Application of a Simple and Efficient Source Excitation Technique to the FDTD Analysis of Waveguide and Microstrip Circuits

An Ping Zhao and Antti V. Räisänen, *Fellow, IEEE*

Abstract— **A simple, efficient, and unified source excitation scheme for the finite-difference time-domain (FDTD) analysis of both waveguides and microstrip circuits is developed and validated. In this scheme, by moving the source plane several cells inside the terminal plane and adding the excitation wave as an extra term in the FDTD equation, the interaction between the excitation and reflected waves are totally separated in time domain. Hence, for both waveguide and microstrip discontinuities, absorbing boundary conditions can be applied on the terminal plane directly. In particular, for microstrip circuits, our scheme does not induce any source distortions when a simplified field distribution is used as the excitation. Consequently, the terminal plane can be moved very close to the discontinuity and thus significant computational savings are achieved. In addition, for microstrip systems, the validity and efficiency of the Mei's simplified field distribution are evaluated and confirmed for the first time.**

I. Introduction

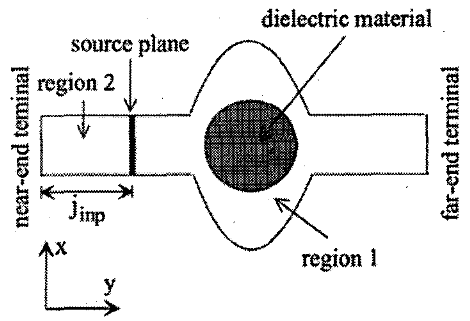
SINCE THE finite-difference time-domain (FDTD) method was introduced by Yee [1], it has been widely used in the analysis of waveguides [2]–[8] and microstrip circuits [9]–[14]. In the application of the FDTD method to waveguide and microstrip discontinuities, one of the most difficult problems is how to separate the interaction between the source excitation and the reflection in time domain. Without an ideal source excitation scheme, absorbing boundary conditions (ABC's) cannot be directly applied on the near-end terminal (or source) plane because strong reflections caused by the discontinuity normally reach this terminal plane before the source excitation is totally launched. In particular, the above separation requirement is always needed if the monochromatic FDTD methods are used since in this case the time stepping must be continued until a steady-state is reached. On the other hand, although the separation requirement is not strict when the discontinuous waveguide or microstrip structure is excited by a type of Gaussian pulses, a sufficiently long uniform feeding port section (which requires significant computation) has to be left between the source plane and the discontinuity.

In the past, to overcome the above difficulty, most efforts for separating the excitation and reflected waves in time domain were paid to waveguides, and several approaches have been developed [2]–[8]. The implementation of the approaches in [2]–[5] is easier than of those in [6]–[8], because in [6]–[8] a long uniform waveguide must be presimulated before the ABC's can be applied. However, there is still one drawback in [2]–[5]: two field components (e.g., E_y and H_x) on the source plane have to be pregiven, and they must be corrected interactively. Certainly, the requirement of the two pregiven field components limits the application of these approaches to arbitrarily-shaped structures (e.g., microstrip), even though it can be satisfied for rectangular waveguides. Therefore, a modification for making the approaches [2]–[5] applicable to general discontinuous structures is needed.

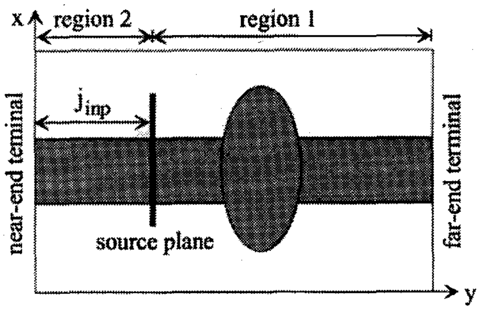
Although attentions for separating the interaction were paid to discontinuous waveguides, no much intentions have been made to microstrip discontinuities. For microstrip discontinuities [9]–[13], the commonly used source excitation scheme is based on the idea presented in [9] and [10]. In [9] and [10], the source plane and the near-end terminal plane were located at the same position, the simplified field distribution on the source plane was used and the ABC was applied on the source plane after the excitation pulse had been fully launched. Furthermore, before the ABC is allowed to 'switch on' on the source plane, dc source distortions on this plane and nearby are induced by either the electric [9], [10] or magnetic [11] wall boundary treatment. It is obvious that this dc source distortion not only causes troubles in the boundary treatment, but also influences the traveling wave. This is why with these source excitation schemes the terminal/source plane cannot be moved very close to the discontinuity. Alternatively, a lumped device model [14], which is able for separating the interaction in time domain, was developed. In this approach [14], however, unrealistic media with a constant conductivity (σ) have to be introduced in the excitation region, and hence it cannot be applied to structures containing lossy materials. To overcome the above difficulties, therefore, it is necessary to develop a better source excitation scheme, for general microstrop and waveguide discontinuities.

