Microwave Education Supported by Animations of Wave Propagation Effects

Wolfgang Menzel, *Fellow, IEEE*

***Abstract*—Dealing with electromagnetic (EM) fields and microwaves for the first time, many students have problems to get an idea of the fields and their behavior in transmission-line structures and components. To reduce these barriers, animations generated by a time-domain field simulator can be used to demonstrate some basic time- and space-dependent properties of EM waves. In this paper, the application of a two-dimensional transmission-line matrix (2D-TLM) code for this purpose is described. Starting points are some introductory animations of basic wave propagation, e.g., in a parallel-plate waveguide, the incidence of a wave onto a lossy wall (skin effect), or the excitation of a wave in a dielectric slab (dielectric line). Later on, the fields in a number of transmission-line components like couplers or filters can be demonstrated in a very nice way. Further applications of this tool are found in demonstrating basic problems of electromagnetic compatibility like penetration through a metal shielding or through openings in a shell including resonance effects. Such animations are shown during the lectures using a video projector. In addition, the examples are offered to the students on a Web page both as animated gifs and as applications files for a 2D-TLM program to repeat and/or modify the experiment.**

***Index Terms*—Animation, education, wave propagation.**

I. Introduction

THE advancement of mobile communication and mobile computing, the development of automotive radar sensors, and processor clock rates in the gigahertz range have brought new attention to the microwave area. The basics of the new information technologies have entered into the curricula of electrical-engineering education, but the "old" contents must not be neglected either, and all that within the same period of time for teaching and learning. This requires an increased effort to teach and to learn more effectively and to use additional tools—mostly including multimedia on the one hand, and more practically oriented lectures and laboratory courses.

In microwave education, efforts are made to support teaching by virtual laboratories of different kinds [1]–[4], Internet-supported teaching [5], [6], or special practically oriented lectures and laboratory courses [7]–[9]. This paper reports on the author's effort to visualize microwave phenomena and to promote a better understanding of these effects by animations created with a two-dimensional transmission–line matrix (2D-TLM) tool as it proposed and used in a similar way in [2] and [3].

Experiences show that many students have an aversion against topics that are quite abstract, difficult to grasp, and require complex mathematics. Consequently, the basic interest at these topics is low, and only a few students specialize in such topics. This is also true for microwaves. Electromagnetic fields are not visible, they are represented by vector fields with a complex structure and behavior as a function of time and space. In general, partial differential equations with respect to three space dimensions and time have to be solved. Complex notation of field quantities eases the mathematical procedures, but problem solving in the frequency domain cannot be imagined as easily as in the time domain, which is much closer to everyday experiences.

Furthermore, phenomena arise in the microwave area that are hardly experienced at lower frequencies like skin effect, propagation in a metal waveguide, or a dielectric guide (although the latter might be known from optical fibers). Transmission-line components, e.g., couplers or filters, with dimensions comparable to wavelength, exhibit complex interaction and performance.

As a contribution to simplify understanding of a number of microwave effects, electromagnetic fields in transmission lines, transmission-line components, and wave propagation in some selected environments are simulated and visualized in the time domain. In principle, some simple tools like a one-dimensional (1-D) finite-difference time-domain (FDTD) code are included in the material provided with the Center of Excellence for Multimedia Education and Technology (CAEME) project (CAEME [1]). Alternatively, freely available[1] or commercial three-dimensional (3-D) codes for FDTD, e.g., [10], *EMPIRE*,[2] finite-element[3] or finite-integration codes[4] in the time domain can be used. In addition, some effects even can be demonstrated on the basis of analytical solutions, possibly applying math programs like Mathcad [4].

For the work described in this paper, a freely available 2D-TLM[5] [11] simulator has proven to be a very effective and fast tool. The visualization in the time domain is close to the students' imagination, and the user interface of the TLM program is simple and nearly self-explaining—basically, the elements of the structure under investigation is drawn into a rectangular mesh using the computer mouse. A detailed user's manual, tutorial, and description of the theoretical background are provided with the program. The restriction

Manuscript received April 26, 2002.
The author is with the Microwave Department, University of Ulm, D-89069 Ulm, Germany (e-mail wolfgang.menzel@ieee.org).
Digital Object Identifier 10.1109/TMTT.2003.809177

[1][Online]. Available: http://www.borg.umn.edu/toyfdtd/, status Sept. 17, 2002.

