Microwave and RF Education—Past, Present, and Future

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Invited Paper

***Abstract*—This paper is an overview of how microwave and RF education has changed over the years and where it is heading. The history of microwave and RF education, and the key events that influenced its development, are summarized. These events include the need for short-wavelength radar during World War II, the invention of printed transmission lines in the 1950s, the emergence of microwave integrated circuits and solid-state devices during the 1960s, the growing availability of computers and the development of numerical methods during the 1970s, and the availability of microwave circuit simulators and field simulators in the 1980s and 1990s, respectively. The likely impact of recent advances in Internet technology for the distribution of multimedia information is then described. The paper concludes by pointing out the outstanding challenges for the education and continuing education of microwave and RF engineers.**

***Index Terms*—History of education, microwave education, RF education, Web-based education.**

I. Introduction

EDUCATION in microwave and RF technology and sciences, based on the underlying fundamental discipline of electromagnetics, has been recognized as an essential core of electrical, electronics, and computer engineering education over the last 50 years. Although some aspects of microwave and RF technologies differ, the basic educational features for each discipline are very similar, and both microwave and RF engineers need to be exposed to the same fundamentals. In the remainder of this paper, therefore, except for Section VI and the figures, we shall drop the term "RF" for simplicity, but with the understanding that when the term "microwave" is used it is meant to imply "microwave and RF."

As microwave techniques developed rapidly during and immediately after World War II, microwave courses were introduced into electrical and electronics engineering curricula all over the world. Today, we are on the threshold of another major paradigm shift in microwave discipline and practice. The end of the Cold War era, the globalization of industry, and the rapid emergence of wireless communications in all facets of today's society have provided microwave technology a renewed prominent role. Microwaves is no longer a technology crucial primarily for military systems, but is playing a very significant role in the current upsurge in wireless communications systems.

The philosophy of engineering education practiced today is mostly based on the so-called "engineering science" model [1], [2] that was established soon after World War II and has stood by successfully for several generations of engineers over the last 50 years. That was the last major shift in engineering education that changed the emphasis from teaching "engineering practice" to "engineering sciences." That shift changed both the contents of the curriculum and the manner in which the courses were taught. Microwave engineering education has seen several other paradigm shifts. The first one occurred approximately 2–3 decades back when planar transmission structures (strip lines, microstrip lines, etc.), and planar antennas (microstrip patches and printed slots) started replacing waveguides, parabolic reflectors, and horn antennas, which have been the landmarks of microwaves since World War II. Associated with those new elements was their use in microwave integrated circuits. At about the same time, computers became available, and numerical methods were developed. The first of these two changes influenced the content of microwave courses, while the primary impact of the second change was to affect the way in which graduate research was conducted. The next major shift in microwave engineering practice and education is more recent, only about a decade old, when microwave computer-aided design (CAD) techniques matured and both designers and educators recognized the need and advantages of employing network and electromagnetic (EM) simulators for engineering design, as well as for education and training [3].

As we now experience the rapid technological changes unleashed by the upsurge in wireless communications and Internet technology, microwave education (in fact, all of engineering education) is facing new challenges and is up for another major paradigm shift [4]. These challenges include: 1) the need for formalized lifelong learning; 2) the need to broaden "engineering fundamentals" beyond mathematics and physics; 3) inadequacy of the first professional degree for engineering careers; 4) , need for engineering practice experience for faculty; 5) diversification of engineering work force and faculty; and 6) the need for enhancement of technological literacy in the general population. In order to train the engineers who will still be practicing 40 years from now, microwave educators have to address these challenges.

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This paper is an overview of how microwave education has changed over years, where it is heading, and what needs to be done to address the outstanding challenges for education and continuing education of microwave engineers. The four salient messages this article intends to emphasize are: 1) electromagnetics, RF, and microwave education is an important component of any educational curriculum for electrical, electronics, and computer engineers; 2) technology has been changing rapidly in recent years, and a microwave education curriculum needs to emphasize that; 3) simulation (and CAD) needs to be used as a critical and efficient tool for microwave education; and 4) Web-based and Web-assisted education is a new paradigm that is going to play an increasingly significant role in education.

