Educating Microwave Engineers in the United States

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***Abstract*—Three knowledge areas in which a Microwave Engineer needs to be educated are reviewed, and implementation means discussed. It is shown that Microwave Engineering education in the U.S. occurs primarily after receipt of the first (Bachelor's) engineering degree. The inevitability of specialized academic education within the field of Microwave Engineering is pointed out. Overall results from a broadly based survey of U.S. Electrical Engineering departments' Microwave Engineering programs are presented. They include information on Master's and Doctorate degrees awarded, faculty, and sources and level of research funding. Additional reference sources which contain information on U.S. Microwave Engineering are identified. Opportunities for making educational improvements on the graduate level of this multifaceted engineering specialization, which is not centrally regulated, are pointed out and illustrated by a specific example.**

I. Introduction

THIS paper is aimed at all engineers, engineering managers, and engineering administrators who are interested in how tomorrow's engineer is educated for tomorrow's engineering assignments. It is tutorial in nature; it presents an overview of Microwave Engineering education in the U.S. rather than a discussion of specific educational techniques employed.

Continued rapid technological advances and market growths are forcing more and more electronic products to operate, at least partly, in the microwave spectrum. Therefore, more engineers can expect to be assigned in the future to research, development, and production engineering tasks on products whose operation—and cost—will be impacted by the quality and creativeness of their Microwave Engineering. Similarly, more future engineers are expected to be engaged in providing engineering services which require a sound understanding of physical phenomena and equipment characteristics related to the microwave spectrum. The authors hope that this paper will lead to a better understanding of present Microwave Engineering education and may stimulate creation of further improvements in the education of future engineers.

The Microwave Theory and Techniques Society (MTT-S) has about 10 500 members. Many of them, as well as many non-MTT members, consider themselves Microwave Engineers. A number of trade journals are specifically devoted to provide this body of professionals with the latest practical Microwave Engineering information, covering such activities as application-oriented technical articles, new products, market projections, contract awards, and personnel changes. With all this activity, it seems logical that a broadly accepted definition for Microwave Engineering would exist, and that a young person aspiring to become a Microwave Engineer could readily identify the educational path that needs to be followed to reach this goal.

But in practice that is not true! Microwaves basically defines a certain portion of the electromagnetic spectrum, and many different engineering activities and applications operate at microwave frequencies. Thus, the realm of Microwave Engineering is multifaceted, and engineers with a variety of skills consider themselves Microwave Engineers. To confuse the issue further, the knowledge bases used by them in industry do not have a one-to-one correspondence to the microwave-oriented academic material that United States universities cover in their courses. Thus, the question legitimately arises: "How are Microwave Engineers prepared for their professional career in the United States?" As a matter of fact—how is Microwave Engineering really defined? Are there one or more orderly paths a student can follow to become a Microwave Engineer? What guidelines and reference sources are available to the student? The answers are anything but straightforward. The authors hope that the remainder of this paper will provide sufficient additional information to clarify this subject, even though it cannot provide a single, simple answer.

II. Definitions and Background

Considering the above, it should no longer be surprising to discover that there is no universally accepted definition for Microwave Engineering, nor is the frequency band (or wavelength range) of Microwaves universally defined. The material that follows is based on the following definitions.

- Microwave Engineering is considered to cover the application of knowledge and judgment to the development of components, devices, circuits, and systems involving the generation, transmission, and detection of microwaves.[1]
- Microwaves generally fall into the 300 MHz–300 GHz portion of the electromagnetic spectrum. (Activity outside this spectrum may be considered microwave if it uses comparable structures, dimensions, and techniques.)
- A Microwave Engineer is normally conversant with not only Electromagnetic Theory, but also draws on several other academic disciplines to accomplish assigned objectives. Further, as an engineer, he/she retains contact with consumer, industrial, and/or governmental needs which could be met through his/her professional effort.

It follows that a Microwave Engineer's knowledge normally covers several disciplines. It further follows that there is a

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wide divergence of overall knowledge/skills needed to be a Microwave Engineer, determined largely by the type of products involved. The microwave engineer who works on system aspects of highly complex space radars draws on a different technical knowledge base than the microwave engineer who develops low-noise amplifiers for large-volume products. Hence, specialization within Microwave Engineering is inevitable.

"Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgement to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind" [1]. A need must exist and the means must be found to fill it in a timely and cost-effective manner. There are two major "consumers" of engineering services in the United States:

1) suppliers to its competitive, product-oriented commercial market; and

2) broad public needs in such areas as national defense, environmental protection, and other regulated activities (for instance, traffic control and communication services).

Commercial market demands are filled by private, commercial U.S. industries, while public needs are met by such agencies as the Department of Defense (DoD), the National Aeronautics and Space Agency (NASA), the Federal Aviation Administration (FAA), and those private industries whose products support these agencies' activities. Broadly speaking, the commercial product is subject only to minimal government influences (for example, safety requirements), while those filling national needs must comply with additional restraints (centralized planning, special requirements, regulations, etc.). Thus, normally, an engineer working on commercial products uses different information, judgement, and (frequently) also different parts and materials than the engineer whose work fulfills public interest needs.

As is evident from the above, the U.S. microwave engineer's know-how needs to cover three dimensions:

1) academic knowledge in such fields as mathematics and the natural sciences (including engineering sciences),

2) knowledge of design techniques/approaches that apply to the microwave product area in which the engineer is working, and

3) knowledge of the competitive market forces and/or applicable regulations and restraints.

Major responsibility for educating a microwave engineer in the first area rests with engineering schools in U.S. universities. Imparting the needed knowledge of the last two areas to the microwave engineer normally occurs primarily "on the job." The basic (undergraduate) U.S. engineering university program, culminating in a Bachelor's degree, does not include "on-the-job" or apprentice-type training, so that learning about the last two areas normally only occurs after a student has completed an engineering Bachelor's degree program. Thus, educating a U.S. microwave engineer involves both academic and employer environments, normally on a sequential rather than interlaced basis.

At this point, it may be worthwhile to briefly review undergraduate engineering education in the U.S. There are about 260 U.S. colleges/universities with "ABET accredited"[2] Electrical Engineering programs. This accreditation is granted by a federation of 27 engineering societies, after an academic engineering program has requested that it be evaluated and then has been found to meet the criteria applicable to its specific program (for example, Electrical Engineering) [2]. ABET's overall criteria cover faculty, curriculum (objective and content), students, administration, institutional facilities, and the institution's commitment to its engineering programs(s). These overall criteria are supplemented by specific program criteria formulated by the applicable engineering society; in the case of Electrical Engineering, this is the Institute of Electrical and Electronics Engineers, Inc. ABET's evaluations thus delve deeply into the overall conduct of an institution's (normally undergraduate) engineering education.

U.S. engineering education's adherence to this accreditation process has a very pronounced effect on its undergraduate engineering education. Two items specifically stand out.

1) Extensively defined curriculum content criteria (subdivided into mathematics and basic sciences, engineering sciences, engineering design, humanities, and social sciences) plus some (inevitable) nonABET requirements imposed by the institution, and/or state or regional educational authorities, result in intensive, well-defined four-year undergraduate programs with hardly any elective engineering courses.

2) Due to the extensively defined curriculum, much similarity in content exists between the many Electrical Engineering programs of U.S. colleges/universities. As a result, students graduating from different schools acquire similar levels of Electrical Engineering knowledge.

These two factors lead to the following:

1) The scarcity of elective courses leads to very little, if any, exposure of students to Microwave Engineering during their undergraduate program. Many students graduating with a Bachelor's degree have no exposure, whatsoever.

2) Since all U.S. students receive their Bachelor's degree when they reach much the same overall knowledge base, all students commence graduate education with very similar academic preparation. Thus, U.S. engineering schools have a good basis for offering cohesive, meaningful, first level (master's degree) graduate programs requiring one to two years of full-time study.

3) Lack of broadly based undergraduate exposure to Microwave Engineering, coupled with a common base of education of entering graduate students, in theory provides a sound base for conducting effective Microwave Engineering-oriented graduate programs leading to a Master's degree.

As a consequence, Microwave Engineering education is essentially a graduate education endeavor in the United States.

