 3(d)] power are shown. Measured data, taken with two network analyzer systems, indicated by the solid line[1] and dotted line [25] is shown in Fig. 3(b). The measured resonant frequencies $f_{mn}$ in the 50–90-GHz range agree well with the simulated values and those obtained from (1). The inset in Fig. 3(a) illustrates the simulated $E_z$-field pattern for the $f_{15}$ mode at 70 GHz. The simulated resonances from $f_{12}$ at 49 to $f_{17}$ at 87 GHz are well defined.

### B. Vias in CBCPW Ground Plane

An amplifier MMIC realized with CBCPWs can be treated as an active patch antenna with integrated gain and backside

[1]Hewlett-Packard Company, Santa Rosa, CA, HP 8510C Network Analyzer.

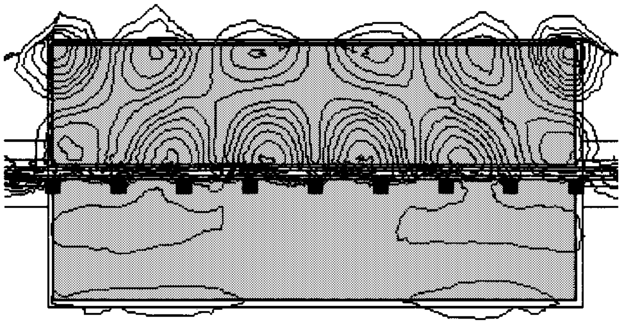
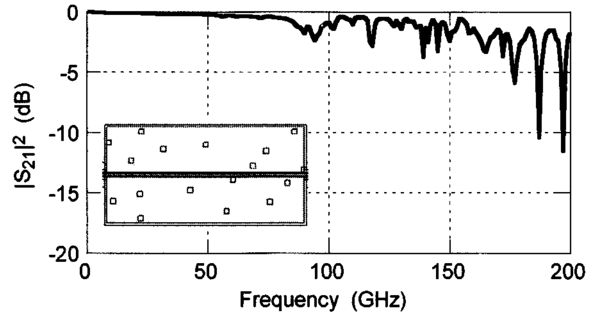


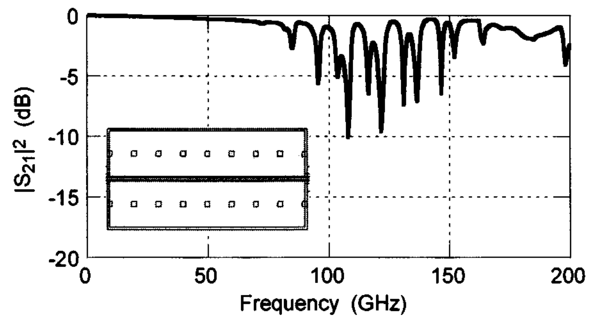
Fig. 4. Simulated $E_z$ electric-field mode pattern (magnitude) for a CBCPW on quartz, as shown in Fig. 1(e). The top half without vias shows the $m = 1$, $n = 5$ resonance at 113.2 GHz. The bottom half with vias is mode free.

ground plane, with resonant frequencies determined by the size and shape of the top-side metallization. At the resonances, feedback in the chip volume below the ground-plane patches, coupled with sufficient gain, may cause amplifiers to become unstable. Experimentally, we have found that broad-band $W$-band amplifiers with GaAs substrate dimensions of 1 mm × 2–3 mm and 0.1-mm thickness, when placed on metal, become unstable at well-defined frequencies if the gain exceeds approximately 20 dB [14], [16], [18]. For such typical MMIC dimensions and for materials with a high dielectric constant such as GaAs and InP, the frequencies $f_{mn}$ lie in the 80–200-GHz range for the lowest well-defined group of $m = 1$, as given by (1). Stable amplifier operation, however, can be realized through the use of vias. The application of vias in GaAs and InP amplifiers in the 60–215-GHz range has been demonstrated by Weinreb *et al.* [13], [15] and Leong and Weinreb [17]. Vias placed randomly across the amplifier MMICs were found to be necessary for stable amplifier operation.