[2]*EMPIRE*, IMST, Kamp-Lintfort, Germany.

[3]*HFSS*, Ansoft Corporation, Pittsburgh, PA.

[4]*CST*, Microwave Studio, Darmstadt, Germany.

[5][Online]. Available: http://www.faustcorp.com/downloads/index.html, status Sept. 17, 2002.

0018-9480/03$17.00 © 2003 IEEE

to two-dimensional (2-D) (or even 1-D) problems keeps the computed structures simple enough and allows fast “online” simulations. The third dimension can be used to plot field quantities in 3-D animated graphs. In spite of the limitation to 2-D problems, quite a number of effects can be demonstrated, like plane-wave propagation, propagation in a parallel-plate waveguide—including microstrip circuits approximated by a magnetic wall model [12], or H-plane metal waveguide problems.

The animations as described in the following are employed in the teaching process as supplementary tools to demonstrate basic waveguiding features. Their use includes several steps. First, the simulations are run on a personal computer (PC) or laptop and are projected on a screen during the lecture, accompanied with the respective explanations and standard theory. To allow the students to review the animations at a later time, both animated gifs (for harmonic excitation of a structure), as well as the application files for a repeated simulation are provided on a separate Web page,[6] together with a free version of the transmission-line matrix (TLM) program. With this program and the application files, the students are able to modify the virtual experiments, e.g., to change frequency, to modify critical circuit dimensions, or even to calculate S-parameters. Furthermore, novel arrangements can be simulated.

II. Basic Wave Propagation

A. Parallel-Plate Waveguide

The first animations presented at the beginning of the first microwave lecture basically are very simple, but they highlight some basic effects and demonstrate what the lecture has to deal with. The first experiment is the elementary propagation of a plane wave with harmonic frequency dependence in a parallel-plate waveguide (Fig. 1). Three aspects of such a wave are pointed out as follows.

- Watching a single cross section of the line, the harmonic time dependence of the (electric) field in this plane becomes evident.
- For constant time—the animation is stopped—the sinusoidal field distribution along the transmission line becomes more clear.
- Concentrating on some section—a “packet”—of the wave and observing its behavior, this is a nice demonstration as to how the complete “packet” moves along the line without changing is shape. [This gets even clearer if not a sinusoidal, but a Gaussian pulse excitation is used (see Fig. 2)].

In this way, the specific time-space dependence $\sin(\omega t - kz)$ of a traveling plane wave becomes more evident and is better understood.

Sending a Gaussian pulse to either an open- or a short-circuit termination of a line, the different reflection behavior of these terminations can be demonstrated—resulting in a direct reversal of the direction of wave propagation or in an additional amplitude/phase reversal for the shorted line (Fig. 2). For a sinusoidal excitation, standing waves with either an electric field maximum or a zero at the termination result.

[6][Online]. Available: http://mwt.e-technik.uni-ulm.de/world/lehre/hf-anim/mefisto/index.html, status Sept. 19, 2002.

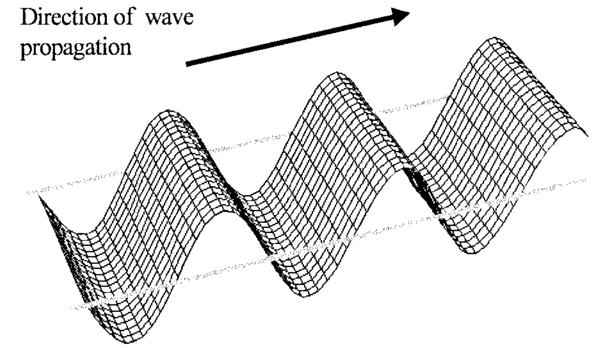


Fig. 1. Electric field of a wave propagating in a parallel-plate waveguide.

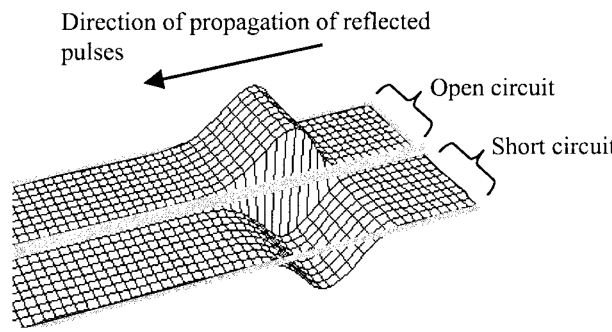


Fig. 2. Gaussian pulses reflected from an open- and a short-circuit termination.