Contrary to the strong role played by the engineering profession in formulating undergraduate engineering education standards through ABET, the engineering profession/societies generally do not get involved in setting standards or monitoring the quality of U.S. graduate engineering programs. The content, quality, etc., of such programs is left up to the

[2] ABET (the Accreditation Board for Engineering and Technology) accredits either an undergraduate or a graduate engineering program. Almost all engineering programs select undergraduate program accreditation.

universities and the regional/state agencies and/or "Boards of Directors" that oversee them. The net result is a great variety of available graduate level engineering education, which includes Microwave Engineering education at some, but not all, universities. When one takes into account that a Microwave Engineer must be conversant not only with electromagnetic theory, but also with several other academic disciplines (the specific ones being determined by the products/service the engineer is to perform), then it is not surprising that different universities focus on preparing Microwave Engineers for different career/application objectives, or—as is equally likely—that the particular combination of course work in disciplines other than electromagnetics offered by a specific university prepares students well for some, but poorly for other Microwave Engineering career paths.

Graduate education in the U.S. can be divided into two phases:

Phase I leads to a Master's degree and consists largely of lecture-type coursework; normally few, if any, laboratory courses are offered. A thesis, calling for significant research and/or design effort, may or may not be required. Some of the course work and, where offered, the thesis activity, can provide a student with important elements of an all-around microwave engineering education, particularly in the mathematical and engineering sciences. Since U.S. university faculty is normally not involved in such aspects as product design, product marketing, or regulatory aspects, the full-time microwave engineering graduate student is unlikely to acquire much knowledge in these areas, and will need to acquire this knowledge after receiving the master's degree. (An exception are programs at universities whose faculty possesses industrial experience and maintains close contact with microwave industries.) When the student pursues graduate studies on a part-time basis, while employed as a microwave engineer, or works summers in industry, becoming knowledgeable in these areas can occur in parallel with the university studies.

Phase II leads to a doctoral degree. This degree normally requires four to six years of study beyond the bachelor's degree, culminating in lengthy, in-depth, original research of a specific topic. Normally, doctoral studies focus very heavily on developing advanced mathematical and scientific skills; thus little or no knowledge or experience covering product design, market demands, etc., is acquired during this phase. For those students who remain in a university environment upon receipt of their doctoral degree, an environment where they normally will not encounter the need for competitive product knowledge and/or customer regulations and restraints, paucity of know-how in these areas is no problem; those that enter industry or public service-oriented activities acquire this know-how only after receiving their degree, or while employed part-time when pursuing their degree.

III. Microwave Engineering University Survey

A significant number of U.S. universities offer microwave-oriented courses and are engaged in microwave-oriented research activities. It is thus desirable to include survey-based data with this description of U.S. Microwave Engineering education. Others have addressed this topic in the past, but from different perspectives, including Besser [3] who addressed the adequacy of microwave education, and McIntosh [4] who addressed the topic from a graduate level, electromagnetic perspective, listing over 60 institutions.

A 3-page survey, prepared by the authors, was sent to 260 ABET-accredited electrical engineering programs in the U.S. It asked for information in the following areas (the definitions cited early in this paper were to be used):

1) Do you educate Microwave Engineers? If yes, then the following:

2) Information on undergraduate Microwave Engineering activity, if any.

3) Information on Master's degree level graduate activity, if any.

4) Information on Ph.D. degree level graduate activity, if any.

5) Detailed information on undergraduate and graduate course offerings in Engineering Science, Engineering Design (Microwave Engineering and related disciplines), and laboratory courses.

6) Special facilities and equipment.

7) Supporting faculty.

8) Linking to industry and governmental agencies (number and funding level).

Forty-two percent of the questionnaires were returned. (Note that the mailing included many—primarily undergraduate—programs which do not offer any microwave engineering-oriented course work.) Eighty responses (30.8%) stated that they did educate Microwave Engineers. Seventy-five of the positive responses came from institutions offering both undergraduate and graduate level education, three from institutions offering only an undergraduate degree program. It appeared, on closer examination of the responses, that definitions provided with the questionnaire (see also the start of Section II) and/or other wording were not completely clear, resulting in a number of specific questions interpreted differently by different responders. For this reason, a detailed complete role of U.S. universities in Microwave Engineering education cannot be portrayed from this survey. However, some specifics, like the listing of universities reporting large Microwave Engineering programs shown in Table I, may be of interest. This table was derived by ranking reporting universities by size in the following four categories (see also footnotes in Table I):

- number of Microwave Engineering M.S. degrees awarded per year,
- number of Microwave Engineering Ph.D. degrees awarded in 3 years,
- number of faculty involved in funded Microwave Engineering research, and
- annual level of Microwave Engineering research funding.

