Bound-Mode Resonance Improving the Input Matching of a Dual-Mode Leaky Guiding Structure

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***Abstract*—A novel approach of incorporating the bound-mode resonance in a uniform micro-CPW (coplanar waveguide) line that shows excellent input matching is presented. The matrix-pencil signal analyses of the CPW-fed micro-CPW guide confirm that two modes, namely, the bound CPW mode and the leaky second higher order microstrip mode, dominate, whereas the microstrip mode contributes too little to be detected. Both theoretical analyses and experimental measurements of the CPW-fed micro-CPW guide show that two well-matched input return losses regions are directly related to the resonances of the CPW mode within the guide.**

***Index Terms*— Bound-mode resonance, CPW mode, even-symmetric fields, input return loss, matrix-pencil method, second higher order leaky mode.**

I. Introduction

Applications of dual modes in cavities [1], microstrips [2], and waveguides [3], [4] may realize very compact high-quality microwave filters and multiplexers. In this letter, a novel approach of incorporating the dual modes in a uniform micro-CPW (coplanar waveguide) leaky line that makes excellent input matching via bound-mode resonance is presented. As shown in the inset of Fig. 1, the micro-CPW line consists of a microstrip and a CPW (coplanar-waveguide) coalesced on both sides of the substrate of relative permittivity ε_r. The input feed line is made by the CPW for direct probing or the CPW–connector interface for coaxial connection to a network analyzer.

Fig. 1 shows the possible modes that exist in the micro-CPW guiding structure. The microstrip mode, denoted as MS, has its electromagnetic energies concentrated between the printed line on top and the CPW on bottom. Therefore, it is essentially a microstrip with two tuning septa [5]. The CPW mode has its electromagnetic fields mostly concentrated between two slots. The CPW mode, however, has its fields altered by the microstrip line on top, which can also be viewed as a finite-width conducting ground plane to the CPW line [6]. The micro-CPW line is fabricated on an ULTRALAM^{TM} 2000 (a trademark of Rogers Corporation) substrate of $\varepsilon_r = 2.55$ and h (thickness) $= 0.762$ mm, where the microstrip line has width (w) of 9 mm and the dimensions of the CPW are 0.508 mm (c), 0.508 mm (g), and 6 mm (s) for the center conductor, gap, and side plane, respectively.

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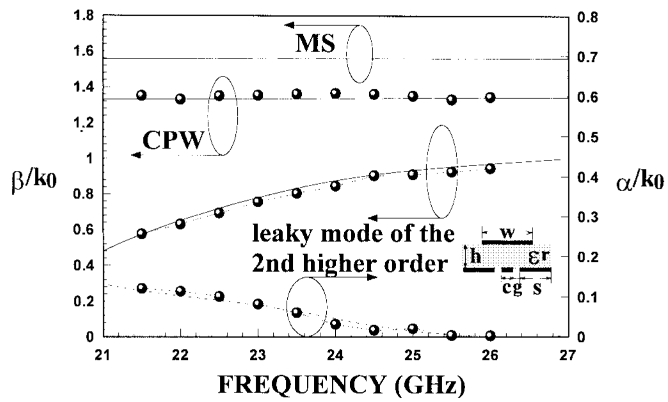

Fig. 1. The normalized phase and attenuation constants of the even-symmetric micro-CPW leaky line, showing the second higher order leaky mode and two well-known bound modes, the MS (microstrip) mode, and the CPW (coplanar waveguide) mode. The cross-section view of the micro-CPW structure is shown in the inset.

II. Principle of Operation for the Micro-CPW Leaky Line

Two bound modes, MS and CPW modes, appear in Fig. 1, where two solid lines obtained by the mode-matching method [7] show that the MS mode has higher normalized propagation constant than the CPW mode. The third mode in Fig. 1 is complex and is a leaky mode originated from the second higher order microstrip mode [8]–[10]. The first higher order leaky mode can be a leaky mode too, but it is discarded because of its odd-symmetric fields which cannot be excited in the micro-CPW guiding structure. All modes appear in Fig. 1 possess even-symmetric fields. The frequency span for the normalized attenuation constant (α/k_0) less than 0.1 is relatively broad, approximately 5 GHz between 22 and 27 GHz. The aim of this paper is to explain why and how the existence of the other mode, that is the bound mode in the particular case study, can drastically improve the input matching for exciting the leaky line through a CPW input interface. Once the CPW mode is launched by the external source, the discontinuities at the source end $(z = 0)$ would potentially excite the MS mode and the leaky mode in addition to the CPW mode. The presence of all these modes in the micro-CPW line pictures a multimode scenario: the leaky mode propagates along the guide, gets attenuated, and reflects at the open end ($z = 36$ mm) in contrast to the bound mode resonating between both ends of the line of length equal to 36 mm (about 2.65 free-space wavelengths at 22.1 GHz). Later rigorous analyses show that the CPW mode and the leaky mode prevail over the MS