Below, we have studied the placement of vias on parallel-plate mode suppression in a systematic manner. For an understanding of the underlying basic phenomena, we have investigated the effect on a variety of transmission lines, as illustrated in Fig. 1. Placing vias anywhere within the ground-plane patch will effect the $E_z$-field mode pattern and, thus, the resonant frequencies. Single $f_{mn}$ modes can effectively be suppressed by placing vias at the positions of the maxima of the $E_z$-field mode pattern. If more modes are to be suppressed over a desired bandwidth, vias must be placed at all maxima of all mode patterns within the operating frequency range. Since parallel-plate modes are excited at the gap $s$ of the CPW, placing vias alongside the gap from the ground patch to the backside of the substrate should be most effective for eliminating or reducing the excitation of the modes. This is demonstrated in Fig. 4, where vias were placed along the CPW, shorting only the lower top ground plane to the bottom ground plane. Modes are excited only in the upper volume of the substrate that does not have vias. In Fig. 5(a), vias were placed at random and, in Fig. 5(b), at some distance from the slot. In both cases, the suppression of resonances is not very effective. A special case is illustrated in Fig 5(b), where the placement of vias has no effect on the $f_{mn}$ resonances for $m$ equal to an odd integer since the vias are placed along a line of zero $E_z$. Thus, the resonances for $m = 1$ in the 80–150-GHz range are observed to be almost unaffected,




(a)




(b)

Fig. 5. Simulated power transmitted through a CBCPW on quartz, as shown in Fig. 1(b) and (c) when the vias are (a) placed at random and (b) along the center of the ground patches.

and those for $m = 2$, above 150 GHz, are suppressed because the vias lie at the field maxima for this mode.

Fig. 6 illustrates the results when vias are placed alongside the slot of the CPW, the most effective way of mode suppression. The spacing between vias (center to center) was varied to be 1.95, 0.875, and 0.4875 mm from top to bottom. As shown, resonances are highly suppressed up to 63 and 95 GHz for the 1.95- and 0.875-mm spacings, respectively, and up to 180 GHz for the smallest spacing of 0.4875 mm, which corresponds to approximately $\lambda/2$ in the quartz substrate at this frequency.

Simulations performed for a GaAs substrate of similar dimensions showed suppression of the resonances up to 35, 54, and 93 GHz for identical center-to-center via spacings of 1.95, 0.875, and 0.4875 mm, respectively. Our data predicts suppression up to approximately 270 GHz for a 150-$\mu$m spacing of the vias, which agrees well with the spacing used for a 160–210-GHz amplifier, reported in [15]. Equation (1) predicts the necessity of vias because the resonances $f_{13}$–$f_{17}$ lie in the 160–230-GHz range if no via-holes are used.

Early experimental work on the effect of vias in considerably larger CBCPWs, as used here, and at much lower frequencies, was reported by Valdieck *et al.* [6]. They found that an increasing number of via-holes and their placement close to the slots of the CPW will improve the transmission properties of the line, which is in basic agreement with our results.

In Fig. 7, we present our experimental results for a small coplanar line with $w = 18$ $\mu$m and $s = 16$ $\mu$m, as is typical for the 50-$\Omega$ lines used in our millimeter-wave MMICs. Measurement and simulation data are presented for two $2 \times 4$ mm GaAs chips, 0.1-mm thick, and placed on metal, one without and one with vias. Fig. 7(a) shows the measured and simulated responses

