

Analysis of a Partially Sealed Package for Microstrip-Line Circuits

Hao-Hui Chen and Shyh-Jong Chung, *Member, IEEE*

Abstract—A partially sealed package formed by two metal diaphragms with or without an absorber is proposed and analyzed for shielded microstrip-line circuits. The mode-matching method, method of lines, and finite-element method are mixed appropriately to investigate the package. For a specific analysis, an electric current filament and a microstrip-line gap are chosen to simulate, respectively, an active circuit element (CE) and a passive CE to be packaged. The suppression effect of the package on the spurious (higher order) modes and the influence on the dominant mode are fully studied by comparing the excitation and scattering characteristics of the CE's with and without the package.

Index Terms—Metal diaphragms, packaged microstrip line, partially sealed cavity, spurious modes.

I. INTRODUCTION

MICROWAVE and millimeter-wave circuits are usually shielded by a rectangular waveguide to prevent the circuits from mechanical destructions and electromagnetic interferences (EMI's) from the environment. In these shielded circuits, parasitic fields may be excited by active devices and/or discontinuities in the circuit and propagate in the forms of the higher order modes (spurious modes) of the shielded transmission lines. As the signals (which are carried by the dominant mode) and the parasitic fields from a circuit element (CE) travel toward another one, the power coupling between modes would be caused through the latter element (which is essentially composed of discontinuities of the transmission lines) and, thus, disturbs the total circuit operation. To avoid these EMI's between the CE's, one of the approaches is to partition a shielded circuit into several cabinets by attaching vertical diaphragms to the lid of the circuit [1].

As presented in [1], a metal diaphragm can mostly reflect the powers of the spurious modes while it has little influence on the dominant mode. A cabinet formed by two such diaphragms thus provides the following advantages. Firstly, since the cabinet is not fully sealed by the diaphragms, the signals (carried by the dominant mode) can be passed from one CE to another without being affected by the package. Secondly, the CE (or sub-circuit) located within the cabinet would suffer very slightly from the interference of the spurious modes excited from the adjacent CE's (owing to the reflection of these modes by the diaphragms). Thirdly, since the spurious modes excited

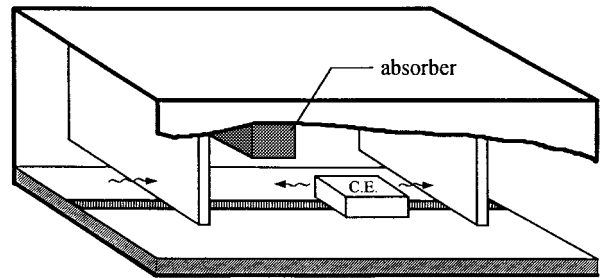


Fig. 1. A partially sealed package for a shielded microstrip circuit.

by the CE located within the cabinet are confined in the cabinet and are weakened due to the destructive interferences between the fields of the modes, the strengths of the outgoing spurious modes from this packaged element are thus greatly reduced. In short, the cabinet can increase the electromagnetic susceptibility (EMS) of a CE (e.g., a receiving CE) and/or reduce the EMI from the element (e.g., a transmitting CE).

However, due to the high reflectivity of the diaphragms (for the spurious modes), the cabinet would behave like a cavity. As the integration and/or operating frequency increases, the electrical size of the cabinet increases and, thus, the resonances of the spurious modes would be difficult to avoid. If the system operates at a frequency near one of these resonances, the coupling between the dominant and spurious modes may become uncontrollable and, thus, alter the electrical performance of the system. Several techniques for reducing the coupling effects of the resonant modes can be found in [2]–[7]. References [2] and [3] used a resistive film coated on a dielectric layer which was, in turn, fixed under the lid of the package to damp the undesirable resonant cavity modes. References [4]–[7] considered a lossy damping layer for reducing the influence of the resonance effect. In general, the attenuation effect by using the absorbing layer would be better than that by coating the resistive film [6]. Also, as was pointed out in [7], the lossy layer should be placed at some suitable location for effectively damping the resonant modes.

In this paper, the partially sealed package, composed of two metal diaphragms and/or an absorbing layer, as shown in Fig. 1, will be studied. In the analysis, the mode-matching method together with the method of lines [1], [8] is first used to determine the scattering matrices of the diaphragms and absorber. While in order to allow for arbitrary geometries and inhomogeneities, the scattering matrix of the CE is calculated by using the finite-element method (FEM) [9]. The total scattering effect of the whole structure is then obtained by

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The authors are with the Department of Communication Engineering, National Chiao Tung University, Hsinchu 30039, Taiwan, R.O.C.