If a university ranked high enough to be included in the group as defined in the footnotes of Table I, then the university was considered to have met this criteria, as indicated by an "x" in Table I. Only those universities which met at least two of the criteria are listed.

TABLE I
SURVEY RESULTS

Institution	Graduate Degrees		Supported Research	
	Ms[a]	Ph.D.[b]	Faculty[c]	Funding[d]
Univ. of California, L.A.		x	x	x
Univ. of Colorado, Boulder	x	x		x
Univ. of Connecticut			x	x
Drexel University	x	x	x	x
Georgia Inst. of Technology	x	x	x	x
Univ. of Massachusetts, Amherst	x	x	x	x
Univ. of Michigan		x	x	x
North Carolina State University	x	x	x	x
Stanford University	x	x	x	x
Syracuse University	x		x	
Texas A & M University	x			x
Univ. of Texas, Arlington	x			x
Univ. of Utah	x		x	x
Virginia Poly. Inst. & State Univ.		x	x	

a) Microwave Engineering only, 10 or more M.S. degrees per year (13 universities).
b) Microwave Engineering only, 8 or more Ph.D. degrees in 3 years (14 universities).
c) Six or more faculty involved in funded Microwave Engineering research (12 universities).
d) $800K or more annual Microwave Engineering research funding (14 universities).

Variations in interpretation (particularly in the "supported research" categories) leave a direct comparison between individual programs with little validity. However, average size of these programs may still have meaning and be of interest. This is shown in Table II. The largest and smallest values in each sample group are included under the "Maximum/Minimum" entry for reference.

No Microwave Engineering Bachelor's degree programs are offered in the U.S., since ABET's requirements lead to these degrees being more broadly based Electrical Engineering degrees. However, some universities offer one or more undergraduate Microwave Engineering courses. Most are elective, but in a few cases the course(s) are required. The survey probed this area and results, based on 66 responses, are listed in Table III.

It is reasonable to assume that most universities which did not respond to the survey did so because they do not offer any Microwave Engineering required or elective courses. Thus, it appears that less than 5% of U.S. universities Electrical Engineering programs require some microwave engineering knowledge of their Electrical Engineering Bachelor's degree students, while an estimated 1/3 give their students the opportunity to acquire such knowledge on an elective basis. Only a small percentage of students actually makes use of this opportunity. One concludes that for a large majority of U.S. Bachelor's degree college graduates, Microwave Engineering is a strange, unfamiliar subject.

TABLE II
AVERAGE SIZE OF LARGEST PROGRAMS

Description	Graduate Degrees		Supported Research	
	MS[a]	Ph.D.[b]	Faculty[c]	Funding[d]
Average	22.5	12.9	11.1	$5.4M
Maximum/Minimum	50/3	45/2	31/5	$12.0/0.8M

a) Microwave Engineering only, 10 or more M.S. degrees per year (13 universities).
b) Microwave Engineering only, 8 or more Ph.D. degrees in 3 years (14 universities).
c) Six or more faculty involved in funded Microwave Engineering research (11 universities).
d) $800K or more annual Microwave Engineering research funding (13 universities).

TABLE III
UNDERGRADUATES TAKING MICROWAVE ENGINEERING COURSES

Percent of B.S.E.E. Students	Number of Universities
0–5%	13
6–10%	17
11–20%	13
21–40%	11
41–60%	3
61–99%	2
Required (100%)	7

IV. OTHER MICROWAVE ENGINEERING EDUCATION INFORMATION

It is believed that a number of the difficulties encountered when interpreting the survey responses can be attributed to the fact that Microwave Engineering is not a generally accepted academic describer, nor is it a heading under which administrative data are recorded and summarized. (Antennas and Electromagnetics are considered somewhat more clearly defined and broadly accepted describers, however, they also are normally not used in academic engineering administration.) Accepting that uncertainties were present when responding to the survey, as well as when drawing conclusions, it is desirable to augment the survey's findings with other information sources that can shed further light on U.S. Microwave Engineering activities. This was done using the smaller sample of universities with large Microwave Engineering programs identified in Table I.

