A 3-D Mode Matching Technique for the Efficient Analysis of Coplanar MMIC Discontinuities with Finite Metallization Thickness

Ferdinando Alessandri, Gianluca Baini, Mauro Mongiardo, and Roberto Sorrentino

Abstract—**A technique is proposed for the efficient analysis of CPW discontinuities including finite metallization thickness. The transverse resonance technique (TRT) is modified by introducing an impressed source that allows a cavity of fixed, instead of variable, dimensions to be analyzed (impressed source technique, IST). At the same time, as with TRT, the field analysis of only homogeneously filled waveguides is required so avoiding the computation of frequency dependent as well as complex modes as with the conventional mode matching technique. On this basis, an extremely efficient code for the analysis of CPW discontinuities, applicable also to interacting discontinuities, is obtained. The same code, which incorporates the modal spectrum of L-shaped waveguide, can be used to compute a large class of CPW discontinuities including steps, gaps, open ends, etc. Computed results are shown to be in remarkable agreement with the experiments and confirm that the finite metallization thickness may significantly affect the electrical characteristics of CPW circuits.**

I. Introduction

SINCE ITS INTRODUCTION [1], coplanar waveguide (CPW) has received increasing attention. Compared to microstrip, it has a number of attracting characteristics. It allows easy mounting of active and passive devices both in shunt and series connection, eliminating the need for via holes and reducing the associated parasitic inductance. Fragile semiconductor substrates need not be made excessively thin, and reduced radiation loss is present. Such advantages appear to overcompensate the necessity for air bridges to suppress the spurious slot mode [18].

Early theoretical investigations were concerned principally with the evaluation of the propagation characteristics of the uniform CPW [2]–[6]. (See also [7] for an extensive review of the literature on this topic). A high accuracy can be attained with relatively modest effort taking into account both the finite metallization thickness as well as the correct edge singularity satisfied by the field components [7].

Because of its attracting features, the CPW has been employed in practical RF circuit design [8]–[13], while the most common discontinuities were characterized only experimentally. For example, the open circuit, the series gap in the central conductor, the step change in the width of the center conductor and the right angle bend have been investigated experimentally in [11]. CPW to slotline transitions have been characterized experimentally in [14], where the simultaneous use of CPW and slotlines for uniplanar MMIC's has been proposed.

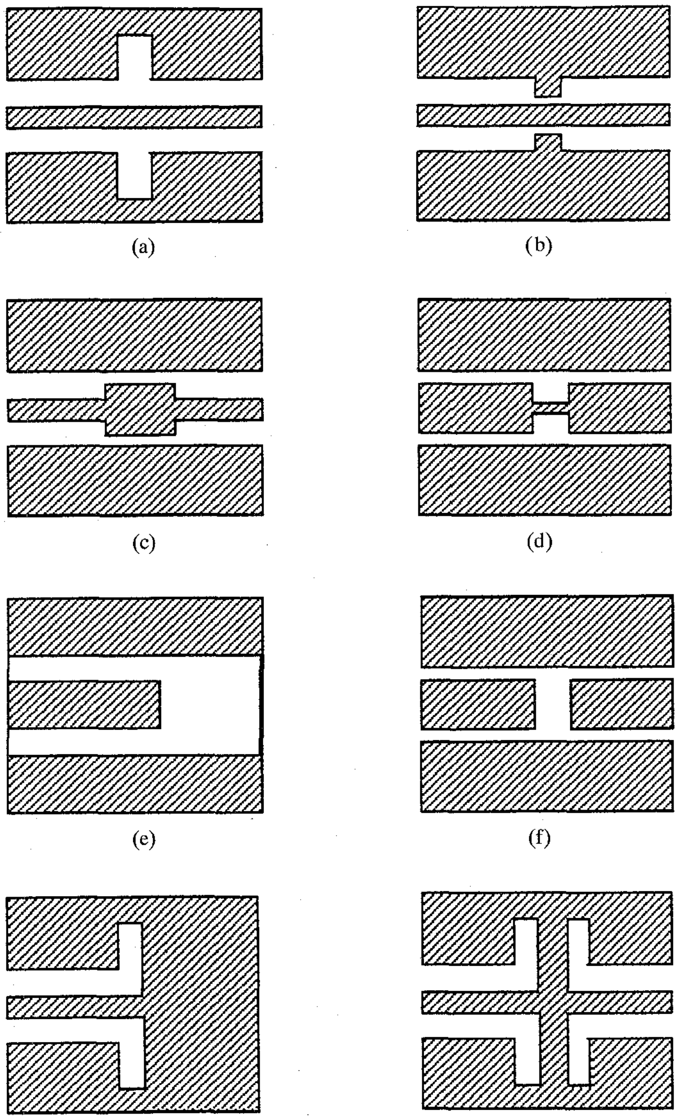
The theoretical modeling of CPW discontinuities has recently become an important research topic [15]–[28] to develop accurate CAD tools. Apart from any consideration of discontinuities involving currents perpendicular to the substrate, such as air bridges, some the most common discontinuities studied in the literature are shown in Fig. 1. The effect of metallization thickness has been taken into consideration only very recently [29] using mode matching technique. It is pointed out that neglecting the effect of finite metallization thickness in MMIC design may result in substantial inaccuracy.