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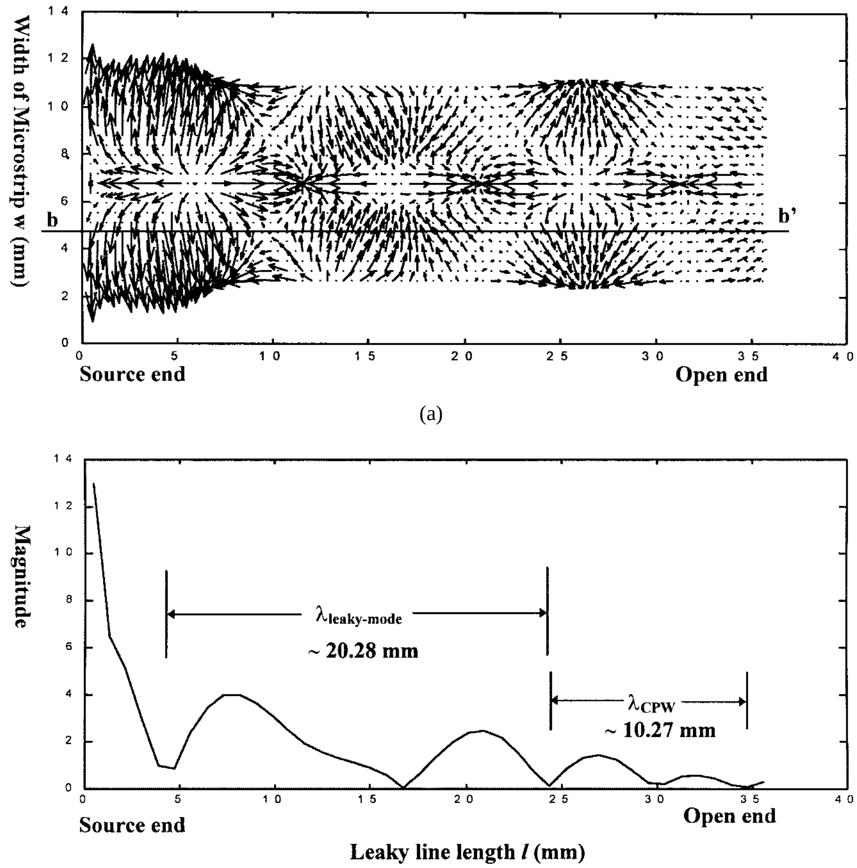

(a)

(b)

Fig. 2. The current distributions in the microstrip portion of the micro-CPW leaky line at 22.1 GHz with the normalized phase constant of the second higher leaky mode of 0.665 obtained by full-wave mode-matching method. (a) The vectored current distributions obtained by full-wave space-domain integral equation method. (b) The magnitude of current distributions along the b–b' cut of (a).

mode. Therefore, we are faced with a physical device where two modes exist and travel back and forth between source and open ends.

III. Signal Analyses of Modal Currents

The micro-CPW line is fabricated and tested. Meanwhile it is analyzed by the three-dimensional full-wave space-domain integral equation method [11] for modal current signal analyses and comparison studies against the measured results. The matrix-pencil signal analyses developed by Sarkar *et. al* [12]–[14] are invoked to study the modal currents traveling back and forth in the micro-CPW line. Fig. 2(a) shows the vectored current distributions, obtained by the rigorous full-wave simulations of the micro-CPW with CPW input, for the microstrip line. For the CPW portion, the vectored current distributions are not shown here due to limited space. However, the propagation of CPW mode is clearly seen, with opposite current flows between center conductor and side planes. Fig. 2(a) shows the current distributions resembling the second higher order leaky mode of a typical microstrip which changes signs once in the transverse direction. Knowing that the excitation points are located at the left end, bottom side of the micro-CPW at $z = 0$, we observe the decayed vectored current distributions of the leaky mode. As shown in Fig. 1, the matrix-pencil signal analyses of the excited currents in the micro-CPW structure indicate that both CPW mode and leaky mode dominate, whereas the amount of MS mode is too little to be detected. The results of the matrix-pencil analyses also yield both complex propagation constant for the leaky mode and the real propagation constant for the CPW mode. Fig. 1 indicates that the propagation constants obtained by the full-wave mode-matching method (in solid lines) and those by the matrix-pencil method (in circle symbols) are in excellent agreement. Furthermore, the currents at the center of the CPW display a standing wave pattern with its period matched to the wavelength of the CPW mode. Notice that the wavelength (λ_{CPW}) obtained by the full-wave integral equation method is 10.27 mm, which agrees with the value of 10.20 mm obtained by the full-wave mode-matching method with normalized phase constant β_{CPW}/k_0 of 1.331 at 22.1 GHz for the CPW mode. Fig. 2(b), plotting the magnitude of currents along the b–b' cut of Fig. 2(a), which is 2.25 mm offset from the center of microstrip, illustrates that both the leaky mode and CPW mode get excited. As the leaky mode travels along the microstrip, its magnitude decays as expected while it radiates energies into space. Since the attenuation constant of this leaky mode was purposely chosen to be large, Fig. 2(b) shows such effect that the leaky mode fades away quickly and leaves the CPW mode obviously present at the open end of the microstrip. It is also clear that the wavelength $(\lambda_{\mathrm{CPW}} = 10.27$ mm)