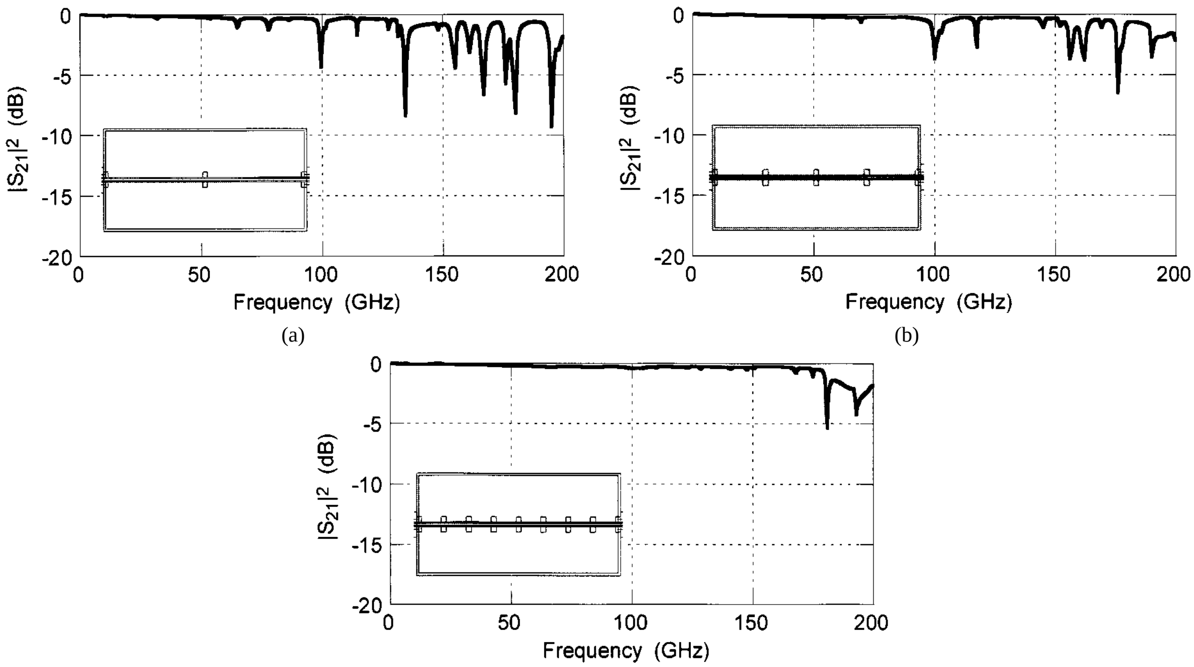



Fig. 6. Simulated power transmitted through a CBCPW on quartz, as shown in Fig. 1(d) when vias are placed along the gap of the CBCPW with decreasing center-to-center spacing. (a) 1.95 mm. (b) 0.875 mm. (c) 0.4875 mm.

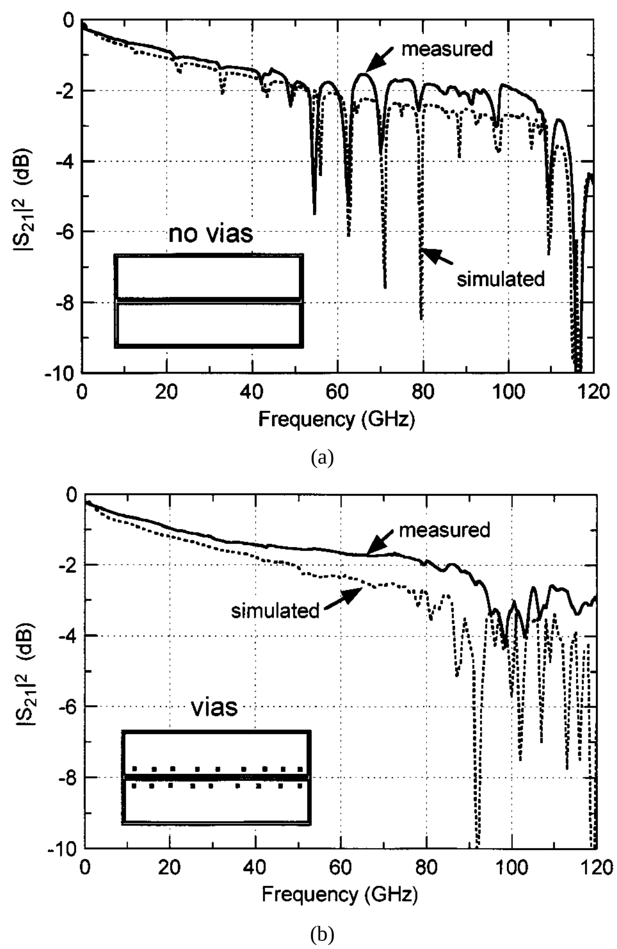



Fig. 7. Simulated and measured power transmitted through a CBCPW on GaAs, which is open along its periphery, as shown in Fig. 1(a) and (c). Resonances are: (a) present without vias and suppressed up to 90 GHz with vias. (b) 100-$\mu$m square and spaced (center to center) approximately 0.45 mm.