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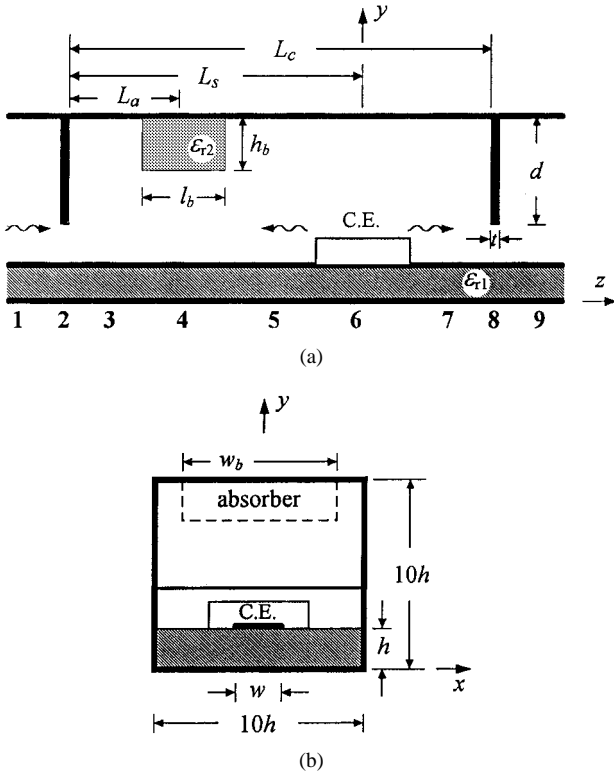


Fig. 2. Cross-sectional views of the partially sealed package.

cascading these scattering matrices. The numerical results for two CE's will be presented, i.e., an electric current filament (representing an active CE) and a microstrip-line gap (representing a passive CE). The suppression effect on the higher order modes and the influence on the dominant mode (of the partially sealed package with or without an absorber affixed inside) will be studied by changing the package length, CE position, and position and size of the absorber. Finally, a separate experiment is carried out to verify the analysis.

II. ANALYSIS

Fig. 2 shows the cross-sectional views of the structure for analysis, where two diaphragms (regions 2 and 8) with depth d and thickness t are attached to the top cover of the shielded microstrip line, forming a partially sealed package with length L_c . A CE (region 6), which may be active or passive, is confined inside this package at a distance L_s from the left diaphragm. Also, an absorber having length l_b , thickness h_b , and width w_b may be affixed to the top of the cabinet for damping the spurious modes. The distance between the center point of the absorber and the left diaphragm is L_a . For simplicity, the microstrip line is located symmetrically in the x -direction and has a width (w) equal to the thickness (h) of the substrate (leading to an impedance of about 50Ω for a substrate of $\epsilon_{r1} = 9.7$). The dimension of the waveguide cross section is set to be $10h \times 10h$. The dominant and spurious modes of the shielded microstrip line may be incident from the left side (region 1) toward the package or be directly excited by the (active) CE inside the package.

To tackle the problem, the diaphragms, absorber, and CE are treated as discontinuities in the shielded microstrip line. The

scattering effect of each discontinuity is solved as follows. For the diaphragm and absorber, we calculate the scattering matrices by using the mode-matching method together with the method of lines [1], [8]. The modes, including propagation, evanescent, and/or complex modes of regions 1 (3, 5, 7, 9), 2 (8), and 4, are first solved by the method of lines. Following the procedure described in [10], the following homogeneous matrix equation is obtained:

$$[\mathbf{Z}(\epsilon_{\text{eff}})] \begin{bmatrix} \mathbf{J}_x \\ \mathbf{J}_z \end{bmatrix}_{\text{strip}} = 0 \quad (1)$$

where \mathbf{J}_x and \mathbf{J}_z are two vectors representing the x and z components of the current distributed on the strip, and ϵ_{eff} is the effective dielectric constant of the corresponding mode.

To get nontrivial solutions of the current distributions, the determinant of the impedance matrix $[\mathbf{Z}(\epsilon_{\text{eff}})]$ should be zero, from which the effective dielectric constants are obtained. In the calculation, the ϵ_{eff} 's for the modes of regions 1 (3, 5, 7, 9) and 2 (8) are calculated by searching the zeros of $f(\epsilon_{\text{eff}}) (= \det[\mathbf{Z}(\epsilon_{\text{eff}})])$ on the real axis of the ϵ_{eff} plane. However, since $\epsilon_{r2} (= a - jb)$ is complex, the ϵ_{eff} 's for the modes of region 4 are obtained by finding the zeros of $f(\epsilon_{\text{eff}})$ within the region

$$\begin{aligned} -\frac{\alpha_{\text{max}}^2}{k_0^2} < \text{Re}(\epsilon_{\text{eff}}) < a \\ -\frac{2\sqrt{a}\alpha_{\text{max}}}{k_0} < \text{Im}(\epsilon_{\text{eff}}) < 0. \end{aligned} \quad (2)$$

Here, only the modes having the attenuation constants $\alpha < \alpha_{\text{max}} (= 3 \text{ mm}^{-1})$ are considered. (The real part of $\epsilon_{r2}(a)$ is assumed to be greater than the dielectric constant of the substrate (ϵ_{r1}), if not, a should be replaced by ϵ_{r1} in (2).)