In this paper, based on the idea presented in [2], we develop a simple, efficient and unified source excitation scheme for both general waveguide and microstrip discontinuities. Unlike the source excitation schemes used in [2]–[5], however, in our scheme *only* one field component is needed to be pregiven and this field component is modified by itself. Due to the above specific nature of our scheme, it can be more easily

Manuscript received June 29, 1995; revised May 24, 1996.
The authors are with Radio Laboratory, Faculty of Electrical Engineering, Helsinki University of Technology, FIN-02150, Espoo, Finland.
Publisher Item Identifier S 0018-9480(96)06382-X.



(a)



(b)

Fig. 1. Division of discontinuous systems. (a) Waveguide. (b) Microstrip.

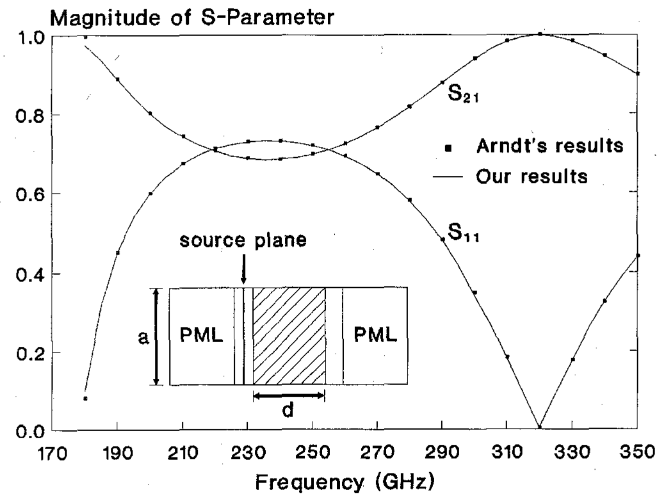


Fig. 2. S-parameter of the discontinuous WR-3 waveguide, where $d = 0.504$ mm and $\varepsilon_r = 3.7$, obtained with the following parameters: $\Delta x = \Delta z = a/24$, $\Delta y = d/14$; $j_{\rm inp} = 11\Delta y$, total mesh size $24 \times 38 \times 12, N_i = 3000$; PML theoretical reflection coefficient $R = 10^{-6}$.

implemented than its original form, and in particular, it is suitable for both general waveguide and microstrip structures excited with any type of excitation waves. Most importantly, with the help of our source excitation scheme, the accuracy and efficiency of the Mei's simplified field distribution for microstrip structures are investigated and confirmed.

II. Numerical Technique

Discontinuous waveguide and microstrip systems considered in this paper are shown in Fig. 1(a) and (b), respectively. The source plane is located several cells inside the near-end terminal plane. For either the waveguide or the microstrip system, the whole computational region is divided into two subregion by this source plane. The discontinuity and the far-end terminal plane are suited in region 1, whereas the near-end terminal plane is in region 2. For a given excitation wave, $E^n_{z,\rm inc}$, the Yee's FDTD equation on the source plane at $j_{\rm inp}$ is simply corrected as [15]

$$\begin{aligned} E_z^{n+1}&(i, j_{\rm inp}, k) \\ &= E_z^n(i, j_{\rm inp}, k) \\ &+ \frac{\Delta t}{\varepsilon \Delta x}\left(H_y^{n+1/2}(i+1, j_{\rm inp}, k) - H_y^{n+1/2}(i, j_{\rm inp}, k)\right) \\ &- \frac{\Delta t}{\varepsilon \Delta y}\left(H_x^{n+1/2}(i, j_{\rm inp}+1, k) - H_x^{n+1/2}(i, j_{\rm inp}, k)\right) \\ &+ E^n_{z,\rm inc}(i, j_{\rm inc}, k). \end{aligned} \tag{1}$$