II. Birth and Flowering of Microwave Network Theory and Microwave Education (1930s–1960s)

The periods shortly before and during World War II, and the period following until the 1960s, saw enormous progress in the development of the microwave field, resulting in the establishment of a thriving microwave industry and fundamental changes in the way electrical engineering was taught. During and immediately after World War II, electromagnetics saw a great revival, and network theory, for the first time, was combined with EM theory to produce a new discipline, which was called microwave network theory. As a result, many new courses, with different names, but based to varying degrees on microwave network theory, were introduced into electrical engineering curricula at many universities. In order to understand how this enormous shift in course content came about, it is helpful to present a brief history of this period.

During the decade of the 1890s, shortly after Hertz demonstrated experimentally that he could actually produce the EM waves predicted by Maxwell's theory, many people in various countries generated EM waves at microwave frequencies and explored their properties. Lord Rayleigh in 1897 even published a theoretical paper [5] on hollow pipes as waveguides, and explained the concept of cutoff frequencies. However, all this work came to an abrupt stop in 1901 after Marconi showed that low-frequency waves could be transmitted over very long distances with equipment that produced higher power at lower cost. Communications after that were based on these lower frequencies and, during the 1920s, the ship-to-shore and transoceanic systems became a practical reality. Although operating frequencies slowly crept higher during those years, the desire to explore still higher frequencies became very strong by 1930. It was recognized, however, that for these higher frequencies, radiation would be produced at every bend and junction in the circuit so that something new was required.

That new element, the use of hollow pipes as waveguides, was reinvented independently by Southworth [6] and Barrow [7] during the middle 1930s. Neither one knew of Rayleigh's much earlier work. Detailed discussions of their contributions, and the interesting history related to them, appear in two papers [8], [9] in the special September 1984 volume published in this TRANSACTIONS celebrating the IEEE Centennial that year. By the end of the 1930s, many papers had been published on the EM field properties of these waveguides. There were also early attempts at combining the field properties with impedance concepts.

During that period, the principles of radar became well understood in various countries. The need was expressed for smaller wavelengths to improve the resolution of radar systems, but no sources of microwaves could then produce sufficiently high power. The discovery of the high-power magnetron in the U.K. shortly before World War II suddenly made radar an exciting possibility. Cooperation with the USA was established, and was intensified during World War II when the Massachusetts Institute of Technology (MIT) Radiation Laboratory and some associated laboratories at universities and in industry were established with the goal of making radar practical.

These efforts, which involved both physicists and engineers, proceeded in a great spirit of cooperation. Circuit theory was applied to EM waves, resulting in a new discipline called microwave network theory. However, the development of the necessary components and, therefore, systems, was hindered by the fact that, although there was some physical understanding of which junctions and discontinuities were capacitive or inductive, there was little or no quantitative information that could be used for accurate design purposes. Schwinger and others, both at the MIT Radiation Laboratory and elsewhere, devised integral-equation and other methods for obtaining accurate equivalent networks for many discontinuities in waveguides. Interesting historical details in this connection are presented in [9].

Remarkable progress was made by the end of World War II in placing microwave network theory on a sound quantitative footing. Several volumes in the 28-volume Radiation Laboratory Series of books [10][1] published shortly after the end of World War II, particularly volumes 8–10 and parts of 11 and 14, contain excellent material in this connection. Volume 10, i.e., the *Waveguide Handbook* [11], was widely used at universities for its introductory chapters, and in industry for component design. EM theory in its classical form also encountered substantial new interest. Several new books were written during the early 1940s, the most comprehensive of them being the one by Stratton [12] in 1941. Other books written about that time also included the information known then about guided waves in hollow waveguides. The most influential and widely used of those books was written by Ramo and Whinnery [13], with their first edition published in 1944.

All this new information, combined with a new understanding of the many potential applications for microwave systems, produced a huge explosion in microwave industry just after World War II, and also resulted in a profound change in the nature of

[1]Reference [10] is a 28-volume series. A CD-ROM version is available from Artech House, Norwood, MA.

university courses involving electromagnetics and microwave networks.