of the coplanar line when no vias are present. A resistivity of 2.4 $\times$ $10^{-6}$ $\Omega \cdot$cm was used in the simulation. A number of resonances exist due to the large ground planes, as discussed above. In Fig. 7(b), the responses of the sample with vias placed alongside the coplanar line are illustrated. All vias were placed 0.175 mm from the center of the coplanar line and spaced apart somewhat at random, as shown in the inset of Fig. 7(b), with an average center-to-center distance of 0.45 mm. The vias had an average diameter if 100 $\mu$m and a 3-$\mu$m-thick gold metallization was used. For the simulation, square vias with 100-$\mu$m side length were used. As simulated and measured, the resonances are suppressed by the vias up to a frequency of approximately 90 GHz. Keeping the position of the vias unchanged, the effect of the size of the vias was simulated, with the results shown in Fig. 8. From these data, it is apparent that the spacing between vias (metal to metal, not center to center) determines the upper frequency limit of the resonances and, thus, leakage into the substrate.

### *C. Shorted CBCPW Ground-Plane Periphery*

We have investigated the effect of shorting the ground planes of the CPW since this is a practice often exercised in the packaging of MMICs. It will be demonstrated below that this shorting practice has no effect on the suppression of the resonances due to the parallel-plate modes. Placing vias along the periphery of the ground-plane patches along $w_g$ and $l_g$ or metallizing these faces of the substrate changes the boundary conditions of the electric field there. The allowed mode patterns must exhibit zero field along the periphery and maximum field along the excitation gap $s$ of the CPW. Simulation results for the quartz substrate are shown in Fig. 9, along with the $E_z$-field mode patterns at $f_{0.5\,4} = 86$ GHz and $f_{1.5\,7} = 179$ GHz. To

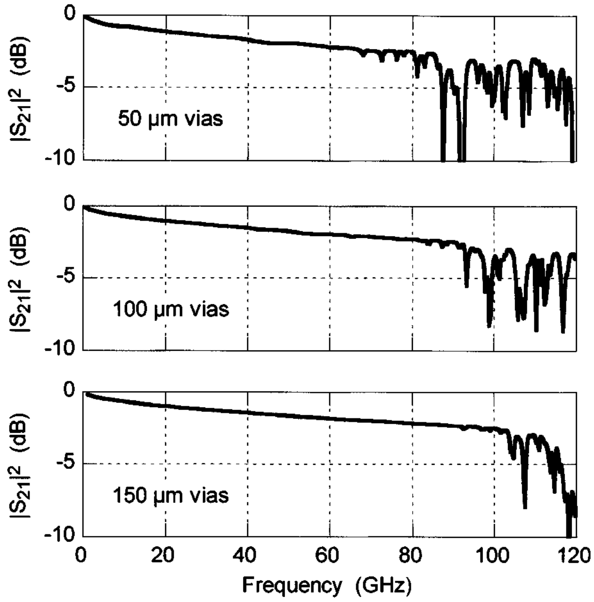



Fig. 8. Simulated power transmitted through a CBCPW on GaAs, as shown by the inset of Fig. 7(b). Square vias are spaced approximately 0.45 mm (center to center), but vary in size, as indicated.