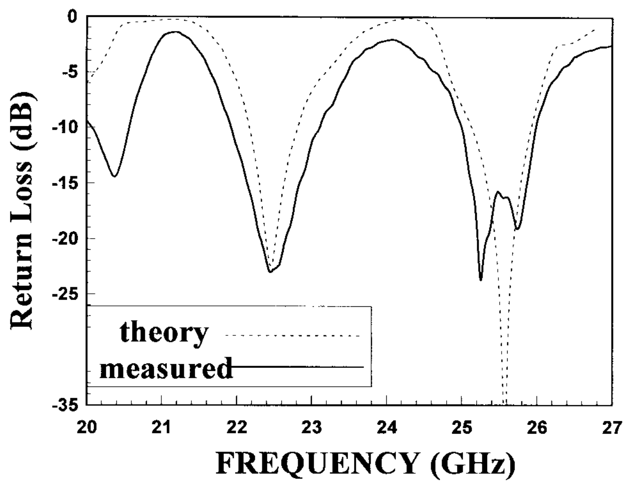

Fig. 3. The measured and theoretical input return losses of the micro-CPW leaky line.

extracted from the full-wave integral equation method matches to that ($\lambda_{\mathrm{CPW}} = 10.20$ mm) obtained by the full-wave mode-matching method for the CPW bound mode at the open end. However, the wavelength ($\lambda_{\mathrm{leaky-mode}}$) of 20.28 mm obtained by the full-wave integral equation method matches that of 20.41 mm derived from the full-wave mode-matching method with normalized phase constant $\beta_{\mathrm{leaky-mode}}/k_0$ of 0.665 at 22.1 GHz. Closely examining the currents on Fig. 2(a) and the CPW portion also reveals that the leaky mode's ground return currents are clearly shown in the side planes of the CPW.

IV. Input Matching Improved by CPW Resonance

Fig. 3 plots the measured input return losses against the full-wave simulation for the one-port CPW-fed micro-CPW guide. Both theory and measurement agree very well in the leaky region, showing two well-matched regions ($S_{11} < -20$ dB) centered approximately at 22.4 and 25.3 GHz, respectively. As discussed in Section III, the CPW modal energy is carried by the bottom CPW guide and the top microstrip line. Thus, the CPW mode propagates back and forth in micro-CPW guide and resonates at frequencies dictated by the relation $\beta_{\mathrm{CPW}} l = n\pi$, where β_{CPW} is the phase constant of the CPW mode and l is the length of the guide. Accordingly, in the leaky regions, the predicted CPW resonant frequencies are at 21.9 and 25.0 GHz, which are very close to the measured and theoretical results. Clearly the resonance of the bound CPW mode directly enhances the input matching of the CPW-fed micro-CPW guide. Near-field measurement [15] together with antenna gain-comparison method [16] shows antenna efficiency of approximately 90% at 22.1 GHz, located in one of the two matched regions. We infer that the CPW mode, through resonance, converts most of its energy into the leaky mode, resulting in excellent input matching.

V. Conclusion

Matrix-pencil signal analyses of the CPW-fed micro-CPW guide reveal that two modes propagate in the guide: the bound CPW mode and the leaky second higher order microstrip mode. The dual-mode guiding structure benefits from the fact that the input CPW mode resonates and converts its energy into the leaky wave, resulting in very good input matching and high efficient leaky-wave antenna when using the micro-CPW guide as an antenna.

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