Prior to World War II, circuit theory and EM field theory tended to be separate worlds in university education, usually taught separately in electrical engineering and physics departments, respectively. Following World War II, they became combined, at least in electrical engineering. This important change has often been characterized as a major part of a general shift from an engineering-practice curriculum to an engineering-sciences one. EM theory was then usually taught in both physics and electrical engineering departments, with a different stress in each, but in most electrical engineering departments, new (microwave) courses were introduced that combined circuit theory with electromagnetics.

The general approach in these new courses was (and is) to view microwave networks as composed of lengths of waveguides connected together by various types of junctions. The lengths of waveguides were treated as transmission lines, and the junctions as lumped discontinuities represented in equivalent network or scattering matrix form. The formulation was systematic and rigorous. Many special network techniques were also developed around this approach.

At many universities, however, the combination of circuit and field theories was initially only partial. As microwave network theory developed further, and became more widely understood, microwave courses across the country slowly absorbed more and more of these techniques. The principal contributor to such developments was Marcuvitz of the Polytechnic Institute of Brooklyn, Brooklyn, NY. Several valuable books devoted to this approach appeared during this period, the most influential of them, in addition to the *Waveguide Handbook*[11], being *Field Theory of Guided Waves* by Collin [14], first published in 1960.

Since there were no electronic computers at that time (although there were mechanical computers that resembled typewriters that provided numerical results for simple problems), it became necessary to develop physical understanding and also various approximation methods. Today, with the universal availability of computers, there is widespread use of numerical techniques, CAD procedures, and even commercial EM solvers, which are a tremendous boon to industry and have allowed the solution of many problems deemed impossible during the period before computers. The absorption of these calculation tools into microwave education is discussed below in Sections III and VI. Unfortunately, along with these calculational tools and their great benefits, physical understanding has suffered greatly because it is believed by the newer generations of students to be of only minor importance since numerical results can often be obtained with only limited understanding. Also, many of the microwave network techniques, and particularly the approximate methods, are largely lost. This sad consequence is unnecessary, and future microwave education must address this highly important issue.

In the remainder of this section, we discuss the invention of printed-circuit transmission lines in the early 1950s, although their full impact on the microwave field did not occur until about two decades later. The dominant mode of rectangular waveguide has a limited bandwidth, and circuits based on those waveguides are large and bulky. Coaxial lines can provide a dominant mode with very large bandwidth and they can be miniaturized, but it is difficult and expensive to build components based on them. Two-wire (or two-strip) line can also provide the bandwidth and miniaturization, but it is inconvenient to work with. The ideal solution is either to cut and then flatten the coaxial line, or to bisect the two-wire line with a ground plane and support the other wire (or strip) with a dielectric layer. One then obtains strip and microstrip lines, respectively. The strip-line version came a bit earlier, and it was actually conceived by its inventor Barrett as a printed line. Its dominant mode is TEM and, therefore, dispersionless, whereas microstrip, because of the dielectric support layer, possessed dispersion. Also, because it is open and unsymmetrical, every discontinuity on the line would radiate. As a result of these deficiencies, microstrip was shelved for the next 15 years or so, and strip line became the line of choice.

Due to its symmetry, strip line is easy to analyze, and many papers appeared on the properties of the dominant mode [15], and even some on equivalent circuits for various discontinuities on the line [16], [17]. Those results were widely used by industry for component design, but the impact on microwave education was minor, except in a few universities, where it was shown that microwave network techniques could be applied to guiding structures other than rectangular waveguide. Microstrip was ignored until the late 1960s, after integrated circuits were introduced and the circuits were miniaturized, so that the effects of dispersion and discontinuity radiation became essentially negligible for low operating frequencies. Further comments on these two lines are given in Section III.

III. Impact of Computers and Numerical Methods (Late 1960s–Early 1980s)

The period roughly from the late 1960s to the early 1980s may be characterized by the emergence of computer power into microwave research and graduate education, particularly in the area of EM aspects of microwave engineering. The emerging technology of microwave integrated circuits based on microstrip line is one of the most significant beneficiaries of this trend. Prior to this period, many microwave problems were attacked based on analytical or semianalytical approaches typically found in the Radiation Laboratory series [10]. Such approaches are still used today, but primarily in the analytic phrasing of the problem, with the remainder of the problem solved using a numerical method.