The mode-matching technique requires the knowledge of the spectra (discrete or continuous [28]) of both sides of the discontinuity. The computation of the modes of the CPW however is by itself a considerable task. Because of the presence of different dielectric layers in the cross section, quite heavy computational effort is involved. Dispersion of the modal fields in fact requires the entire spectrum to be computed again at each spot frequency, and roots must be searched for in the complex plane, since the spectrum generally contains complex modes.

To alleviate the computational effort, the Transverse Resonance Technique (TRT) was proposed [30], [31]. With this technique, one looks for the resonances of a cavity containing the discontinuity under investigation. At each frequency, the dimensions of the cavity are changed until resonances are found. From the knowledge of the resonant dimensions the relevant parameters are calculated. The basic advantage of TRT is that the analysis can be performed in terms of modes travelling in the direction perpendicular to the substrate, so that only homogeneous waveguides are to be considered and no complex modes are to be searched for.

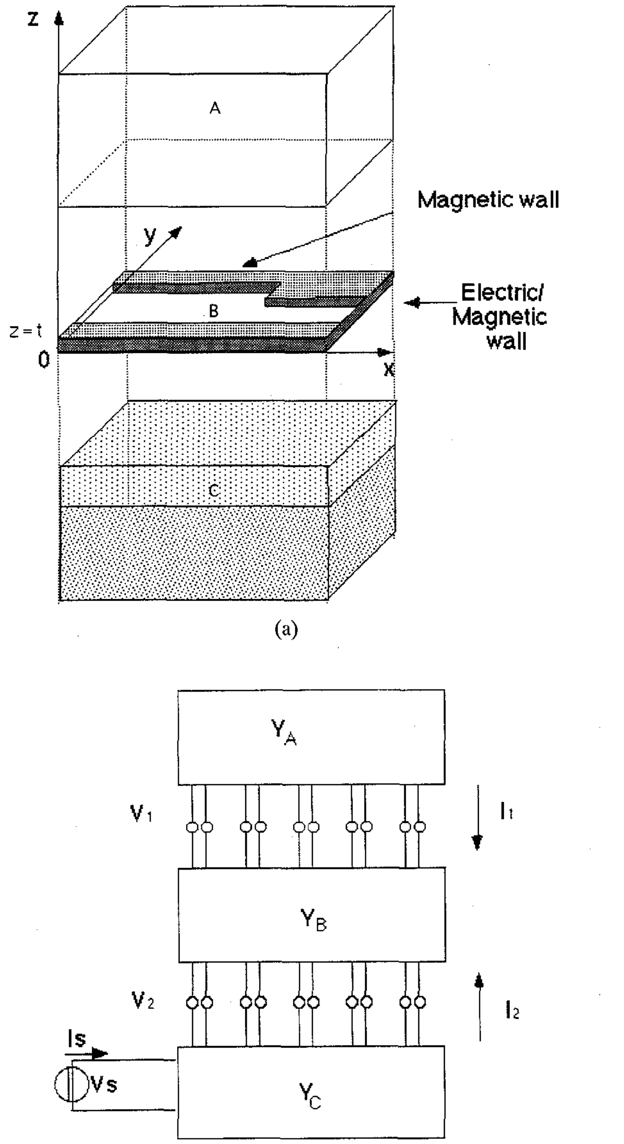
In spite of these advantages, the TRT still involves a considerable computation time since it requires repeated analyses at each frequency. These can be avoided by the Impressed Source Technique (IST) recently developed for the analysis of microstrip via holes [32]. The IST can be viewed as a modification of the TRT to solve a deterministic instead of an eigenvalue problem. Accordingly, just two analyses at each frequency are required to compute the parameters of a two port discontinuity, without having to change the dimensions of