With ϵ_{eff} known, the propagation constants, current distributions on the strip, and all normalized fields of each mode are explicitly calculable. The scattering matrices $[\mathbf{S}_{\text{junc}}^i]$ ($i = 1, 2, 3, 4$) of the junctions formed by regions i and $i + 1$ can then be obtained via the mode-matching method [11]. The details of calculating $[\mathbf{S}_{\text{junc}}^i]$ can be found in [1] and [8]. Once the scattering matrices $[\mathbf{S}_{\text{junc}}^i]$ are determined, those of the diaphragms ($[\mathbf{S}_{\text{dia}}]$) and the absorber ($[\mathbf{S}_{\text{abs}}]$) can be obtained by cascading the scattering matrices $[\mathbf{S}_{\text{junc}}^1]$, $[\mathbf{S}_{\text{junc}}^2]$, and $[\mathbf{S}_{\text{junc}}^3]$, $[\mathbf{S}_{\text{junc}}^4]$, respectively.

However, for the CE (region 6), in order to allow for arbitrary geometries and inhomogeneities, the FEM [9] is adopted to determine the scattering and excitation characteristics of the element, which yields the following relation:

$$[\mathbf{b}] = [\mathbf{S}_{\text{CE}}][\mathbf{a}] + [\mathbf{b}_0] \quad (3)$$

where $[\mathbf{a}]$ and $[\mathbf{b}]$ are the amplitude vectors for the incoming and outgoing modes, respectively. $[\mathbf{S}_{\text{CE}}]$ is the scattering matrix of the CE without sources. $[\mathbf{b}_0]$ is the amplitude vector for the excited outgoing modes due to the source in the (active) CE.

After determining the scattering matrices and/or the source vector of the diaphragms, absorber, and CE, the scattering characteristics of the whole structure can then be obtained by cascading these matrices and vector.

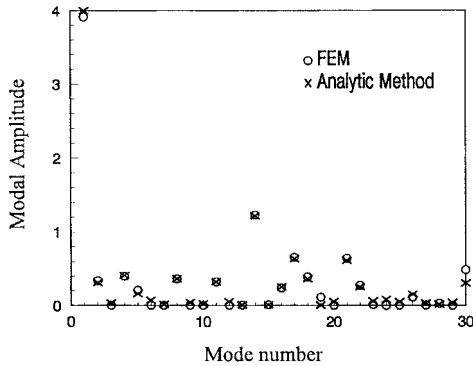


Fig. 3. Modal amplitudes of the shielded microstrip line excited by a current filament.

III. RESULTS AND DISCUSSIONS

In this section, we set $h = w = 0.635$ mm, $\epsilon_{r1} = 9.7$, $\epsilon_{r2} = 12 - j12$, and the operating frequency $f = 25$ GHz. Under this choice of parameters, there are three propagation modes for the microstrip line with housing $10h \times 10h$. The first two (i.e., the dominant mode and the second-order mode) are even modes and the last one is an odd mode. The two identical diaphragms are with thicknesses (t) of 2 mm and depths (d) of $8h$. From [1], the reflected power of the dominant mode at each diaphragm is -78.01 dB, while those of the second- and third-order modes are -0.49 and -0 dB, respectively.

Two CE's are considered. One is a unitary electric-current filament of length h placed symmetrically under the microstrip

$$\mathbf{J}(x, y, z) = \begin{cases} \hat{\mathbf{y}}\delta(x)\delta(z), & 0 < y < h \\ 0, & \text{elsewhere.} \end{cases} \quad (4)$$

The other is a microstrip-line gap of length $g = 0.2$ mm. For the first CE, which is an active element, the package is expected to suppress the excited spurious modes, especially the propagating higher order modes, while cause little influence on the dominant mode. For the second CE, which is a passive one, the power coupling between the dominant and higher order modes occurs when a dominant or higher order mode is incident upon the element. The package confining this CE can directly reflect the powers of the incident higher order modes and, in the meanwhile, when a dominant mode is incident on the element, weaken the excited spurious modes.

Before studying the effects of the partially sealed package, the excitation and scattering characteristics of the two CE's are first examined. Fig. 3 shows the modal amplitudes of the first 30 modes excited by the current filament without the package. The first mode is the dominant mode of the shielded microstrip line and the second and third modes are the other two propagation modes. It is noticed that, due to the symmetry of the current filament in the x -direction, the third-order mode and the other odd modes (modes 6, 7, 9, etc.) are not excited. The good agreement between the two curves ensures the validity of the treatment of the FEM in the CE region.

For the microstrip-line gap without the package, the finite-element analysis shows that $P_{11}^- = -1.99$ dB, $P_{11}^+ = -4.74$ dB, $P_{21}^- = -18.53$ dB, $P_{21}^+ = -17.47$ dB, and $P_{22}^- = -34.30$ dB, $P_{22}^+ = -0.14$ dB, $P_{12}^- = -18.53$ dB,

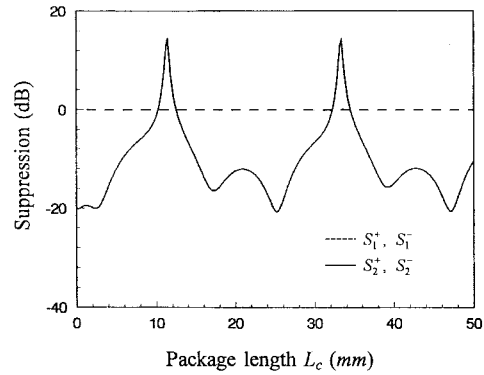


Fig. 4. The suppressions of the package (without absorbers) on the excited modes of the current filament as a function of the package length (L_c). $L_s = L_c/2$, $f = 25$ GHz.