In the early stages of microstrip-line research, the analysis methods were based on the quasi-TEM approximation for its dominant mode, in which the axial components of the modal EM fields are neglected. This approximation is found to be acceptable at lower microwave frequencies. On the other hand, strip line has a cross section homogeneously filled with a dielectric material so that the dominant mode of this configuration is TEM. A large body of literature based on TEM analysis, such as conformal mapping, was available at that time for strip-line analysis [15]. Other comments on the distinctions between strip and microstrip lines are presented at the end of Section II. Typical of the early work on microstrip line is a modified conformal mapping by Wheeler [18].

Since computer power was still quite primitive at that time, substantial effort was expended by a number of research groups involving graduate studies. For instance, Miyoshi and Okoshi introduced the planar circuit approach to simplify the analysis of microstrip discontinuities [21] while Wolff's group worked on the waveguide model based on a similar concept [22]. These approaches were introduced primarily to avoid complicated full-wave three-dimensional field analyses for discontinuities in microwave integrated circuits. It is interesting to note that one of the most popular three-dimensional full-wave analysis methods, i.e., the finite difference time domain (FDTD), was considered to be impractical at that time, as it required too much computer memory, even though the leap-frog method and Yee's mesh were invented in the 1960s [23]. The use of FDTD for microstrip discontinuities did not enter the mainstream of numerical electromagnetics until the late 1980s [24].

In parallel with the slowly improving computational capability, novel numerical methods were introduced. Yamashita [19] introduced a new method based on the Fourier transform technique and the variational principle. For this method, the use of computers was essential, even though the computer is more or less used as a powerful calculator. In the case of Yamashita's approach, the variational integral needs to be computed numerically. All of these quasi-TEM approaches required calculations of the capacitance per unit length of the transmission line. In the meantime, it was gradually recognized that a full-wave analysis is needed to characterize the dispersion characteristics of the microstrip lines. Several methods including the widely used spectral-domain method [20] then emerged. In these methods, extensive use of the computer became a necessity. For instance, in the spectral-domain method, several rather slowly converging integrals need to be computed, as well as the numerical solution of the linear simultaneous equations.

In the late 1960s to at least the mid-1970s, EM education leaned heavily toward antennas and propagation. Relatively few educational institutions had been engaged in the EM aspects of microwave guided-wave problems. Therefore, much of the educational effort did not distinguish between those problems involving microwaves (guided waves), which includes microwave network theory, which is a combination of electromagnetics and networks, and free-space radiation, which includes only electromagnetics. With the improvements in computing power, and with the availability of numerical methods, an increasing number of guided-wave problems were solved, and the university courses contained an increasing proportion of topics of interest to the microwave field.

The need for computers in solving electromagnetics problems has grown steadily. Many of these problems have been attacked by research teams involving graduate students who quickly became adapted to the computer environment. Nevertheless, they were faced with the everlasting problem of insufficient computational power, both in terms of memory and speed. Most of the computations for research and education were carried out on a main frame, such as an IBM 370 typically located at the computation center of the university. The input mechanism used was initially tapes and then a deck of IBM programming cards. Typical turnaround time for a computer program for the propagation constant of microstrip line was overnight. Therefore, the students often duplicated the deck of programming cards or a box of them and submitted them simultaneously (earlier form of parallel processing) or sequentially so that, within a given time, one can obtain multiple sets of answers. Of course, there were many opportunities to make punching errors on the card. One night is then completely wasted if you submit a program containing such a card. This situation has, of course, been alleviated gradually, first by remote access using dumb terminals, then by the use of minicomputers and finally workstations with a computation power much exceeding that of the previous main frames.