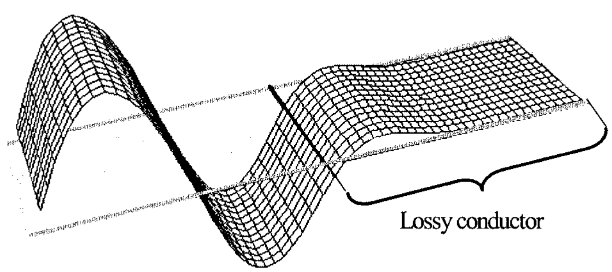


Fig. 3. Plane wave incident on a lossy conductor.

Instead of an ideal short circuit, a lossy conductor is used in the next experiment, demonstrating the penetration of a wave (harmonic time dependence) into a conductor (skin effect). With a suitable choice of conductor loss (10 S/m), the propagation of the wave into the conductor and its exponential decay can be observed, while (nearly) a standing wave builds up in the lossless part of the transmission line (Fig. 3).

B. Wave Propagation in Metal Waveguide

A simple way to introduce metal waveguide propagation—at least that of TE_{m0}-modes—is to superimpose two parallel-plate (plane) waves incident at opposite slanting angles or to have one parallel-plate wave incident on a metal wall at a slanting angle, superimposing with the reflected wave. The latter easily can be done using the 2-D simulation shown in Fig. 4(a). Looking at the resulting field, incident and reflected waves superimpose to a pattern that seems to move parallel to the shorting plane. With proper selection of the parameters, one or more lines of zero electric field can be seen where an additional shorting wall could be inserted, forming a closed waveguiding “tube”—a metal waveguide. Furthermore, the

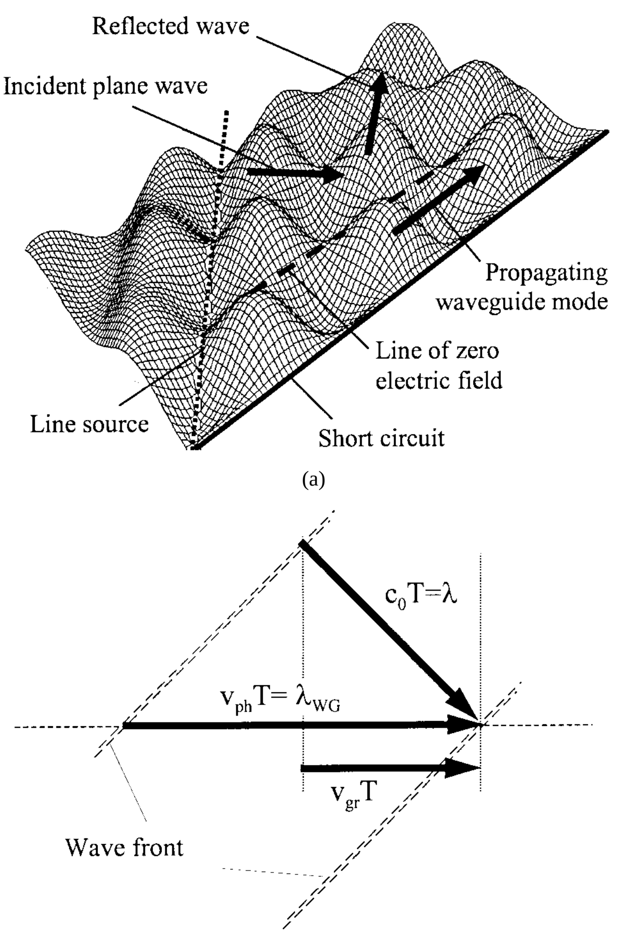


Fig. 4. (a) Plane wave (parallel-plate wave) incident on a short circuit. (b) Sketch illuminating speed of light, phase, and group velocity. The line source excites waves traveling to both sides; only the wave on the right-hand side is relevant for this experiment.