The Yee's FDTD equations for the other EM-field components remain unchanged on the source plane. With the above arrangements, within the first part (i.e., between the incident plane and the discontinuity) of region 1 the EM fields contain the incident wave (propagates in $+y$ direction) and the reflected wave; whereas the EM fields in region 2 contain the incident wave (propagates in $-y$ direction) and the reflected wave. In region 2 the incident wave propagating in $-y$ direction and the reflected wave are immediately absorbed on the near-end terminal plane, while the incident wave (within the first part of region 1) propagating in $+y$ direction is used to examine the discontinuous system itself. Moreover, for microstrip systems, when the Mei's simplified field distribution is used as the initial source excitation, during the excitation no special boundary treatment is applied to the remaining EM fields on the source plane, and they are calculated from the normal Yee's FDTD formulation. Hence, unlike the source excitations employed in [9]–[13], the dc source distortions caused by the electric (or magnetic) wall boundary treatment, are not apparent in our excitation scheme.

III. Numerical Results

To validate and confirm the proposed excitation technique, in this section we apply it to waveguide and microstrip discontinuities excited with different type of excitation waves.

A. Waveguide Discontinuities

A short-circuited waveguide excited with a single frequency sinusoidal wave was analyzed with the proposed excitation scheme [16]. We here calculate the scattering parameters for a step discontinuity in a WR-3 waveguide due to waveguide section of finite length homogeneously filled with dielectric material [17]. In the study of this waveguide, an Gaussian pulse imposed on a sinusoidally varying carrier in a specific frequency range ($f_{\rm min} = 210$ GHz, and $f_{\rm max} = 333$ GHz) is used as the source wave [4], [5], and a 10-cell perfectly matched layer (PML) ABC [18], [19] is used in the front and back regions of the waveguide. Numerical results are given in Fig. 2. As can be seen from Fig. 2, our results agree very well with Arndt's results [17] obtained with 2-D FDTD method.

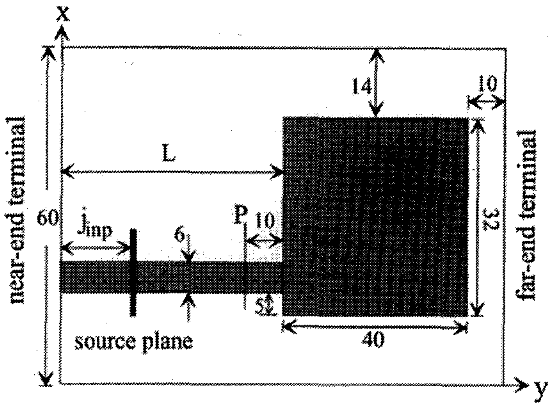


Fig. 3. Top-view of the line-fed rectangular microstrip antenna.

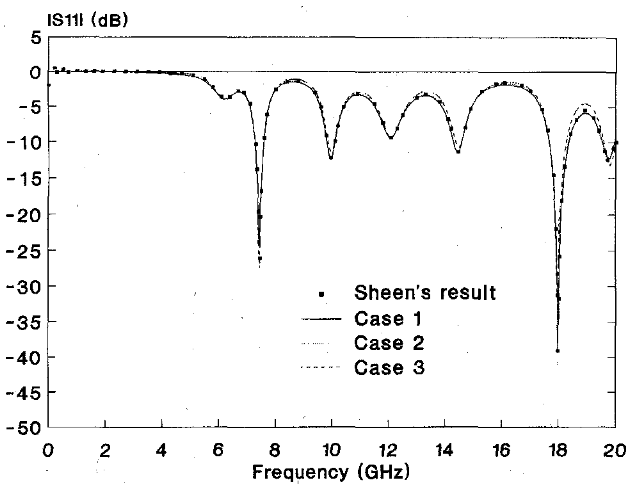


Fig. 4. S-parameter of the rectangular microstrip antenna for case 1 ($L = 50\Delta y, j_{\rm inp} = 5\Delta y$), case 2 ($L = 50\Delta y, j_{\rm inp} = 25\Delta y$), and case 3 ($L = 50\Delta y, j_{\rm inp} = 45\Delta y$).