Unlike today, the computer language taught at school has been FORTRAN and later on BASIC in some instances. Also, practically no commercial software for EM simulation for microwave programs existed then, but circuit design programs had been developed, although rather primitive by today's standards, by such companies as COMPACT and EESof.[2] However, these programs were not used extensively in the academic environment. A substantial portion of the graduate study, therefore, was expended for developing computer programs, debugging, and waiting for responses from the computer. Nevertheless, the mode of graduate research has not essentially changed, at least for microwave problems involving electromagnetics. One first analyses the EM-wave phenomena and extracts necessary system parameters. They are compared with published results by other methods or by other authors. More comprehensive research programs carried out experiments to validate the numerically simulated results. The major difference is that today it is often not necessary for the students to be equipped with computer programming capability, thanks to the availability of software packages for EM field simulation.

One of the dangers associated with the use of computers in EM education has been a tendency to increase the number of students who believe that whatever the data punched by the computer tells us are accurate or even rigorous. Another is the apparent decrease in the capability to carry out "back-of-the-envelope" calculations to estimate the EM phenomena or data. Of course, these problems are not caused by the computer itself, but often by the educational environment. Since the computational power was minimal at that time (and still is in some cases), it was almost impossible to visualize the distribution of the EM fields and currents. As pointed out in Section IV, as well as in [34], the visualization capability of the computer for these quantities is one of the major assets in modern EM education assisted by computer. Only then has the computer-assisted education become effective for undergraduate teaching.

IV. Impact of CAD (Simulators) on Microwave Education

The introductions of microwave circuit simulators in the early 1980s [25]–[27] and of EM field simulators in the early 1990s [28] have drastically changed the design procedures followed for microwave circuits and microstrip antennas. Computer-aided analysis and optimization have replaced the design process of iterative experimental modifications of the initial design. In addition to their impact on design practice in

[2]COMPACT has since become a part of Ansoft, and EESof is now a part of Agilent.

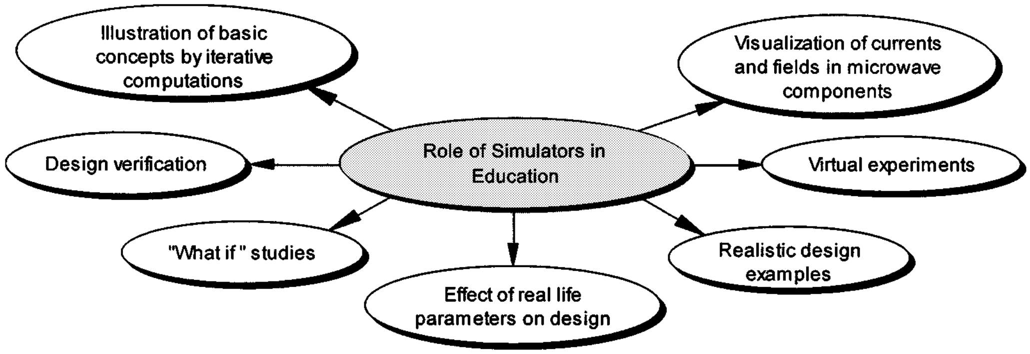

Fig. 1. Application of simulators in microwave and RF instruction and independent learning.

industry, microwave circuit and field simulators have found extensive applications in undergraduate, graduate, and continuing education in electromagnetics, RF, microwave, and millimeter-wave areas [29], [30]. Many of the software tool vendors have educational/student versions of their software and provide substantial discounts to educational institutions. The major impact of simulators in education is in making realistic design examples and case studies available to students. Thus, the introduction of these simulators has contributed to bridging the gap between classroom instruction of microwaves and the practice of microwaves in industry. For the first time in the history of microwave education, it has become possible to provide classroom instruction that is 100% relevant to the practice in industry. Some of the applications of simulators in education are depicted in Fig. 1, and are discussed briefly in this section as well as in [3].

A. Illustration of Basic Concepts by Iterative Computations

The students can learn some of the very basic concepts by repeated computations making use of microwave circuit and field simulators. For example, the reflection of waves by a complex impedance load terminating a uniform transmission line is traditionally studied by deriving the relevant results using transmission-line equations. However, the same concept can be illustrated in a more student-friendly way by simulating a simple circuit consisting of a transmission line with a variable load at one end and a dual directional coupler at the other end. The student varies the load impedance and observes the reflected power as seen by the voltage probe sampling the reflected voltage at the appropriate port of the directional coupler in the circuit. Observations in this interactive simulation experiment constitute a powerfully effective way to learn that there is no reflected wave when the load impedance is equal to the characteristic impedance of the transmission line. This simulation experiment can also be used for illustrating the properties of a directional coupler (by monitoring the incident and reflected waves), and the concept of a matched source (by varying the source impedance and monitoring the wave reflected from the source). This learning process is similar to what a student will pick up in a corresponding laboratory experiment.