$P_{12}^+ = -17.47$ dB. Here, $P_{ij}^-(P_{ij}^+)$ denotes the $-z(+z)$ propagating power of the i th-order mode due to a j th-order mode incidence (from $z = -\infty$ toward the gap). It is noticed that $P_{ij}^- = P_{ji}^-$ and $P_{ij}^+ = P_{ji}^+$, which are the results of the reciprocity theorem. Also note that, owing to the symmetry of the gap in the x -direction, there are no couplings between the third-order mode (odd mode) and the first two modes (even modes).

To describe the effect of the package, a dimensionless quantity (named *suppression*: S) is defined in this paper as follows:

$$S_i^\pm = \frac{P_i^\pm(\text{with package})}{P_i^\pm(\text{without package})} \quad (5)$$

for the current filament (P_i^\pm denotes the power of the excited i th-order mode); and

$$S_{ij}^\pm \equiv \frac{P_{ij}^\pm(\text{with package})}{P_{ij}^\pm(\text{without package})} \quad (6)$$

for the microstrip-line gap. Here, P^\pm (with package) represents the power going away from the package and propagating in the $\pm z$ -direction.

A. Partially Sealed Package Without Absorbers

The characteristics of the partially sealed package without absorbers are first examined in this section. Fig. 4 shows the suppressions of the package on the excited modes of the current filament as a function of the package length L_c . The filament is located at the central position of the package ($L_s = L_c/2$, see Fig. 2). It is seen that the excited dominant mode is not affected by the existence of the package, and that, on the other hand, for most package sizes, the outgoing second-order modes are weakened (by about 15 dB) when the diaphragms are introduced. However, the latter phenomenon disappears when the package length approaches some critical values (11.4 mm, 33.4 mm, etc.), where the powers of the second-order modes increase to the levels 15 dB higher than those without packaging. This is caused by the field constructive interference of the second-order modes bouncing between the two diaphragms. Since the diaphragms are essentially perfect electric conductor (PEC) walls for the second-order mode (the

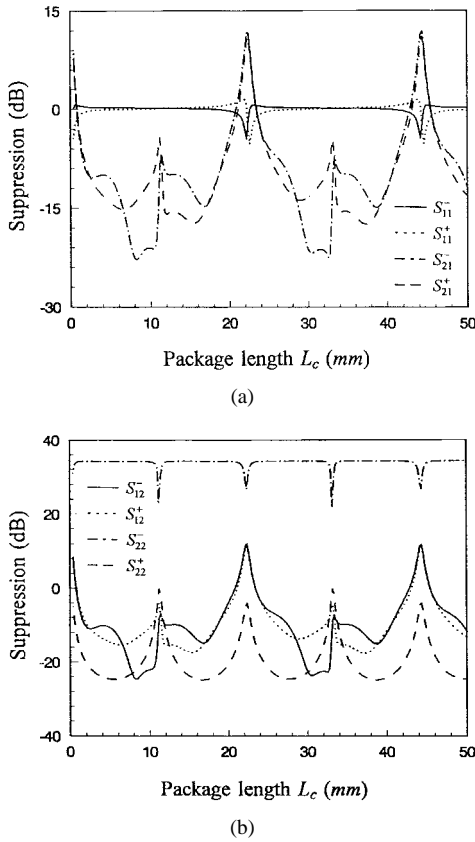


Fig. 5. The suppressions of the package (without absorbers) on the propagation modes scattered by the microstrip-line gap as a function of the package length (L_c) for (a) the dominant-mode incidence and (b) second-order-mode incidence. $L_s = L_c/2$, $f = 25$ GHz.

calculated reflection coefficient is $0.945\angle-174^\circ$, resonances of the excited second-order modes are expected when L_c gets near a multiple of the half-wavelength of the second-order mode ($\lambda_{2nd} = 22.00$ mm). Nevertheless, only when L_c is near the odd multiples of the half-wavelength can the resonances be observed in Fig. 4. To answer the question why the even multiple resonances disappear, one notices that the $+z$ propagating and $-z$ propagating second-order modes excited at the filament position are with the same amplitudes and same phases [12]. As L_c equals an even multiple of $\lambda_{2nd}/2$, a phase difference of -174° is introduced when the excited $-z(+z)$ propagating mode travels to the left (right) diaphragm and is then reflected back to the filament position, thus leading to the cancellation of the second-order mode.