Since Microwave Engineering education occurs primarily on the graduate level, broadly used graduate study data were consulted. The first source consulted is a listing of "Areas of Engineering Excellence" [5] of U.S. Graduate Study and Research activities, identified by the universities. Only one of these universities used the words Microwave Engineering. Table IV identifies areas of excellence listed by these universities which most closely correspond to Microwave Engineering.

TABLE IV
ASEE Directory Information

Institution	Related Area(s) of Excellence
Univ. of California, LA	Center for High Frequency Electronics, Joint Services Electronics Program
Univ. of Colorado, Boulder	Optoelectronic Computing, VLSI Tools
Univ. of Connecticut	Systems
Drexel University	Microwave/Lightwave Engineering
Georgia Inst. of Technology	Microelectronics Research Center
Univ. of Massachusetts, Amherst	Microwave Remote Sensing, Microwave Engineering
Univ. of Michigan	Advanced Electronics & Optics
North Carolina State Univ.	Advanced Electronic Materials Processing
Stanford University	None identified
Syracuse University	None identified
Texas A & M University	Electrooptic Laboratory
Univ. of Texas, Arlington	None identified
Univ. of Utah	Microwaves and Electromagnetics
Virginia Poly. Inst. & State Univ.	Communications, Fiber & Electro-Optics

TABLE V
1988/1989 Electromagnetics Survey Data

Institution	Graduate Degrees		Supported Research	
	M.S.[a]	Ph.D[b]	Faculty[c]	Funding[d]
Univ. of California, L.A.	x	x	x	x
Univ. of Colorado, Boulder		x		x
Univ. of Connecticut			x	
Drexel University				
Georgia Inst. of Technology	x		x	x
Univ. of Massachusetts, Amherst	x	x	x	x
Univ. of Michigan	x	x	x	x
North Carolina State University			x	x
Stanford University	not included			
Syracuse University	x	x	x	x
Texas A & M University		x	x	
Univ. of Texas, Arlington	x	x	x	x
Univ. of Utah				x
Virginia Poly. Inst. & State Univ.	x	x	x	x

a) Same cutoff as 1991/1992 survey of Table I.
b) One-third of cutoff of 1991/1992 survey of Table I.
c) Faculty involved in Electromagnetics; used 1991/1992 survey numerical cutoff (Table I).
d) Annual Electromagnetics research funds; used 1991/1992 survey numerical cutoff (Table I).

The information in Table IV supports previous observations in Sections I and II to the effect that Microwave Engineering is a multifaceted realm which draws on several academic disciplines, the specific ones needed being dependent on the application involved. While [5] provides excellent statistical information on enrollment, faculty, and research funding on a departmental and engineering unit level, it is not possible to identify from it these same elements for a single departmental area of activity, such as Microwave Engineering.

U.S. graduate programs and faculty research specialties are also tabulated in Peterson's Guides [6]. However, this source also does not present data on a detail level which would permit identifying only Microwave Engineering activities, or compiling summaries in this field for a group of (or all) U.S. universities. Reference [6] supplies even greater detail than [5] on research areas and facilities of many universities, often listing individual faculty and their research interests. It supplies no information on research funding, but normally supplies enrollment and degree data by organizational units (departmental and/or college).

McIntosh [4] repoerted on "Electromagnetics" activities of U.S. universities, which included most of the universities identified in Tables I and IV. His 1990 report included U.S. universities with strong antenna and nonmicrowave electromagnetic activities. Many of these did not respond to the Microwave Engineering survey. Since there is overlap between these two fields, a tabulation, similar to Table I, based on McIntosh's data may be of interest. This tabulation for the same universities using the same cutoff criteria is shown in Table V. This information generally agrees with the findings of Table I. Note that Table I data reflect 1991/1992 status, while Table V reflects 1988/1989 status. The differences between these tables are not only due to the difference in technical focus of the two surveys, but also due to technology changes and research funding shifts in the intervening years.