B. Design Verification

Microwave network simulators provide a powerful tool for the verification of designs carried out by students. For example, a student designs a microwave amplifier (for the first time in his life) by starting from the S-parameters of an available transistor, finding what impedances the transistor should see at the two ports, and designing appropriate input and output matching networks. A quick simulation of the designed circuit on a microwave network simulator confirms to the student that the design process has been learned and applied correctly. This verification provides an immediate confidence buildup needed for further learning. Any such similar feedback was not possible earlier before the availability of microwave simulators. The only procedure at that time was to turn in the assignment to the instructor who could provide the needed confirmation (hopefully within a few days) or go to the laboratory to collect the components, build the amplifier, and make actual microwave measurements. Thus, the circuit simulators have opened up a new learning paradigm intermediate between the design and experimental verification thereof.

C. "What if" Explorations

Simulators allow the students to explore how the design performance will be affected if the value of a design parameter were to be altered either intentionally or because of the unavoidable tolerances in the values of the components or in the fabrication process. For any design, several questions may be asked. "What will happen to my amplifier bandwidth if the transconductance of the MESFET were to go down by 10%?" "How will the performance be altered if during the photoetching process all the microstrip lines in the circuit are over-etched by 10 μm?" "How will the output power be changed if the load impedance is 60 Ω in place of the 50-Ω value used in the design calculations?" Answers to such questions were not easily obtainable before the availability of network simulators. These additional pieces of information can now be conveniently obtained through circuit simulations.

D. Effect of Real-Life Parameters on Design

Every design process involves a number of engineering approximations. For example, in arriving at the initial design of microwave circuits, we normally assume the transmission-line sections to be lossless. This makes the design process tractable. However, we know that, in real life, these transmission lines (particularly when we are dealing with planar transmission structures on ceramic and semiconductor substrates) have finite losses that can alter the circuit performance appreciably. Effects of such real-life parameters on circuit characteristics can now be evaluated before investing in the actual fabrication of the circuits. Students come to learn facts like: the line loss can add to the insertion loss of a bandpass filter significantly, but the effect of line loss on the gain of an amplifier may be ignored. Investigations of the effect of temperature variations, of package enclosures, of close proximity between two circuits in a system layout, etc., can now be studied economically before sending the circuit for manufacture.

E. Realistic Design Examples

Before the availability of microwave simulators, examples of design performed by students in a classroom environment had to be kept simple because of the computational complexity involved. For example, students could handle a single-stage amplifier design, but multistage amplifier design could not be easily carried out. The use of microwave simulators overcomes such limitations. Students in the academic environments of universities can now carry out practical system and subsystem designs. This has brought instruction in universities much closer to actual professional practice in industry. Thus, the availability of microwave simulators has increased the university–industry collaborations that are very desirable for the advancement of the state of technology.

F. Virtual Experiments

As mentioned in Sections IV-A–E, the use of simulators can provide design performance evaluation experience that was obtainable earlier only through practical experimental measurements in a microwave laboratory. Several universities have used this feature to substitute some of the laboratory hours in the microwave curriculum with what are sometimes called simulation experiments or virtual experiments [31]. More recently, software has been developed [32] to convert simulators into what are known as "virtual instruments." Virtual instruments are claimed to provide us with a unique method for speeding up the analysis of microwave circuits within simulation software. These "instruments" look like and can be used like their real counterparts. They make the step from the real laboratory environment to the software solution easy, and provide software substitutes for really hard laboratory experiments.