Fig. 5 shows the suppression effects of the package on the propagation modes scattered by the microstrip-line gap as a function of the package length L_c . For the dominant-mode incidence [see Fig. 5(a)], it is seen that, except near the resonance lengths (22.2 mm, 44.2 mm, etc.), the package suppresses the excited outgoing second-order modes, while it has little influence on the dominant mode. Unlike those for the case of the electric current filament, here the resonances occur at L_c equal to even multiples of $\lambda_{2nd}/2$. The reason is as follows. By the equivalence principle [13], the outgoing second-order modes excited at the gap is caused by an equivalent x -directed magnetic-current filament of length w lying on the strip. The $\pm z$ propagating modes excited by this magnetic

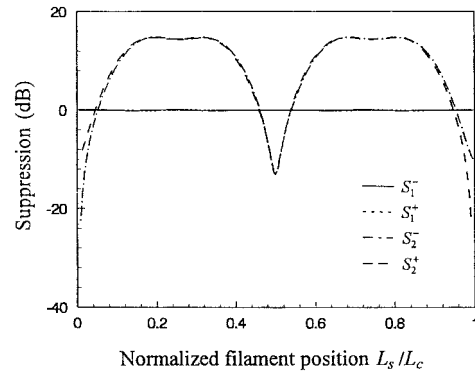


Fig. 6. The suppressions of the package (without absorbers) on the excited modes of the current filament as a function of the normalized filament position (L_s/L_c). $L_c = 22.4$ mm, $f = 25$ GHz.

current possess the same amplitudes, but out of phases [12]. When L_c equals an even multiple of $\lambda_{2nd}/2$, the bouncing wave due to the excited $-z$ propagating mode and that due to $+z$ propagating mode thus constructively interfere with each other, resulting in the resonances at these package lengths.

For the second-order-mode incidence [see Fig. 5(b)], since the first diaphragm reflects most of the incident power, P_{22}^- is greatly raised and P_{22}^+ reduced, causing a high S_{22}^- (larger than 30 dB) and a low S_{22}^+ (smaller than -20 dB). Consequently, the power coupled to the dominant mode is reduced. The situations change when the package length approaches one of the resonance lengths. Two types of second-order-mode resonances happen in this case. One is caused by the equivalent magnetic current at the gap position and is of resonance lengths equal to even multiples of $\lambda_{2nd}/2$ (22.2, 44.2 mm, etc.). This type of resonances produces high-power coupling (S_{12} up to 11 dB) to the dominant mode. The second type is due to the in-phase bouncing (between the diaphragms) of the second-order mode directly coming from the outside of the package and, thus, has resonance lengths at all multiples of $\lambda_{2nd}/2$. Since the sources of these bouncing waves are not from the gap, the power coupling to the dominant mode is, therefore, not so strong as that of the first-type resonance. (Note that S_{12}^- 's at odd multiples of $\lambda_{2nd}/2$ are about 17 dB lower than those at even multiples.) Finally, it is noticed that the curves of S_{21}^\pm [see Fig. 5(a)] are identical to the curves of S_{12}^\pm [see Fig. 5(b)], which is due to the reciprocity theorem (and the symmetry of the structure in the z -direction).

From the above discussions, when the package length gets near the resonance length (or the operating frequency gets near the resonant frequency of the package), it seems possible to avoid the resonances by placing the CE at some suitable positions. Figs. 6 and 7 present the results for, respectively, the current filament and the microstrip-line gap located at various positions ($0 < L_s < L_c$) in a package of length about a resonance length ($L_c \approx \lambda_{2nd}$). It is seen from Fig. 6 that the resonances can be avoided if the electric-current filament is placed near the center ($L_s = 0.5\lambda_{2nd}$) or the two ends ($L_s = 0, \lambda_{2nd}$) of the package (where the y component of the electric field of the standing second-order mode is zero). For the case of the microstrip-line gap (see Fig. 7), since the scattering is due to the x -directed equivalent magnetic current,

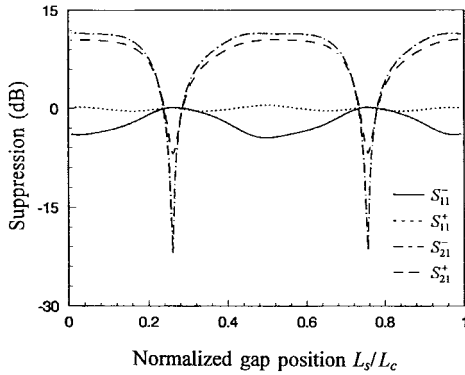


Fig. 7. The suppressions of the package (without absorbers) on the propagation modes scattered by the microstrip-line gap as a function of the normalized gap position (L_s/L_c) for the dominant-mode incidence. $L_c = 22.2$ mm, $f = 25$ GHz.

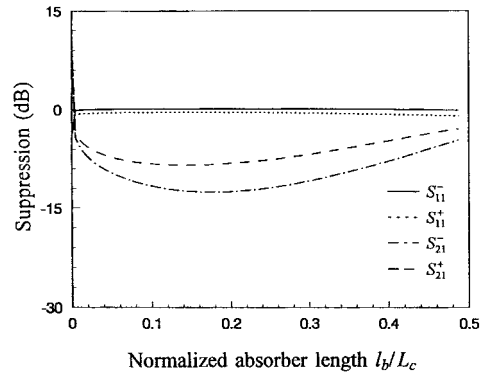


Fig. 9. The suppressions of the absorbing package on the propagation modes scattered by the microstrip-line gap as a function of the normalized absorber length (l_b/L_c) for the dominant-mode incidence. $L_c = 22.2$ mm, $L_s = L_c/2$, $L_a = 5.6$ mm, $h_b = 4h$, $w_b = 10w$, $f = 25$ GHz.