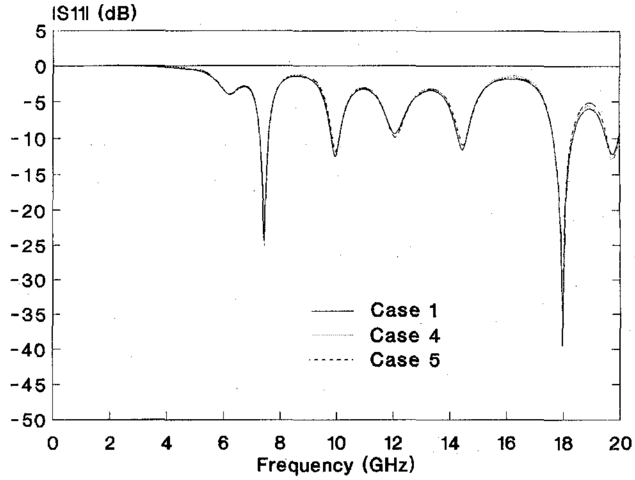


Fig. 5. S-parameter of the rectangular microstrip antenna for case 1, case 4 ($L = 25\Delta y, j_{\rm inp} = 5\Delta y$), and case 5 ($L = 11\Delta y, j_{\rm inp} = 5\Delta y$).

B. Microstrip Discontinuities

For microstrip systems, the line-fed rectangular microstrip antenna [11], as shown in Fig. 3, is analyzed. In this study, the simplified field distribution (i.e., uniform between the strip and the ground plane) [9], [10] is used as the excitation. Except that the source plane is separated from the near-end terminal plane, all parameters are chosen to be the same as those used in [11]. The numerical results for cases 1–3 obtained with our FDTD algorithm are shown in Fig. 4. It can be seen from Fig. 4 that our results are in good agreement with those obtained in [11], even for case 3 where the source plane is located only 5 cells away (i.e., $j_{\rm inp} = 45$) from the discontinuity. It should be noted that in case 3 the source plane is actually located behind the reference plane, P. Particularly, in case 3 the incident wave propagating in $-y$ direction (i.e., the wave in region 2) is used in the S-parameter calculation. In addition, as shown in Fig. 4 our results are more accurate than those given in [11] when the frequency is below 2.5 GHz. The appearance of the ripples in this lower frequency range might be caused by the dc distortion. Numerical results presented in Fig. 4 (and others presented in [15]) prove the validity of our excitation scheme. To examine the efficiency of our source excitation scheme, we next carry out our calculations by reducing the length of the feeding port (i.e., moving the near-end terminal plane toward the discontinuity). Numerical results for cases 4 and 5 are given in Fig. 5, and for comparison the results of case 1 are shown again in this figure. As shown in Fig. 5 quite accurate results can still be obtained even when the terminal plane is 11 cells away (i.e., case 5) from the discontinuity. It should be noted that in case 5 the computational volume for the microstrip structure has been reduced from $60 \times 100 \times 16$ to its minimum $60 \times 61 \times 16$. It is also worth mentioning that with our scheme the GRT requirement is automatically satisfied for calculating S_{11} parameter, even though it was claimed that the GRT can only be used to calculate S_{21} parameter [13]. Hence, making the GRT applicable to S_{11} could be seen as one of the advantages (or byproducts) of our excitation scheme.

Both the validity and efficiency of our source excitation scheme are confirmed by the numerical results presented in Figs. 4 and 5. However, it is still necessary to make a complete examination on the efficiency (and accuracy) of the simplified field distribution adopted in the computations. Even though an exploration of the simplified field distribution was made in [9], [10] by applying it to many different microstrip structures and its accuracy had been confirmed by many other investigators [11]–[13], the efficiency of this simplified field distribution was still obscure. For instance, can the source plane with such a simplified field distribution be moved very close to the discontinuity? To answer this question, the cases (i.e., cases 6 and 7) where the source plane located very close to the discontinuity are investigated and the numerical results for these cases are presented in Fig. 6. To give a comparison, also the result of case 5 is shown in Fig. 6. From Fig. 6, one can see that the simplified field distribution is still valid even when the source plane is located only one cell in front of the discontinuity (i.e., case 7). It must be emphasized that the validity and efficiency of the simplified field distribution cannot be examined in full without using our source excitation scheme.

Finally, it should be mentioned that the very detailed scattering parameters presented in Figs. 4–6 are obtained with

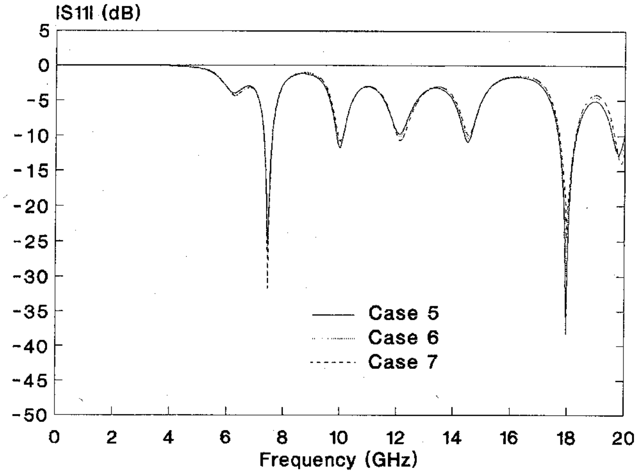


Fig. 6. S-parameter of the rectangular microstrip antenna for case 5, case 6 ($L = 11\Delta y, j_{\rm inp} = 8\Delta y$), and case 7 ($L = 11\Delta y, j_{\rm inp} = 10\Delta y$).

the spectral estimation technique [20] based on the frequency shifting.