Manuscript received September 20, 1992: revised February 1, 1993.
F. Alessandri, M. Mongiardo, and R. Sorrentino are with the Istituto di Electtronica, Università di Perugia, I-06100 Perugia, Italy.
G. Baini is with the Alenia Spazio S.p.a., Via Saccomuro 24, 00131 Rome, Italy.
IEEE Log Number 9211847.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 1. Some common CPW discontinuities.



(a) (b)

Fig. 2. Reduced structure of a double step in the central strip of a CPW. Symmetry planes have been replaced by electric or magnetic walls. (b) Generalized equivalent network of (a) excited by an impressed source on the boundary of region C.

the cavity. In addition, modes need to be calculated just once for the entire frequency band with considerable advantages in terms of computation time.

An additional advantage of this technique is that it closely models the actual operating conditions of packaged circuits, accounting for possible interaction with the package. The IST can also be applied in conjunction with other methods other than mode-matching, such as finite element or finite difference.

II. Method of Analysis

A number of typical CPW discontinuities are sketched in Fig. 1. When symmetry is taken into account, all can be reduced to an L-shaped geometry. As an example, the double step of Fig. 1(c) can be reduced to one fourth, as depicted in Fig. 2(a). For the EM analysis, we will therefore limit our attention to the L-shaped circuit of Fig. 2(a), since the analysis can immediately be extended to all other geometries.

In the direction perpendicular to the metallization (z-direction of Fig. 2(a) the structure is seen as the cascade of three waveguide sections, two of rectangular cross section (A and C, top and bottom), the central one (B) with an L-shaped cross-section. The modes of the L waveguide can be obtained by a standard procedure [30]. They are frequency independent, since the waveguide is homogeneous.

The application of the mode matching technique to the cascade of the three waveguide sections reduces the problem to the analysis of the equivalent generalized circuit of Fig. 2(b) where each multiport network represents a waveguide section, each port being associated to a mode propagating in the central waveguide. The relevant equations characterizing the equivalent circuit of Fig. 2(b) are

$$[I_1] = -[Y^A][V_1] \tag{1}$$

$$[I_2] = -[Y^C][V_2] \tag{2}$$

and

$$\begin{bmatrix}[I_1]\\ [I_2]\end{bmatrix} = \begin{bmatrix}[Y_{11}^B] & [Y_{12}^B]\\ [Y_{21}^B] & [Y_{22}^B]\end{bmatrix}\begin{bmatrix}[V_1]\\ [V_2]\end{bmatrix}, \tag{3}$$

where $[I_1]$ $[I_2]$, $[V_1]$, $[V_2]$ are current and voltage vectors associated with modes of region B, $[Y^A]$, $[Y^C]$ are the generalized admittance matrices of regions A and C seen from the openings at $z = t$, 0 respectively; $[Y_{ij}^B]$ are diagonal admittance matrices associated with region B. As shown in [33], [34], the admittance matrices are calculated analytically without any matrix inversion. Various expressions of the dyadic Green's function can be found in [35] and their numerical behavior is described in [36].

The homogeneous system of linear equations (1)–(3) has non trivial solutions when the coefficient matrix is singular. In physical terms, this corresponds to the cavity being resonating. The resonance condition depends on both the frequency and cavity dimensions. To extract the parameters of the discontinuity the transverse resonance technique can now be applied [31]. At each frequency point repeated field analyses are performed in the numerical search for the resonant dimensions of the enclosing cavity. In spite of the advantage of working with homogeneous regions, thus with frequency independent modes, each time the cavity size is varied modal spectra must be computed again.