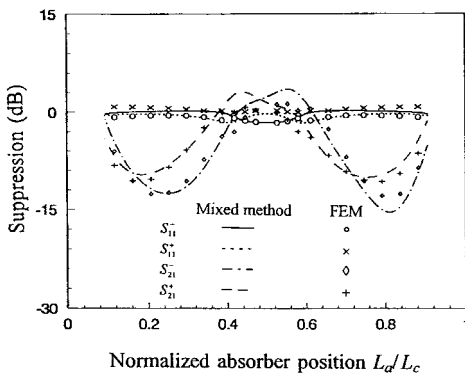


Fig. 8. The suppressions of the absorbing package on the propagation modes scattered by the microstrip-line gap as a function of the normalized absorber position (L_a/L_c) for the dominant-mode incidence. $L_c = 22.2$ mm, $L_s = L_c/2$, $l_b = 4$ mm, $h_b = 4h$, $w_b = 10w$, $f = 25$ GHz.

the positions to avoid the excitations of the resonances are located at $L_s/L_c \approx 0.25$ and 0.75 (where the x component of the magnetic field of the standing second-order mode vanishes). Similar results have been found for the second-order-mode incidence.

B. Partially Sealed Package with an Absorber

To avoid the strong coupling caused by the resonances of the spurious modes, an absorber can be affixed on the top of the package to damp the resonances. Fig. 8 illustrates the suppression effects of the absorbing package with length $L_c \approx \lambda_{2nd}$ when the dominant mode is incident on the microstrip-line gap. The absorber ($\epsilon_{r2} = 12 - j12$) has a length $l_b = 4$ mm, thickness $h_b = 4h$, and width $w_b = 10w (= 10h)$. The gap is located at the middle of the package ($L_s = L_c/2$), while the position (L_a) of the absorber is varied. It is noted that, from Fig. 5, the suppressions at $L_c \approx \lambda_{2nd}$ are bad before the absorber is introduced. The couplings between the dominant and second-order modes are about 11 dB higher than those without the diaphragms ($S_{21}^- = S_{12}^- = 11.5$ dB, $S_{21}^+ = S_{12}^+ = 10.5$ dB). However, these couplings are greatly reduced when the absorber is placed inside the package, as can be seen from Fig. 8. Since the absorber is a dielectric one ($\mu_r = 1$), the best absorbing effect occurs when the absorber is

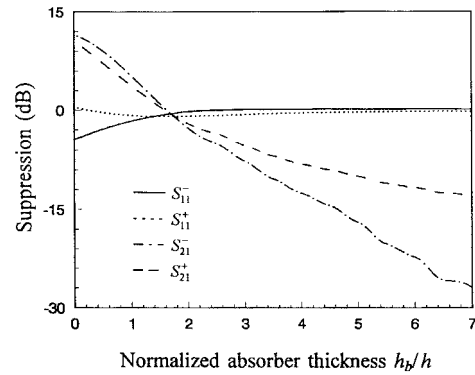


Fig. 10. The suppressions of the absorbing package on the propagation modes scattered by the microstrip-line gap as a function of the normalized absorber thickness (h_b/h) for the dominant-mode incidence. $L_c = 22.2$ mm, $L_s = L_c/2$, $L_a = 5.6$ mm, $l_b = 4$ mm, $w_b = 10w$, $f = 25$ GHz.

located at the positions where the electric fields of the standing second-order mode are maximum (i.e., $L_a/L_c \approx 0.25$ and 0.75). As another check of the present analysis using the mixed method, the results obtained from the full FEM analysis are also presented in Fig. 8. Good agreement is observed between the two approaches.

Fig. 9 depicts the suppression effects, as functions of the normalized absorber length (l_b/L_c), of an absorbing package with length $L_c \approx \lambda_{2nd}$ for the case of a centrally located microstrip-line gap illuminated by the dominant mode. The thickness and width of the absorber are $4h$ and $10h$, respectively, and the center position is fixed at $L_a = 5.6$ mm ($\approx 0.25\lambda_{2nd}$). It is seen that, unlike that of the dominant mode, the levels of the scattered second-order modes vary with the change of the absorber length. It is also interesting to observe that the levels do not decrease monotonously with the increase of the absorber length. The best suppression effect happens when the absorber is with length $l_b = 0.16L_c (= 3.56$ mm), where $S_{21}^- = -12.7$ dB and $S_{21}^+ = -8.6$ dB.

The influence of the absorber thickness on the suppressions is shown in Fig. 10, where the absorber with length $l_b = 4$ mm and width $w_b = 10h$ is put at the position of $L_a = 0.25L_c$ ($L_c \approx \lambda_{2nd}$). The damping of the packaging resonance by the absorber is not distinct until the thickness is raised up to $2h$. When the absorber thickness is less than this value, the

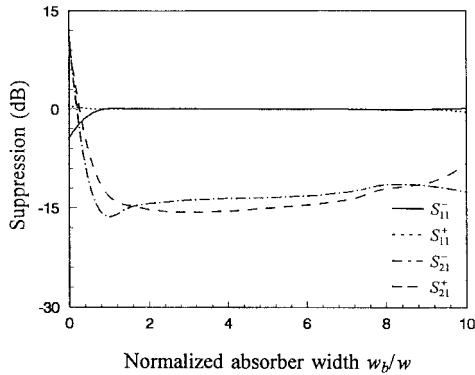


Fig. 11. The suppressions of the absorbing package on the propagation modes scattered by the microstrip-line gap as a function of the normalized absorber width (w_b/w) for the dominant-mode incidence. $L_c = 22.2$ mm, $L_s = L_c/2$, $L_a = 5.6$ mm, $h_b = 4h$, $l_b = 4$ mm, $f = 25$ GHz.