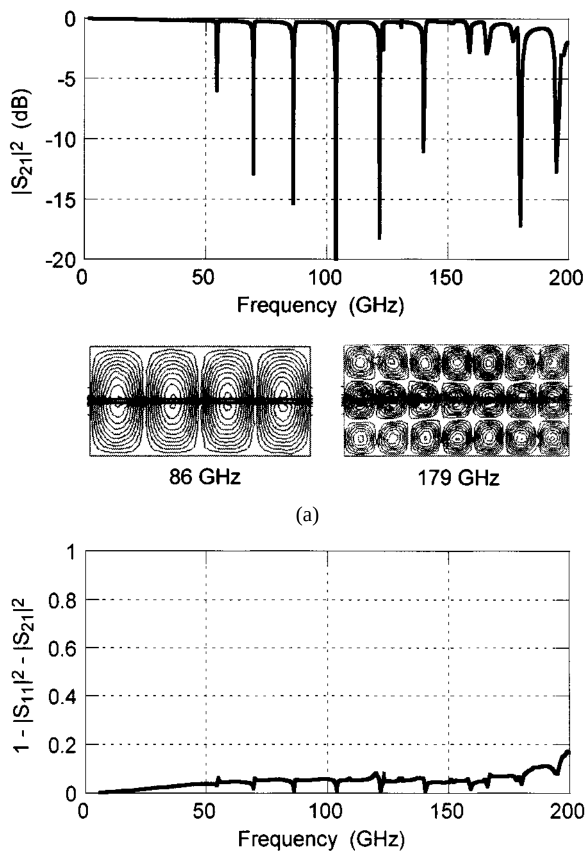



Fig. 9. Simulated power transmitted: (a) through a CBCPW on quartz, which is shorted along its periphery as shown in Fig. 1(f) with $E_z$ electric-field mode patterns of the resonances at 86 and 179 GHz. (b) Negligible power is radiated.

determine the resonance frequencies $f_{mn}$, (1) still applies with $m$ replaced by odd multiples of 0.5 and $n$ an integer. As expected, power lost by radiation should be negligible, as shown in Fig. 9(b).

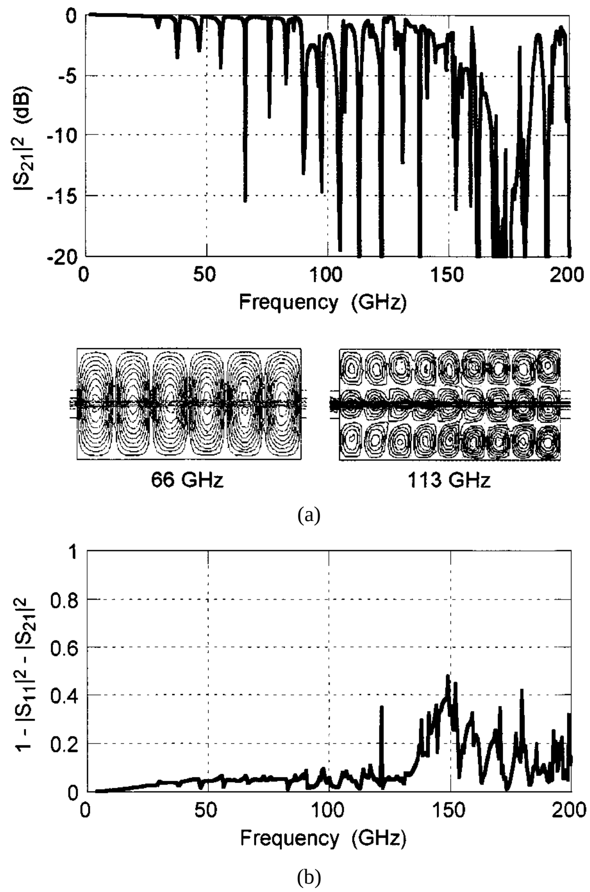



Fig. 10. Simulated power transmitted: (a) through a CBCPW on GaAs, which is shorted along its periphery, as shown in Fig. 1(f) with $E_z$ electric —field mode patterns of the resonances at 66 and 113 GHz. (b) Power lost from this CBCPW.

Simulation results for a GaAs substrate are shown in Fig. 10, together with the $E_z$-field patterns at $f_{0.5\,6} = 66$ GHz and $f_{1.5\,9} = 113$ GHz. The unequal spacing between peaks or nulls in $E_z$ in the $x$- and $y$-directions are apparent. The radiated power increases above approximately 130 GHz.

## III. Conclusion

It has been shown that a CBCPW behaves like a slot-line-coupled patch antenna, with analytically predictable resonance frequencies for simple rectangular geometries. At millimeter-wave frequencies, ground planes with dimensions of several millimeters cause resonances above about 50 GHz. At a resonance, the incoming signal is partly reflected due to a low input impedance, partly transmitted and partly radiated from the edges of the substrate.

The effect of vias, which short the ground planes on the top of the substrate with the metal on the bottom, has been systematically investigated. It has been shown that it is sufficient to strategically place vias near the excitation region of the ground patch, which is the gap of the CBCPW. A random distribution over the ground patch is not superior and does not improve suppression of the substrate modes. Grounding the periphery of the ground plane, as might often be the practice in mounting and packaging of coplanar MMICs, does not suppress substrate modes, it only causes a shift in the resonance frequencies of the ground patch.

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