To reduce the numerical expenditure, the impressed source technique (IST) has been developed in [32]. Rather than an eigenvalue problem, a deterministic field problem is formulated by introducing a magnetic current source. This is impressed on some aperture produced on the cavity wall. In terms of generalized network representation, the aperture corresponds to a set of additional ports, where voltage generators, each for one waveguide mode, represent the impressed source. This is shown schematically in Fig. 2(b), where the voltage generator (for simplicity only one generator is considered) corresponds to an impressed magnetic current on the side wall of the C waveguide of Fig. 2(a).

In this manner, the known voltage V_S and an additional unknown current I_S are introduced in vectors V_2, I_2 in equation (2). An inhomogeneous system of equations must now be solved. The great advantage is that only one analysis per frequency point is required. Moreover, for any given structure, the modal spectra of each waveguide length must be computed only once. A further advantage is that the enclosing cavity (in contrast with the TRT it has now fixed dimensions) can simulate the actual enclosure, so accounting for package interaction.

The source should be chosen in such a way as to excite the dominant CPW mode impinging on to the discontinuity. To prevent higher order interaction between the source and the discontinuity, the former must be placed far enough to allow higher order modes to die out. Observe that the closer the source distribution to the dominant mode, the closer the source can be put to the discontinuity.

To compute the scattering parameters of the discontinuity, it is sufficient to determine the incident and reflected wave amplitudes of the fundamental mode. In a region far enough from both the impressed source and the discontinuity, higher order modes have negligible amplitudes so that the electric field E_y along x has the form

$$V(x) = V^+ e^{-j\beta x} + V^- e^{j\beta x}. \tag{4}$$

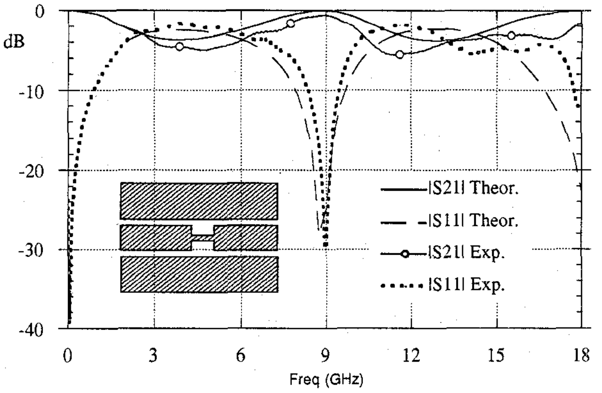


Fig. 3. Theoretical and experimental scattering parameters of the reduction-type double step discontinuity in CPW. Feeding line: width 3.22 mm, gap 0.1 mm. Central line width: 1.0 mm. Distance between the steps 15 mm. Substrate: $\varepsilon_r = 2.2$, thickness 0.254 mm.

The phase constant β of the CPW being computed in advance, the values of V^+, V^- are evaluated by a least square approach using sampled values of $V(x)$. The scattering parameters are then computed by a straightforward analytical procedure.

Although not specifically considered in this paper, the case of an interacting discontinuity can also be considered by computing its generalized scattering matrix. The necessary information on higher order modes can be extracted from the electric field distribution by precomputing the relevant propagation constants and using an obvious extension of (4).

III. RESULTS

A computer code has been developed according to the approach described in the previous section and several CPW discontinuities have been investigated. Because of the symmetry considerations pointed out in Section II, the same computer code can handle all types of discontinuities.

A comparison with experimental data is shown in Fig. 3 for a double step discontinuity in the inner conductor (Fig. 1(d)). A 70-ohm line length of approximately $\lambda/2$ at 9 GHz is inserted between two 50 ohm lines. The CPW structure was manufactured and measured at the University of Ulm [37]. The agreement is remarkable up to 12 GHz and can be considered very satisfactory in the whole frequency band. The discrepancies observed over 12 GHz can be abscribed to imperfect coax-to-CPW transitions and losses. Another source of discrepancy can be due to the measurements being performed on an open structure, while a WR28 enclosure was assumed in the theoretical simulations.