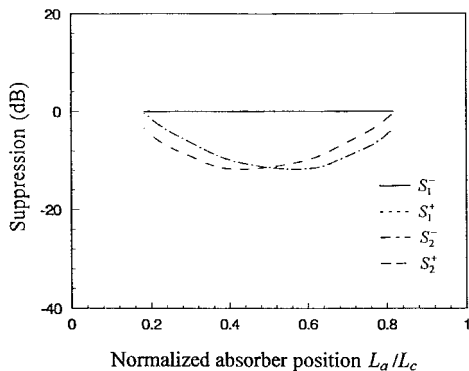


Fig. 12. The suppressions of the absorbing package on the excited modes of the current filament as a function of the normalized absorber position (L_a/L_c), $L_c = 11.4$ mm, $L_s = L_c/2$, $l_b = 4$ mm, $h_b = 4h$, $w_b = 10w$, $f = 25$ GHz.

scattering of the dominant mode is disturbed by the package, and the levels of the scattered second-order modes are higher than those without packaging ($S_{21}^{\pm} > 0$ dB for $h_b/h < 2$). However, as the absorber length becomes larger than $2h$, both S_{11}^- and S_{11}^+ remain at approximately 0 dB, (which means that the scattered dominant modes are approximately the same with or without the absorbing package), and the outgoing second-order modes are suppressed monotonously with the increase of the absorber thickness. The suppression when $h_b = 7h$ is -27 dB for S_{21}^- and is -13.3 dB for S_{21}^+ .

Fig. 11 displays the variations of the suppressions as functions of the normalized absorber width w_b/w ($w = h$), where the absorber with length 4 mm and thickness $4h$ is placed symmetrically in the x -direction and at $L_a = 0.25L_c$ ($L_c \approx \lambda_{2nd}$) in the z -direction. As can be seen, as long as the absorber width is larger than w , the absorber can damp the second-order-mode resonance effectively. The suppressions do not change much with the increase of the width in the range of $w_b > w$.

For the case of the electric-current filament, the suppression effects of the absorbing package have also been observed. Fig. 12 presents the results for the centrally located current filament in an absorbing package with the absorber placed at various positions. The package length is about a half-

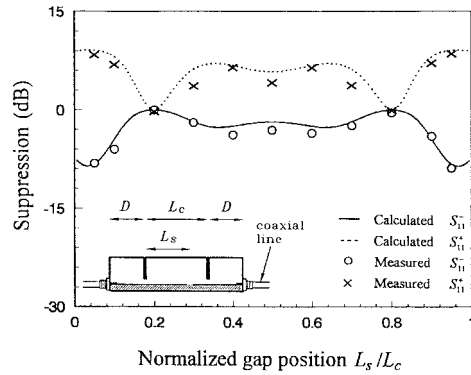


Fig. 13. The suppressions of the package (without absorbers) on the dominant mode scattered by the microstrip-line gap as a function of the normalized gap position (L_s/L_c) for the dominant-mode incidence. $\epsilon_{r1} = 2.33$, $h = 0.7874$ mm, $w = 2.34$ mm, $g = 0.3$ mm, $D = 30$ mm, $L_c = 39.9$ mm, $f = 10$ GHz. The shielded microstrip line can support two propagation modes.

wavelength of the second-order mode ($L_c \approx 0.5\lambda_{2nd}$). Similar to Fig. 8, it is found that when the absorber is put near the position where the electric field of the standing second-order mode is maximum ($L_a/L_c \approx 0.5$), the best suppression effects are obtained ($S_2^+ = S_2^- = -11.4$ dB). Also note that the excited dominant mode is not affected by the absorbing package. Finally, although not presented in this paper, the dependence of the suppression effects on the size of the absorber has also been analyzed, which is found to be similar to those for the case of the microstrip-line gap (see Figs. 9–11).

IV. EXPERIMENT

In addition to the numerical results presented above, the suppression effect of the package for the scatterings of the microstrip-line gap was measured to further verify the analysis. Here, due to the limitation of the experiment environment, the operating frequency was chosen as 10 GHz. Also, to avoid tackling the complicated terminations at $z = \pm\infty$ for the higher order propagation modes, the packaging waveguide (with a cross section of 22.86×10.16 mm²) was truncated in the z -direction by two metal walls, as shown in the inset of Fig. 13. The length of the truncated waveguide ($L_c + 2D$) was 104.9 mm, which had been examined not to be a resonant one at the operating frequency. Two SMA connectors were inserted in the metal walls so that the power of the dominant mode in the 50- Ω microstrip lines could be passed to the coaxial lines with a negligible loss.