G. Visualization of Currents and Fields

EM simulators yield not only terminal information about the characteristics of a component at the port locations, but also tell us a lot more about what is happening inside the component. Planar EM field simulators (based on method-of-moments, spectral-domain analysis, or variations thereof) base their results on computations of current distributions over the metallized portion of the circuit and/or calculations of equivalent magnetic current distributions (corresponding to the transverse E-field) in the slots of coplanar waveguide (CPW) or slotline components. These current distributions can be used to learn qualitatively about the reasons for the component's terminal behavior. For example, looking at the current distribution on the surface of a right-angled microstrip bend, one observes a crowding of current lines at the bend and can thereby conclude that an increased series inductance is contributed by the bend geometry. For a uniform microstrip line, the distribution of the current lines along the width of the microstrip provides a clear visual demonstration of the current-crowding effect near the edges. Thus, displays of current distributions associated with microstrip, CPW, and slotline discontinuities yield pedagogically significant information about the behavior of these components.

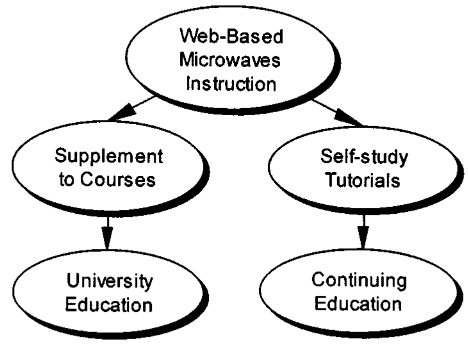

Fig. 2. Two approaches for the use of the Internet in higher education and continuing education in microwave studies.

Two-dimensional field solvers (such as is available with three–dimensional finite-element analysis-based EM simulators) provide us with two-dimensional electric field distributions in the cross-sectional planes of transmission-line structures. Comparing the electric field distributions in a coaxial line and a microstrip line, for example, one observes the crowding of E-field lines at the edges of the microstrip line. This increased E-field at the edges accounts for the lower values of voltages for dielectric breakdown in microstrip lines leading to the lower peak power-handling capability of these lines. Observation of the field distributions for even and odd modes in coupled transmission lines is a very useful step in appreciating the differences in the characteristics of these modes. Three-dimensional EM simulators also serve the useful purpose of visualizing the fields in three-dimensional components. From an educational point-of-view, this visual representation is even more important because of the lack of a complete analytical understanding of several three-dimensional microwave components.

While using EM or circuit simulators for educational purposes, it is necessary to emphasize that the experience with simulators does not replace the insight or the precise details that are obtained by a mathematical analysis of the EM structure. Simulators should be used for supplementing the knowledge attained by mathematical analysis and/or getting the feel of the performance of complicated physical structures for which mathematical analysis is not easily tractable.

V. WEB-BASED AND WEB-ASSISTED EDUCATION

Education is among the various aspects of modern society that are experiencing significant impact from recent inventions, and now from the ubiquitous popularity of the Internet or Web. Universities (and other educational enterprises) are making increased use of Internet technology to enhance and supplement the classical classroom style of education. Websites are being created for a number of courses (particularly those with large

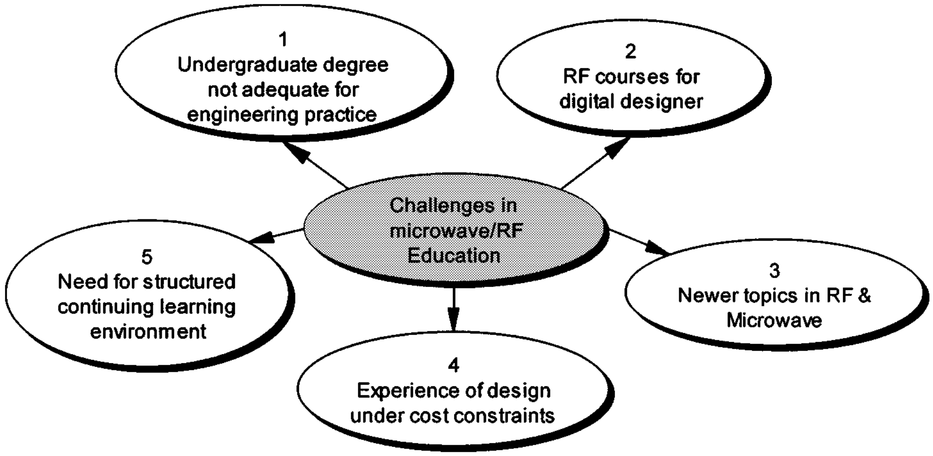

Fig. 3. Current challenges in RF and microwave education.