The influence of the metallization thickness on the behavior of the double step of reduction type of enlargement types in the central strip is demonstrated in Fig. 4 and Fig. 5, respectively. The computed return losses $|s_{11}|$ are plotted versus the frequency for three metallization thickness. The thicker the metallization the higher the frequency of the reflection zero because of the higher reactance associated with

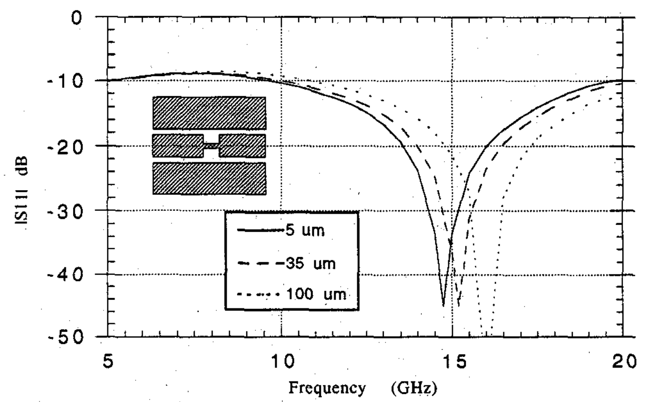


Fig. 4. Computed return loss of a reduction-type double step discontinuity in CPW for three metallization thicknesses. Feeding line: width 0.5 mm, gap 0.2 mm. Central line width: 0.2 mm. Distance between the steps 4.36 mm. Substrate: $\varepsilon_r = 9.9$, thickness 0.635 mm. Housing: WR28.

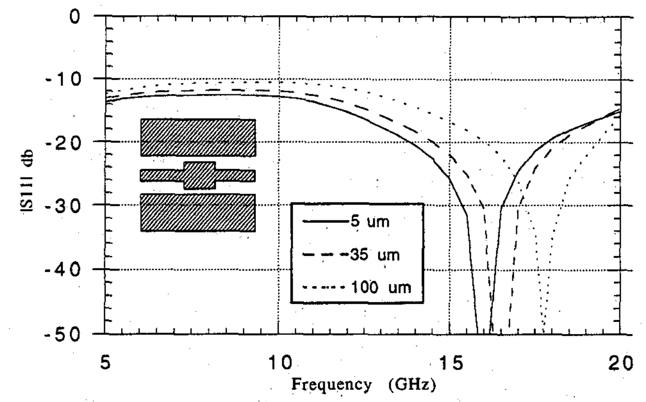


Fig. 5. Computed return loss of an enlargement type double step discontinuity in CPW for three metallization thicknesses. Feeding line: width 0.5 mm, gap 0.2 mm. Central line width: 0.7 mm. Distance between the steps 4.36 mm. Substrate: $\varepsilon_r = 9.9$, thickness 0.635 mm. Housing: WR28.

the discontinuity. These results confirm that even at relatively low frequencies, the metallization thickness can have a notable influence in effecting the performance of CPW circuits [29]. Such effects become extremely important in high density monolithic circuits.

All the analyses have been performed on a IBM 320 RISC 6000 and the computation of the scattering parameter at each frequency point takes approximately 2 seconds. The same code has also been used on a 486/33 MHz IBM compatible PC. In this case, the computation of the scattering parameters takes approximatively 8 seconds per frequency point.

IV. Conclusion

A procedure has been developed for the efficient analysis of CPW discontinuities including the finite metallization thickness. The transverse resonance technique (TRT) has been modified by introducing an impressed source that allows a cavity of fixed dimensions to be analyzed. At the same time, the advantage of TRT of performing the field analysis of only homogeneously filled waveguides is retained. This avoids the computation of frequency dependent as well as complex modes as with the conventional mode matching technique. On the contrary, the modal spectra need to be computed just once. On this bases, an extremely efficient code for the analysis of a vast class CPW discontinuity that includes double step discontinuities, gaps, open ends, stubs, etc., has been set up. Excellent agreement with experiments has been demonstrated. Numerical results confirm that, as already observed in [29], the finite metallization thickness may play a significant role especially at higher frequencies.

Acknowledgment

Prof. W. Menzel is gratefully acknowledged for providing the experimental data on the CPW structures.