Comparing the data of Table II with detailed data available on Electrical Engineering departments of universities in [5] can add further perspective. The information in Table VI covers the same universities as Tables I and II, as well as all reporting universities, for a total of 201.

V. Additional Observations

Information on microwave laboratory instrumentation was reported by 68 universities. This information showed the following:

Fifty nine (87%) had one or more Automatic Network Analyzers, 58 (85%) had one or more Microwave Spectrum Analyzers, 42 (62%) had a Microwave CAD Facility, 36 (53%) reported having a Semiconductor Fabrication Laboratory, and 22 (32%) reported having a Microwave Wafer-Probe Station.

Other equipment reported by a number of respondents included indoor and/or outdoor antenna ranges, anechoic chambers, gigabit data-rate test equipment, and high power test equipment.

As mentioned in Section II, the total education of a Microwave Engineer is influenced by the application area (such as commercial products or national needs) in which the engineer acquires experience. Similarly, one might expect that the source of funds which supports graduate students' education will exert some influence on their overall educational experience. Since most electrical engineering graduate students are supported through graduate student assistantships provided by their department's research funds, the balance between governmental and industrial research support provides a glimpse into this subject.

The author's survey asked for the annual funding level from industry and from governmental agencies. Estimates were acceptable, when exact numbers were not available. Forty-three (43) respondents answered this question. The reported average percent of research funding from industry (21%) and from governmental sources (79%) is considered meaningful information. Since over 80% of this funding was reported by the four largest Microwave Engineering programs, this same information was examined for the 39 remaining smaller university programs. For these universities, the industry/government funding ratio was 28% to 72%. The average annual industry/government/total externally funded research support for one of these 39 universities was determined to be $93/$239/$332K.

It is considered more likely that industrial research support relates to competitively oriented commercial products (for example, communications equipment), while governmental support is more likely to provide the Microwave Engineering student with experience to meet broad public needs (examples here are earth and planetary observation equipment operating at microwave frequencies, nano- and femtosecond instrumentation, ultrasensitive microwave and millimeter-wave devices). To strengthen U.S. Microwave Engineering education's impact on future commercial products will require greater interaction with industry and bringing more "commercial" problems into the classroom. This, in turn, presents a significant educational challenge. While the engineering profession is motivated to constantly create improvements and changes, engineering education, in general, is very conservative and resists changes. Leading educators and industrial executives are seriously addressing this general problem. One interesting proposal involves establishing industrial professorships to expose students to industrial projects and corporate practices early in their educational career and to increase faculty awareness of industry needs and how these can be met through curricular changes in the classroom [7]. The desire for universities and their research to leave a greater impact on commercial, competitive products is not unique to the U.S. For example, in referring to engineering education in the United Kingdom, Duggan [8] states that "... new courses need to be designed with a sensitivity to the marketplace ... ."

Table III illustrates the very limited extent to which U.S. undergraduates are exposed to Microwave Engineering. Those who have contact with foreign graduate student applications are well aware that in other countries, required undergraduate microwave courses are the rule, not a rare exception. Among the factors creating this U.S. undergraduate curriculum de-

TABLE VI
AVERAGE SIZE OF ELECTRICAL ENGINEERING PROGRAMS

Description	Graduate Degrees		Supported Research	
	M.S.	Ph.D.	Faculty	Funding
Average, Table I Universities	102.7[a]	22.3[b]	70.8[c]	$8.7M[d]
Average, all Universities	38.3	7.3	24.1	$2.4M

a) Electrical Engineering M.S. degrees per year (14 universities).
b) Electrical Engineering Ph.D. degrees per year (14 universities).
c) Faculty involved in funded Electrical Engineering research (14 universities).
d) Annual Electrical Engineering reported research funding (14 universities).

emphasis is the rigid curriculum structure, believed to be imposed by ABET requirements, coupled with the hesitancy to make changes which might lead to later accreditation renewal complications. Despite this, a general awareness exists in U.S. engineering circles that major changes need to be made in undergraduate education [9], [10]. Many of the overall changes proposed for undergraduate education are designed to provide more room for electives, and to increase the project/design content of undergraduate engineering programs. It is believed that such flexibility can lead to strengthened Microwave Engineering education.