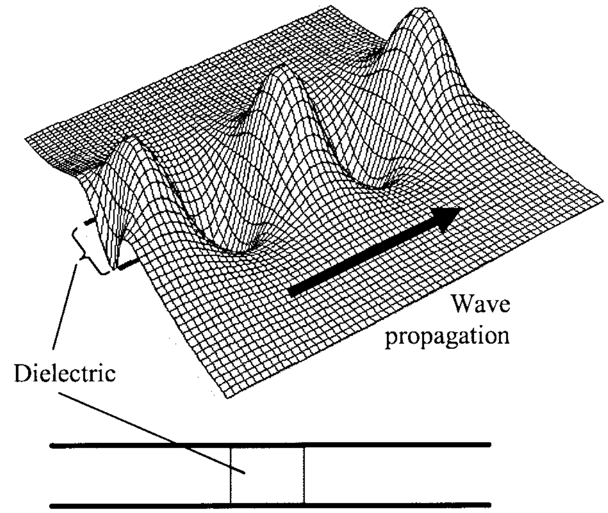


Fig. 5. Wave guidance by a dielectric slab.

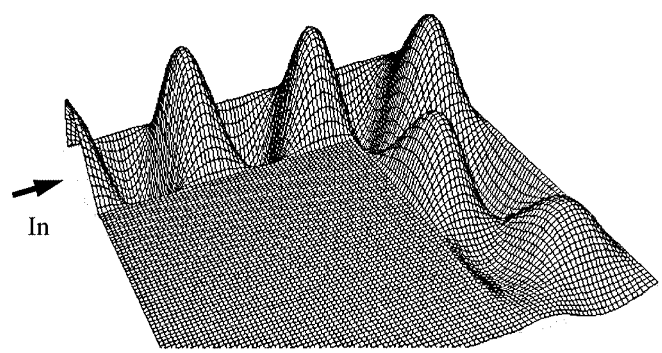


Fig. 6. Waveguide 90°-bend with strong reflection and excitation of higher order modes.

relations of speed of light, phase velocity, and group velocity can be explained easily with this model, as shown in Fig. 4(b). The waveguide field is formed by two superimposed plane waves traveling at the speed of light. A given phase state of the resulting pattern moves along the sides of a waveguide faster than the original wave, like a wave incident on a beach at a flat angle. Energy or information, on the other hand, has to be transported by the original two waves in zigzag, thus its speed in a waveguide is lower than the speed of light.

Once the propagation of waves in a waveguide is introduced, the wave behavior at a step to a reduced waveguide width can be easily demonstrated, showing an exponential decay of the field if frequency is below cutoff.

C. *Wave Guidance by a Dielectric Slab*

Not only the propagation of plane waves or waves in a waveguide can be demonstrated, but also the guiding properties of dielectric structures. To this end, a dielectric slab is used, surrounded by air. A wave (lateral extension is limited to the width of the slab) is excited at one end of the slab. As a result, a wave is propagating along the slab; outside of the slab, the fields decay exponentially (Fig. 5). This clearly demonstrates that metal is not necessary for guidance of a wave, and reference can be made to optical fibers or integrated optical circuits.

If the slab is made wide enough, and if a wave is excited with slanting incidence similar to Fig. 4(a), refraction or even total reflection of a wave at a dielectric interface can be shown.

III. Transmission-Line Discontinuities and Components

A. *Waveguide 90°-Bend*

As discussed above, H-plane waveguide circuits and microstrip circuits (in the form of an equivalent magnetic-wall model) can be simulated easily using the 2D-TLM code. As an example for a discontinuity, a 90° waveguide bend is shown. If the frequency of an incident wave is close to the cutoff frequency of the waveguide, two effects occur and can be visualized easily. The first one is a strong reflection of the incident wave, resulting in a standing-wave pattern in the input waveguide (Fig. 6). The second effect, which can be clearly demonstrated with this example, is the excitation of higher order modes—mainly the TE_{20} mode. On the right-hand side of Fig. 6, a full period of the lateral field distribution can be recognized clearly. With proper selection of frequency, even the exponential decay of this mode is visible.

Adding a simple matching element in the corner of the waveguide bend (a rough approximation of a mitered bend), wave

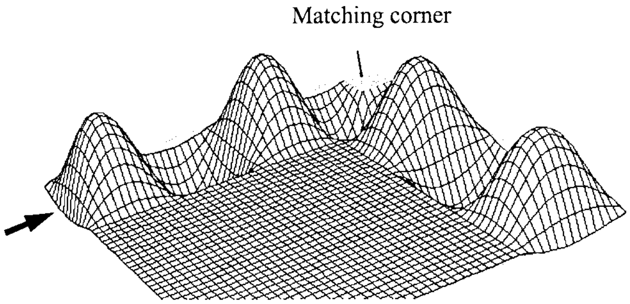


Fig. 7. Waveguide 90°-bend with matching corner.