References

[1] C. P. Wen, "Coplanar waveguide: A surface strip transmission line suitable for nonreciprocal gyromagnetic device applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 1087–1090. Dec. 1969.

[2] M. E. Davis, "Finite boundary corrections to the coplanar waveguide analysis," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 594–596, 1973.

[3] J. B. Knorr, and K. D. Kuchler, "Analysis of coupled slots and coplanar stirps on dielectric substrate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 541–548, 1975.

[4] R. Sorrentino, and G. Leuzzi, "Full-wave analysis of integrated transmission lines on layered lossy media," *Electron. Lett.*, vol. 18, no. 14, pp. 607–609, July 1982.

[5] R. Sorrentino, G. Leuzzi and A. Silbermann, "Characteristics of metal-insulator-semiconductor coplanar waveguides for monolithic microwave circuits" *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 410–415, Apr. 1984.

[6] G. Ghione and C. U. Naldi, "Coplanar waveguides for MMIC applications: Effect of upper shielding, conductor backing, finite-extent ground planes, and line-to-line coupling," *IEEE Trans. Microwave Theory Tech.*, vol. 35, pp. 260–267, Mar. 1987.

[7] R. Sorrentino, M. Mongiardo, and F. Alessandri, "Numerical Analysis of printed transmission lines on semiconductor substrates," *J. Electromagnetic Waves Applicat.*, vol. 5, no. 4/5, pp. 353–370, 1991.

[8] M. Houdart, "Coplanar lines: Application to broadband microwave integrated circuits," in *Proc. 6th European Microwave Conf., Rome*, Sept. 1976, pp. 49–53.

[9] P. A. Holder, "X-band microwave integrated circuits using slot-lines and coplanar waveguide," *Radio Electron. Eng.*, vol. 48, pp. 38–42, Jan./Feb. 1978.

[10] D. F. Williams, and S. E. Schwarz, "Design and performance of coplanar waveguide bandpass filter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 558–566, July 1983.

[11] R. N. Simons, and G. E. Ponchak, "Modeling of some coplanar waveguide discontinuities," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1796–1803, Dec. 1988.

[12] D. Leistner, W. Schmid, and G. Eggers, "Application of coplanar waveguide microwave integrated circuits," in *Proc. 20th European Microwave Conf.*, Sept. 1990, pp. 1021–1026.

[13] M. Raziat, E. Par, G. Zdasiuk, S. Bandy and M. Glenn, "Monolithic millimeter wave CPW circuits," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Long Beach, CA, 1989, pp. 525–528.

[14] T. Hirota, Y. Tarusawa, and H. Ogawa, "Uniplanar MMIC Hybrids—A propose of a new MMIC Structure," *IEEE Trans. on Microwave Theory Tech.*, vol. 35, pp. 576–581, June 1987.

[15] R. H. Jansen, and N. H. Koster, "A unified CAD basis for the characterization of strip, slot and coplanar MIC components," *Proc. 11th European Microwave Conf.*, Sept. 1981, pp. 682–687.

[16] R. W. Jackson, "Considerations in the use of coplanar waveguide for millimeter wave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1450–1456, Dec. 1986.

[17] C. W. Kuo, and T. Itoh, "Characterization of the coplanar waveguide step discontinuity using the transverse resonance method," in *Proc. 19th European Microwave Conf.*, London, Sept. 1989, pp. 662–665.

[18] R. W. Jackson, "Mode conversion at discontinuities in finite-width conductor-backed coplanar waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1582–1589, Oct. 1989.

[19] M. Riaziat, "Propagation modes and dispersions characteristics of five classes of coplanar waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 245–251, Mar. 1990.

[20] N. I. Dib, P. B. Katehi, G. E. Ponchak, and R. N. Simons, "Coplanar waveguide discontinuities for P-I-N diode switches and filter applications," in *IEEE MTT-S Int. Microwave Symp. Dig,* Dallas, TX, 1990, pp. 399–402.

[21] N. I. Dib and P. B. Katehi, "Modeling of shielded CPW discontinuities using the space domain integral equation method (SDIE)," *Electromagnetic Waves Applicat.,* Apr. 1991.