IV. Conclusions

A simple, efficient and unified source excitation scheme for the FDTD analysis of waveguide and microstrip discontinuities is demonstrated. In this scheme, the source plane is located several cells inside the near-end terminal plane and the excitation wave is added as an extra term in the FDTD equation. Such a treatment totally separates the source excitation and the reflected wave in time domain. Hence, for both waveguide and microstrip discontinuities, ABC's can be applied at the near-end terminal plane directly, without any special treatment. Most importantly, for microstrip circuits, our source excitation scheme does not produce any dc source distortion on the source plane and nearby. Therefore, with our source excitation technique, the computational volume for both waveguide and microstrip discontinuities can be reduced very significantly by moving the terminal plane close to the discontinuity. This in turn saves computer memory and CPU time. Numerical results obtained from our algorithm confirm the validity and efficiency of this new excitation scheme and the approach proposed in this paper should be very useful in computer-aided-design (CAD) of a variety of microwave and microstrip integrated circuits.

References

[1] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations on isotropic media," *IEEE Trans. Antennas Propagat.*, vol. AP-14, pp. 302–307, 1966.

[2] M. De Pourcq, "Field and power-density calculations in closed microwave systems by three-dimensional finite differences," *IEE Proc.*, vol. 132, pt. H, pp. 360–368, 1985.

[3] S. T. Chu, W. P. Huang, and S. K. Chaudhuri, "Simulation and analysis of waveguide based optical integrated circuits," *Comp. Phys. Commun.*, vol. 68, pp. 451–484, 1991.

[4] P. Alinikula and K. S. Kunz, "Analysis of waveguide aperture coupling using the finite-difference time-domain method," *IEEE Microwave Guided Wave Lett.*, vol. 1, pp. 189–191, 1991.

[5] N. I. Dib and L. P. B. Katehi, "Analysis of the transition from rectangular waveguide to shielded dielectric image guide using the finite-difference time-domain method," *IEEE Microwave Guided Wave Lett.*, vol. 3, pp. 327–329, 1993.

[6] T. W. Huang, B. Houshmand, and T. Itoh, "Efficient modes extraction and numerically exact matched sources for a homogeneous waveguide cross-section in a FDTD simulation," in *1994 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 31–34.

[7] ——, "The implementation of time-domain diakoptics in the FDTD method," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2149–2155, 1994.

[8] Z. Q. Bi, K. L. Wu, and J. Litva, "Application of the FD-TD method to the analysis of H-plane waveguide discontinuities," *Electron. Lett.*, vol. 26, pp. 1897–1898, 1990.

[9] X. Zhang, J. Fang, K. K. Mei, and Y. Liu, "Calculations of the dispersive characteristics of microstrips by the time-domain finite difference method," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 263–267, 1988.

[10] X. Zhang and K. K. Mei, "Time-domain finite difference approach to the calculation of the frequency-dependent characteristics of microstrip discontinuities," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1775–1787, 1988.

[11] D. M. Sheen, S. M. Ali, M. D. Abouzahra, and J. A. Kong, "Application of the three-dimensional finite-difference time-domain method to the analysis of planar microstrip circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 849–857, 1990.

[12] W. L. Ko and R. Mittra, "A combination of FD-TD and Prony's methods for analyzing microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 2176–2181, 1991.

[13] X. P. Lin and K. Naishadham, "A simple technique for minimization of ABC-induced error in the FDTD analysis of microstrip discontinuities," *IEEE Microwave Guided Wave Lett.*, vol. 4, pp. 402–404, 1994.

[14] T. Shibata and H. Kimura, "Computer-aided engineering for microwave and millimeter-wave circuits using the FD-TD technique of field simulations," *Int. J. Microwave Millimeter-Wave Computer-Aided Eng.*, vol. 3, pp. 238–250, 1993.