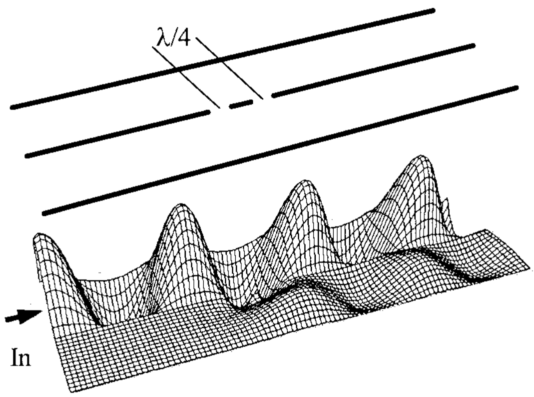


Fig. 8. Top view and electric-field distribution in a waveguide narrow wall coupler.

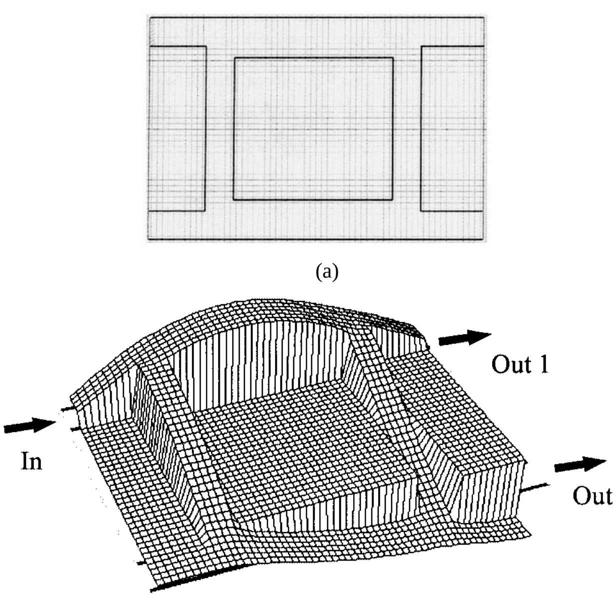


Fig. 9. Basic layout and field distribution in a microstrip hybrid-ring coupler.