[22] M. Drissi, V. Fouad Hanna, and J. Citerne, "Analysis of coplanar waveguide radiating end effects using the integral equation technique," *IEEE Trans. Microwave Theory Tech.,* vol. 39, pp. 112–116, Jan. 1991.

[23] N. I. Dib, P. B. Katehi, G. E. Ponchak, and R. N. Simons, "Theoretical and experimental characterization of coplanar waveguide discontinuities for filter applications," *IEEE Trans. Microwave Theory Tech.,* vol. 39, May 1991.

[24] R. Bromme and R. Jansen, "Systematic investigation of CPW MIC/MMIC structures using strip/slot 3D Electromagnetic simulator," in *IEEE MTT-S Int. Microwave Symp. Dig.,* Boston, MA, 1991, pp. 1081–1084.

[25] N.I. Dib, and P.B. Katehi, "The effect of mitering on CPW discontinuities," in *Proc. 21st European Microwave Conf.,* Sept. 1991, pp. 223–228.

[26] U. Mueller, M. Rittweger, and A. Beyer, "Coplanar short considered by the TLM method with symmetrical condensed nodes," in *Proc. 21st European Microwave Conf.,* Sept. 1991, pp. 999–1003.

[27] J. McLean, A. Wieck, K. Ploog, and T. Itoh, "Full-wave analysis of open end discontinuities in coplanar stripline and finite ground plane coplanar waveguide in open environments using a deterministic spectral domain approach," *Proc. 21st European Microwave Conf.,* Sept. 1991, pp. 1004–1007.

[28] T. Rozzi, G. Gerini, P. Sewell, F. Moglie, and M. Ridolfi, "The complete spectrum of coplanar waveguide and its application to scattering problems," in *Proc. 22st European Microwave Conf.,* Aug. 1992, pp. 267–272.

[29] W. W. Kuo, and T. Itoh, "Characterization of shielded coplanar type transmission line junction discontinuities incorporating the finite metallization thickness effect," *IEEE Trans. Microwave Theory Tech.,* vol. 40, pp. 72–80, 1992.

[30] R. Sorrentino and T. Itoh, "Transverse resonance analysis of finline step discontinuities," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-32, pp. 1632–1638, 1984.

[31] R. Sorrentino, "Transverse resonance technique," in T. Itoh, Ed., *Numerical Techniques for Microwave and Millimeter-Wave Passive Structures.* New York: J. Wiley, 1989, ch. 11, pp. 637–696.

[32] R. Sorrentino, F. Alessandri, M. Mongiardo, G. Avitabile, and L. Roselli, "Full-wave modeling of via-hold grounds in microstrip by three-dimensional mode-matching technique," *IEEE Trans. Microwave Theory Tech.,* vol. 40, no. 12, pp. 1992.

[33] F. Alessandri, G. Bartolucci, and R. Sorrentino, "Admittance-matrix formulation of waveguide discontinuity problems. Application to the design of branch-guide couplers," *IEEE Trans. Microwave Theory Tech.,* vol. 36, pp. 394–403, Feb. 1988.

[34] F. Alessandri, M. Mongiardo, and R. Sorrentino, "Transverse segmentation: A novel technique for the efficient CAD of $2N$-port branch-guide couplers," *IEEE Trans. Microwave Guided Wave Lett.,* vol. 1, no. 8, pp. 204–207, Aug. 1991.

[35] C. T. Tai and P. Rozenfeld, "Different representations of Dyadic Green's functions for a rectangular cavity," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-24, no. 9, pp. 597–601, Sept. 1976.

[36] F. Alessandri, M. Mongiardo, and R. Sorrentino, "A technique for the full-wave automatic synthesis of waveguide components: Application to fixed phase shifters," *IEEE Trans. Microwave Theory Tech.,* vol. 40, no. 7, pp. 1484–1495, 1992.

[37] W. Menzel, private communication.

Ferdinando Alessandri, photograph and biography not available at the time of publication.

Gianluca Baini, photograph and biography not available at the time of publication.

Mauro Mongiardo, photograph and biography not available at the time of publication.

Roberto Sorrentino, photograph and biography not available at the time of publication.