As was pointed out in the beginning, Microwave Engineering is multifaceted and, as Table IV illustrates, different universities aim to satisfy different technological needs. It is not necessary to improve and update Microwave Engineering education "from the top down," as would be the case in a centrally regulated system, to create educational improvements. Creative grass-roots approaches advancing specific facets can and are generated by both large and smaller Microwave Engineering programs. An example is the Microwave Engineering program at the authors' university, formulated to concurrently develop closer industry ties, and to graduate new microwave engineers who are highly skilled in the very latest MMIC CAD techniques and who also know the practical aspects of formatting their design for foundry processing and of wafer testing a final product. This is accomplished through a 2-year 4-course MMIC sequence. It starts with an Introduction to Microwave Circuit Design course, followed by a Monolithic Microwave IC Design course in the first year. With industry support, MMIC designs are processed through the foundry. In the second year, the student takes a Microwave Measurements course which includes on-wafer testing technology. The sequence ends with an advanced Active Microwave Devices: Principles and Modeling course and/or a course on Microwave Systems Analysis and Design. Since the university's undergraduate program includes two elective courses, a student can complete the first two courses as part of the undergraduate program with proper planning. In this manner, a thorough Microwave Engineering education can be completed within one year of completing the Bachelor's degree. In this program, the student extensively uses the latest commercially available microwave CAD programs, employs Automatic Vector Network Analyzers, and carries out on-wafer and other microwave testing. Additional coursework strengthens the student's mathematical skills and knowledge in related academic disciplines (electromagnetics, semiconductors, network synthesis or analysis, etc.). The student's thesis normally is devoted to a practical problem which is pursued in close contact with industry.

VI. Conclusions

1) Educating a Microwave Engineer involves the following:

a) acquiring academic mathematics and basic and applied science knowledge;

b) acquiring knowledge of applicable design techniques/approaches; and

c) acquiring an understanding of applicable matket forces and/or applicable regulations and restraints.

Universities are strong in providing the first element; the microwave engineer's own initiative, with possible employer assistance, is largely responsible for implementing the other two.

2) The academic part of Microwave Engineering education in the U.S. occurs primarily on the graduate (postbaccalaureate) level. Many Bachelor's degree engineering graduates never encounter Microwave Engineering.

3) Specialization within Microwave Engineering education is considered inevitable.

4) Individual universities associate their programs with different specializations—normally determined by their faculty's research competence and funding.

5) Linkage to governmental, "public service"-oriented applications appears much stronger than linkage to industrial/product applications. The need to strengthen industries' coupling to Microwave Engineering education exists.

6) Recognition that U.S. undergraduate education requires refocusing may lead to significant changes in undergraduate programs. If properly monitored, preplanned, and orchestrated, this could become a major opportunity to strengthen Microwave Engineering education.

7) No "standards" appear to exist to monitor "progress" in Microwave Engineering education. The U.S. has no widely accepted national policy or goals pertaining to Microwave Engineering education. Developing standard definitions to be used by industry, government, academia, and the profession, as well as defining standard types of information that should be recorded and shared to establish and thereafter monitor Microwave Engineering education performance, should be considered.

8) The multifaceted nature of Microwave Engineering, coupled with the relative freedom from external regulating agencies, permits the creation of innovative Microwave Engineering programs at universities of all sizes.

9) The opportunities to strengthen Microwave Engineering education through closer industry/university partnerships should be explored, including industrial professorships and industry-linked course sequences.

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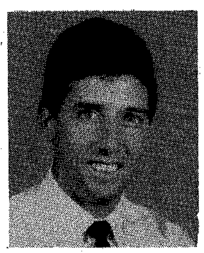

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Dr. Dunleavy's current research emphasizes microwave device measurement and modeling, and computer-aided-design of monolithic microwave integrated circuits. He is also teaching a unique, industry-coupled, senior/graduate level course sequence focusing on microwave integrated circuit design. He is the author or co-author of more than 17 technical papers.