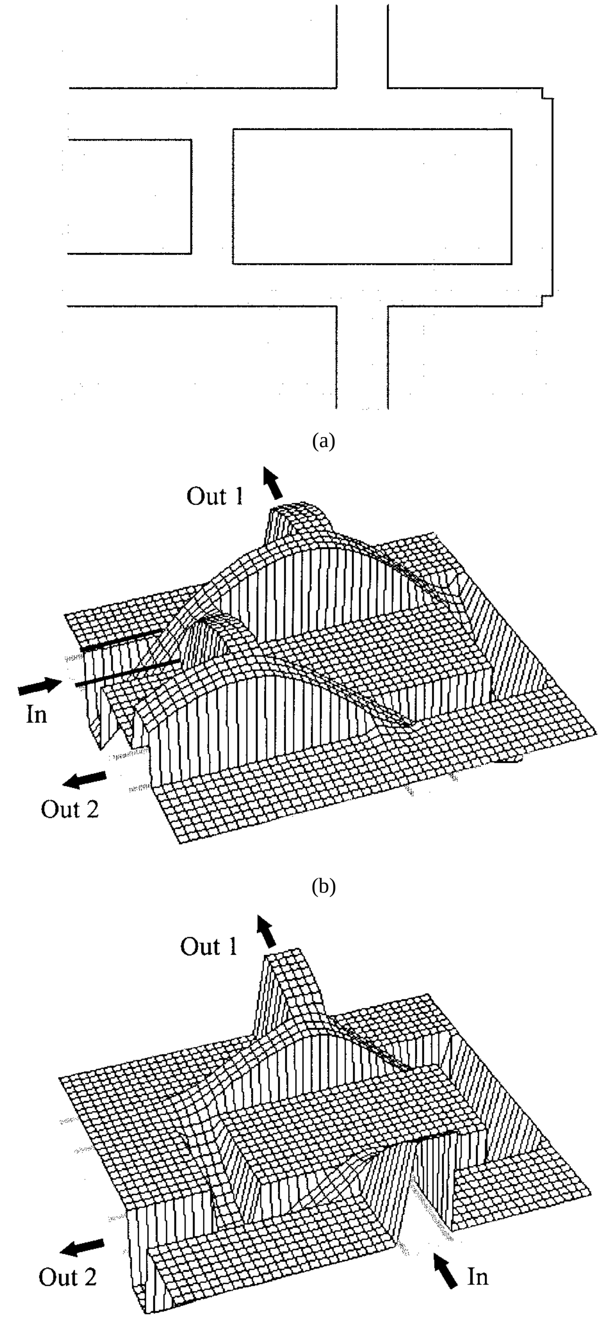


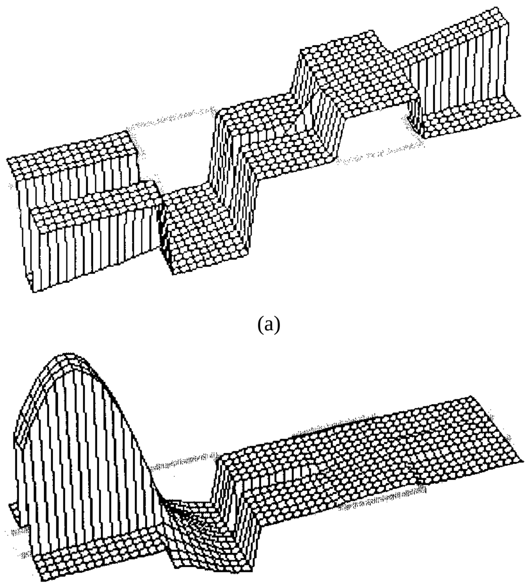
Fig. 10. Basic layout and field distribution in a microstrip rat-race coupler with 0° (left-hand side) and 180° (right-hand side) output phase difference.

propagation around the corner can be made very smooth without relevant reflections (Fig. 7).

Comparable simulations can be done for microstrip bends with and without miter or waveguide and microstrip T-junctions with matching septum.

B. Waveguide Directional Coupler

A first component that can be simulated in a very effective way is a waveguide sidewall coupler with two coupling holes separated by a quarter-wavelength (hole height is equal to the waveguide height). At each hole, a small amount of the wave is injected into the lower waveguide (Fig. 8). In the forward direction, these add in-phase (traveling to the right-hand side), but cancel traveling to the left-hand side, i.e., backward, clearly visible in the field plot and original animation. To enable a clear effect of this demonstration, the structure should be precalculated thoroughly in advance using either the scattering param-



(a)

(b)

Fig. 11. Electric-field distribution in a three-element low-pass filter. (a) Low-frequency (passband). (b) Frequency of maximum attenuation (input from the left-hand side).

eter option of the TLM software or another method like mode matching.

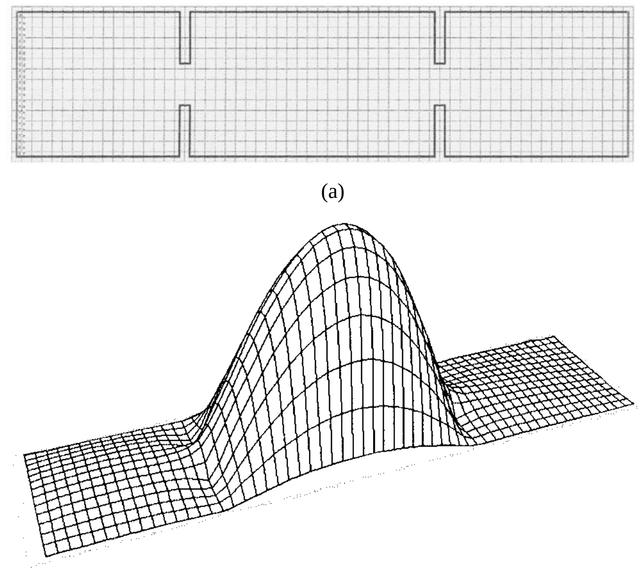
C. Microstrip Couplers

Based on equivalent magnetic-wall models [12], the basic functions of microstrip hybrid-ring and rat-race couplers can be simulated and made evident as well. To fit the structure of the rat-race coupler into the rectangular grid of the simulator, but avoiding excess reflections at the resulting 90°-bends, compensating corners are introduced, similar as shown in Section III-A for a waveguide bend.