The spacing L_c of the two identical diaphragms (with depth 8 mm and thickness 2.5 mm) was designed to 39.9 mm, which was about the calculated wavelength (38.30 mm) of the second-order mode of the shielded microstrip line. Fig. 13 shows the measured and calculated suppressions S_{11}^{\pm} as functions of the normalized position of the gap. (Here, for each gap position, the suppressions were defined as the ratios of the scattered powers with diaphragms to those without diaphragms.) In the calculation, all the scattered higher order modes were assumed to be totally reflected by the two lateral metal walls (with reflection coefficients equal to -1), and the dominant mode was assumed to be able to

penetrate the walls (through the SMA's) without any loss. The excellent agreement between the measurement and the calculation ensured the validity of the analysis.

V. CONCLUSIONS

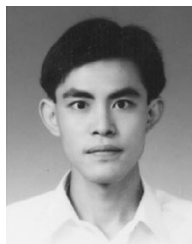
The suppression effects of a partially sealed package with or without an absorber affixed inside have been analyzed by an approach mixing the mode-matching method, method of lines, and FEM. The validity of the analysis has been checked numerically and experimentally. Two CE's, i.e., an electric-current filament and a microstrip-line gap, have been examined to verify the effectiveness of the package.

It has been shown that, when the distance between the diaphragms is not near a resonance length, the package has little influence on the propagation of the dominant mode and, in the meantime, it can effectively suppress the outgoing second-order modes excited by the current filament or scattered by the microstrip-line gap, no matter where the filament or the gap is located. The diaphragms of this package can also highly reflect the incoming second-order modes to prevent the interference on the functions of the circuit packaged inside. When the package length is near a multiple of $\lambda_{2nd}/2$, the resonance of the second-order mode is excited. Placing an absorber inside the package has been shown to be able to destroy the resonance and, thus, resume the performance of the package. The sizes and locations of the absorber can be suitably designed to get a better damping effect on the resonances.

REFERENCES

- [1] H.-H. Chen and S.-J. Chung, "Shielding effect of a diaphragm in a packaged microstrip circuit," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1082–1086, May 1995.
- [2] D. F. Williams, "Damping of the resonant modes of a rectangular metal package," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 253–256, Jan. 1989.
- [3] D. F. Williams and D. W. Paananen, "Suppression of resonant modes in microwave packages," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Long Beach, CA, June 1989, pp. 1263–1265.
- [4] J. J. Burke and R. W. Jackson, "Reduction of parasitic coupling in packaged MMIC's," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Dallas, TX, May 1990, pp. 255–258.
- [5] ———, "A simple circuit model for resonant mode coupling in packaged MMIC's," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Boston, MA, June 1991, pp. 1221–1224.

- [6] R. W. Jackson, "Removing package effect from microstrip moment method calculation," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Albuquerque, NM, 1992, pp. 1225–1228.
- [7] P. Mezzanotte, M. Mongiardo, L. Roselli, R. Sorrentino, and W. Heinrich, "Analysis of packaged microwave integrated circuits by FDTD," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1796–1801, Sept. 1994.
- [8] P. Meyer, "Solving microstrip discontinuities with a combined mode-matching and method-of-lines procedure," *Microwave Opt. Technol. Lett.*, vol. 8, pp. 4–8, Jan. 1995.
- [9] J. Jin, *The Finite Element Method in Electromagnetics*. New York: Wiley, 1993.
- [10] R. Pregla and W. Pascher, "The method of lines," in *Numerical Techniques for Microwave and Millimeter Wave Passive Structures*, T. Itoh, Ed. New York: Wiley, 1989, ch. 6.
- [11] S. Chu, T. Itoh, and Y.-C. Shih, "Comparative study of mode-matching formulations for microstrip discontinuity problems," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 1018–1023, Oct. 1985.
- [12] D. M. Pozar, *Microwave Engineering*. Reading, MA: Addison Wesley, 1990.
- [13] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*. New York: McGraw-Hill, 1993.



Hao-Hui Chen was born in Kaohsiung, Taiwan, R.O.C., on April 11, 1969. He received the B.S. degree in physics from the National Central University, Taiwan, R.O.C., in 1991, and the Ph.D. degree in communication engineering from the National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 1998.

His research interest include electromagnetic theory, antenna and waveguide analysis, packaging effects of microwave circuits, and numerical techniques in electromagnetics.



Shyh-Jong Chung (M'91) was born in Taipei, Taiwan, R.O.C. He received the B.S.E.E. and Ph.D. degrees from National Taiwan University, Taipei, Taiwan, R.O.C., in 1984 and 1988, respectively.

Since 1988, he has been with the Department of Communication Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C., where he is currently a Professor. From 1989 to 1991, he served in the Taiwan Army as a Second Lieutenant, where he was in charge of the maintenance of communication equipment. From September 1995 to August 1996, he was a Visiting Scholar in the Department of Electrical Engineering, Texas A&M University, College Station. His areas of interest include propagation and scattering of transmission lines, packaging effects of microwave circuits, numerical techniques in electromagnetics, and the designs and applications of active or passive planar antennas.