student enrollment) and these are used to distribute course material as enrichment to the normal course materials. Typically the materials on the Web include the course syllabus, semester schedule, assignments, assignment solutions (posted after assignments have been turned in), additional course notes and papers, and in some cases, copies of viewgraphs or handwritten notes used by the instructor. The students have access to and download the needed material at any time and at any place at their convenience. This arrangement assumes the students have access to the Web either on the campus or at their homes. In this model, most of the instruction is in synchronous mode (with regularly scheduled lectures) with some asynchronous communication via e-mails between the individual student and the instructor and among the students within the course.

For continuing education, including that in microwaves and related areas, another model for Web-based instruction [33] (see Fig. 2) is convenient for completely asynchronous distance education. In this model, the whole course, a set of courses, or a program is delivered over the Web. In this case, Web pages incorporate hypertext, video, graphics, sound, pictures, animations, spreadsheets, and presentation packages. Such courses can allow the student to access remote library systems and remote databases anywhere in the world. Asynchronous communication among the class students and the instructor is possible via a discussion-group type of arrangement on the Internet. The instructor can post the assignments and the students can submit homework and participate in collaborative projects with other students around the world. In this model of continuing microwave education, it is convenient to couple microwave simulators with the Web-based educational material made available to learners. A model for this coupling between the traditional educational material and microwave design software tools has been reported recently [3].

A companion paper [34] in this issue presents a detailed discussion on Web- and multimedia-based microwave and electromagnetics education.

VI. Challenges for Microwave and RF Education

Several factors are likely to change in profound ways the current setup of the higher education enterprise, including microwave education, all over the globe [4], [35][3]. These include: 1) the current evolution from an industrial to a knowledge-based society; 2) demographic changes; 3) increased globalization of professional activities; 4) priorities in the post-cold-war era; and 4) the development of market forces in the education field. Consequently, a number of new themes are being recognized to be crucial for higher education in this century. Among these are: 1) learner-centeredness; 2) affordability; 3) need for lifelong learning; 4) need to address diverse populations; and 4) need for intelligent and adaptive learning environments. As conventional universities have started to respond slowly (compared to the rapidity of changes in information technology) to these recent needs in higher education, a few institutions based on newer models (such as the University of Phoenix, Phoenix, AZ, and the Open University, Milton Keynes, U.K.) have made a definite presence and are challenging the concept of the traditional system of universities.

Due to this changing educational scenario, there are a number of challenges facing microwave and RF educators today. These are summarized in Fig. 3. Some of these echo the opinion articulated by Prof. Wulf (President, U.S. National Academy of Engineering) for engineering education in general [36]. The first one is reflected in the growing recognition in academia as well as industry that the bachelor's degree does not adequately prepare the students for the practice of RF and microwave engineering. Everyone agrees that the undergraduate curriculum should emphasize the fundamentals, but the challenge is in deciding what the fundamentals are. Do they include information technology, biological materials and processes, engineering systems, global business issues, etc? The introduction of RF/microwave courses for digital designers is another challenging issue. As clock rates reach the gigahertz domain, an understanding of microwave phenomena becomes essential for the design and packaging of high-speed digital circuits. This has presented an educational curriculum development challenge. The introduction of an ever-increasing number of new topics in microwave and RF engineering is an item that calls for judgment and wisdom on the part of edu-

[3]Reference [35] is a quarterly publication published by the National Academy of Sciences, National Academy of Engineering, and The Cecil and Ida Green Center for the Study of Science and Technology at the University of Texas at Dallas.

cators. The urgent need to include experience in design under cost constraints is another challenge for any specialization in engineering. In addition to all these curriculum issues is the global need and challenge of designing a structured continuing lifelong learning environment for microwave and RF engineers.

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