The cancellation of two waves with equal amplitude and opposite phase at the respective isolated ports becomes apparent in both examples (Figs. 9 and 10), as well as the output phase difference of 90° for the hybrid ring coupler (Fig. 9) and 0° or 180° for the rat-race coupler, depending on the excited port (Fig. 10).

D. Filters

Microstrip bandpass filters based on high–low impedances are further good candidates to demonstrate their basic mechanisms. Fig. 11(a) shows the electric field of a three-element filter at a low frequency. While the field is nearly constant in the capacitive sections, a strong variation occurs in the inductive section, but the wave can still pass. At a higher frequency—it is selected for maximum attenuation, i.e., the filter elements are approximately a quarter-wavelength long—a strong decrease of the field along the filter can be observed [see Fig. 11(b)]. Watching the animated field, the short-circuiting function of the capacitive elements and the strong voltage decay of the narrow inductive line become even more apparent. Employing user-defined excitation functions of the TLM code, a chirped signal can be generated, and the transition between pass and reject can be observed in the animation, showing a field strength increase in the transition frequency range.



(a)

(b)

Fig. 12. Waveguide resonator with strong increase of the interior field.

Waveguide bandpass filters are further candidates for simulations as described here. However, due to the high-Q factor of waveguide resonators, a very long simulation time is necessary to reach a steady state of the simulation. The simplest structure is a single iris-coupled resonator. If the simulation has been running long enough, the increase of the field within the resonator compared to that of the connected waveguides becomes very evident (Fig. 12). Based on this structure, different facts can be explained. Firstly, some time is required to feed the necessary energy into the resonator. Next, a high field strength is necessary to finally allow the complete power to pass the two irises, which, as single elements, have a rather low transmission coefficient. Finally, it becomes clear that such a high field strength will result in increased losses, especially for narrow-band filters where the effect of field-strength overshoot is quite strong.

IV. Electromagnetic Compatibility (EMC) Problems

Another area of application for animations is EMC. One example, extending the skin-effect demonstration, shows the limited shielding effect of thin metallization at low frequencies. A plane wave is incident on a sheet of lossy conductor. In this case, an animated representation of the electric field along the direction of wave propagation only gives an excellent impression of the physical effects. Most of the wave is reflected. Within the conductor, some wave propagation with exponentially decaying amplitude can be observed. The remaining field strength at the opposite side of the shielding layer then launches a wave traveling to the right-hand side, possibly into the interior of a housing (Fig. 13).

Other EMC problems suitable for demonstrations as described in this paper (and shown in an introductory EMC lecture) are the penetration of plane waves through apertures of different sizes into a box, the dependence of field strength in a box depending on frequency (resonances), and higher order resonances in boxes. With the last experiment, even the effect of inhomogeneous heating in a microwave oven can be explained easily.

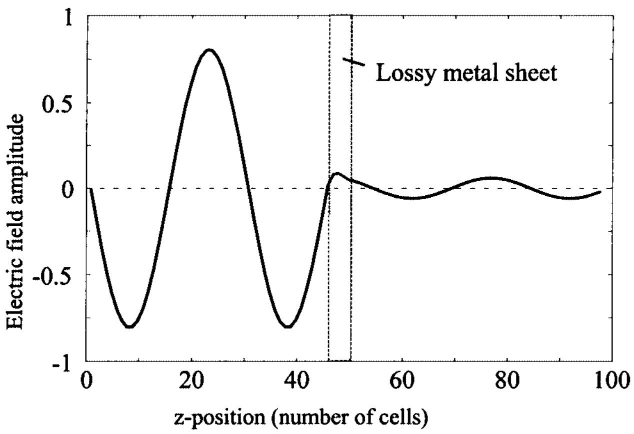


Fig. 13. Snapshot of the electric field of a wave incident on a lossy metal sheet.

V. Conclusion

A number of examples have been shown of 2D-TLM simulations and animations of electromagnetic fields in microwave transmission lines and components to demonstrate basic effects and functions. These examples have been presented to students during lectures on basic microwaves, integrated microwave circuits, or an introduction to EMC. In addition, the animations are provided for later reviewing on a Web page, both as animated gifs, as well as application files that can be downloaded together with a free version of the TLM software. The intention of this effort is to visualize basic microwave aspect to the students, to enhance the understanding, and to reduce barriers to deal with this topic. Experiences and response from students are very encouraging to continue and improve these methods.