[15] A. P. Zhao, A. V. Räisänen, and S. R. Cvetkovic, "A fast and efficient FDTD algorithm for the analysis of planar microstrip discontinuities by using a simple source excitation scheme," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 341–343, 1995.

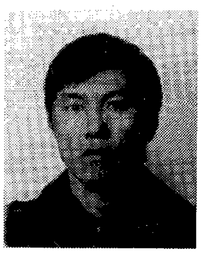
[16] A. P. Zhao and A. V. Räisänen, "A simple source excitation scheme for the FD-TD analysis of waveguide discontinuities," in *Proc. 25th European Microwave Conf.*, Bologna, Italy, Sept. 4–7, 1995, pp. 761–764.

[17] D. V. Krupezevic, V. J. Brankovic, and F. Arndt, "The wave-equation FDTD method for the efficient eigenvalue analysis and S-matrix computation of waveguide structures," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 2109–2115, 1993.

[18] J. P. Berenger, "A perfectly matched layer for the absorption of the electromagnetic waves," *J. Comput. Physics*, vol. 114, pp. 185–200, 1994.

[19] Z. Wu and J. Fang, "Numerical implementation and performance of perfectly matched layer boundary condition for waveguide structures," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2676–2683, 1995.

[20] A. P. Zhao and A. V. Räisänen, "Accurate and detailed FDTD solution of microwave integrated circuits using the frequency shifting technique," in *1996 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 577–580.



An Ping Zhao was born in Siping, China, on March 16, 1963. He received the B.Sc. degree in optical physics in 1984 from the Institute of Optics and Fine Mechanics, Changchun, China, the M.Sc. degree in optics in 1987 from Changchun Institute of Physics, Chinese Academy of Sciences, and the Ph.D. degree in electronic and electrical engineering in 1994 from Brunel University, England.

From 1987 to 1989, he worked as an Associate Researcher at Changchun Institute of Physics. In January 1990, he joined the Department of Electronic and Electrical Engineering, Surrey University, England, as a Visiting Research Fellow, where he worked on the computer verification of optical waveguide characteristics based on multiple-quantum-well (MQW) structures in III-V semiconductor materials. In October 1991, he became a Ph.D. student at Surrey University. In October 1992, he moved to the Department of Electrical Engineering and Electronics, Brunel University, for continuing his Ph.D. study. Since September 1994, he has been working as a Research Engineer at the Radio Laboratory, Helsinki University of Technology, Finland. His current research interests are the numerical modeling of integrated microwave circuits.

Antti V. Räisänen (S'76–M'81–SM'85–F'94) was born in Pielavesi, Finland, on September 3, 1950. He received the Diploma Engineer (M.Sc.), the Licentiate of Technology, and the Doctor of Technology degrees in electrical engineering from Helsinki University of Technology (HUT), Finland, in 1973, 1976, and 1981, respectively.

From 1973 to 1978, he worked as a Research Assistant at HUT Radio Laboratory. From 1978 to 1979, he was a Research Assistant at Five College Radio Astronomy Observatory (FCRAO) of the University of Massachusetts, Amherst. From 1980 to 1983, he was a Research Fellow of the Academy of Finland, working mainly at HUT, but also for shorter periods at FCRAO and Chalmers University of Technology, Gothenburg, Sweden. In 1984, he was a Visiting Scientist at the Department of Physics of the University of California, Berkeley. From 1985 to 1989, he was an Acting Professor of Radio Engineering with HUT, working also for short periods at the University of California, Berkeley. In 1989, he was appointed by invitation to the Professor Chair of Radio Engineering with HUT. In 1992–1993 he was on sabbatical leave from HUT and had a Senior Research Fellowship from the National Research Council at the Jet Propulsion Laboratory, Pasadena, CA. He was also a Visiting Associate in Electrical Engineering at California Institute of Technology. He is supervising research in millimeter components, antennas and receivers, microwave propagation in satellite links, microwave measurements, etc. at HUT Radio Laboratory. He has authored and co-authored more than 200 scientific or technical papers and three books: *Microwave Measurement Techniques, Radio Engineering*, and *RF and Microwave Techniques* (in Finnish).

Dr. Räisänen was the Secretary of the 12th European Microwave Conference, 1982. He was Counselor of the IEEE Student Branch in Helsinki from 1982 to 1989, and the Chairman of the IEEE MTT/AP Chapter in Finland from 1987 to 1992. In 1992, he served as the Conference Chairman for the 22nd European Microwave Conference.