Acknowledgment

The author extends special thanks to Dr. W. J. R. Hoefer, University of Victoria, Victoria, BC, Canada, for providing the TLM program and for many valuable discussions and tips.

References

[1] M. F. Iskander and J. C. Catten, "The CAEME center for multimedia education," in *IEEE AP-S Int. Symp. Dig.*, vol. 32, June 1994, pp. 80–83.

[2] M. Righi, W. J. R. Hoefer, and T. Weiland, "A virtual field-based laboratory for microwave education," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. II, 1998, pp. 555–558.

[3] W. J. R. Hoefer, "The effective use of computer modeling and visualization in microwave education," in *29th Eur. Microwave Conf.*, vol. 2, Munich, Germany, 1999, pp. 86–89.

[4] K. W. Whites, "Visual electromagnetics for Mathcad: A computer-assisted learning tool for undergraduate electromagnetics education," in *Int. IEEE AP-S Int. Symp. Dig.*, vol. 36, June 1998, pp. 2288–2291.

[5] A. S. Daryoush, "Microwave engineering education using web-based instruction," *IEEE Microwave Mag.*, vol. 2, pp. 114–118, June 2001.

[6] M. Pasch and M. Hoffmann, "Internet-based lectures in electrical and information engineering—Design and implementation of a framework for easy course creation," in *Proc. EAEEIE 11th Annu. Conf.*, M. Hoffmann, Ed., Ulm, Germany, Apr. 26–28, 2000.

[7] T. M. Weller, P. G. Flikkema, L. P. Dunleavy, H. C. Gordon, and R. E. Henning, "Educating tomorrow's RF/microwave engineer: A new undergraduate laboratory uniting circuit and system concepts," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, 1998, pp. 563–566.

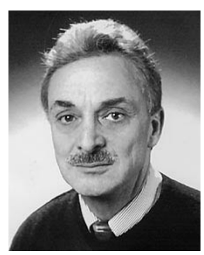
[8] T. Weller and L. Dunleavy, "Wireless and microwave education: From circuits to systems," in *29th Eur. Microwave Conf.*, vol. 2, Munich, Germany, 1999, pp. 93–96.

[9] S. Toutain, C. Person, and J. P. Coupez, "Electromagnetic theory, CAD and experimental approach bases of an efficient education in microwave and RF techniques," in *31th Eur. Microwave Conf.*, vol. 1, London, U.K., 2001, pp. 453–456.

[10] *QuickWave 3D Software Manual*, QWED, Warsaw, Poland, 1999.

[11] W. J. R. Hoefer and P. P. M. So, *The Electromagnetic Wave Field Simulator*. New York: Wiley, 1991.

[12] G. Kompa and R. Mehran, "Planar waveguide model for calculating microstrip components," *Electron. Lett.*, vol. 11, pp. 459–460, 1975.



Wolfgang Menzel (M'89–SM'90–F'01) received the Dipl.-Ing. degree in electrical engineering from the Technical University of Aachen, Aachen, Germany, in 1974, and the Dr.-Ing. degree from the University of Duisburg, Duisburg, Germany, in 1977.

From 1979 to 1989, he was with the Millimeter-Wave Department, AEG, Ulm, Germany [now European Aerospace, Defense, and Space Systems (EADS)]. From 1980 to 1985, he was Head of the Laboratory for Integrated Millimeter-Wave Circuits. From 1985 to 1989, he was Head of the entire Millimeter-Wave Department. During that time, his areas of interest included planar integrated circuits (mainly on the basis of fine-line techniques), planar antennas, and systems in the millimeter-wave frequency range. In 1989, he became a Full Professor with the University of Ulm, Ulm, Germany. His current areas of interest are multilayer planar circuits, waveguide filters and components, antennas, millimeter-wave and microwave interconnects and packaging, and millimeter-wave application and system aspects.

Dr. Menzel is currently an associate editor for the IEEE Transactions on Microwave Theory and Techniques. From 1997 to 1999, he was a Distinguished Microwave Lecturer for Microwave/Millimeter Wave Packaging. From 1997 to 2001, he chaired the German IEEE Microwave Theory and Techniques (MTT)/Antennas and Propagation (AP) Chapter. He was the recipient of the 2002 European Microwave Prize.