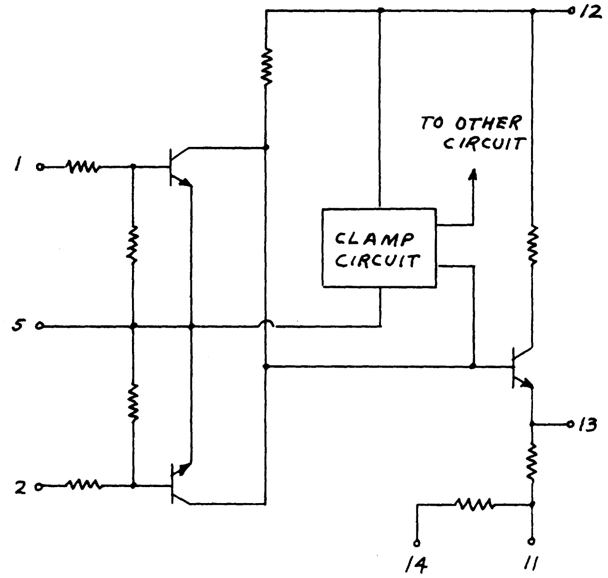

Fig. 3. 9952 NOR gate (one of two circuits in package).

counter problem well. Although we covered a wide range of topics at the project meetings, each student was primarily concerned with his own design problem.

Student Evaluation

Student reaction to the course was highly supportive. Comments submitted with their reports emphasized the learning value of a practical system implementation requiring team effort.

In a university-run evaluation of the course, 13 out of 15 students gave anonymous ratings to 25 separate attributes. On a scale ranging from 1 (strongly disagree) to 5 (strongly agree), the overall average rating was a favorable 4.17. Some sample entries include the following:

The material covered in class was not excessive (Rated 3.08);

What was actually taught conformed to the objectives (Rated 4.54);

My interest in the subject area has been stimulated by this course (Rated 4.42).

EPILOGUE

Over the summer I made the clock operational by rewiring the backplane and repairing broken or loose connections. Given another two to three weeks, my team could have completed the project with little help from me. The returning electrical engineering seniors viewed their working creation with pride ("See that circuit board on the end? That's mine.").

For two months, the clock was on display in our College of Engineering office. It is now kept in my office where it keeps time faithfully and serves as a conversation piece.

There is something special in the way a team project motivates students. It is a worthwhile and realistic experience, which I intend to repeat. However, I plan to make a few changes in the approach I take the next time.

For example, in the clock effort all subsystems were being designed separately and the knowledge gained by each group became narrow and confined. For my next project, all groups will participate in the design of the same subsystem, and when that's done, proceed to the next subsystem. I'll also try to be more careful in choosing a project that can be completed on time.

And what shall the next project be? Well, there's room in the clock cabinet for another sixteen circuit boards. We could provide a month and day readout—and a temperature readout—and chimes on the quarter and half hours—and maybe, for the Bicentennial, a playing of "The Stars and Stripes Forever" at noontime.

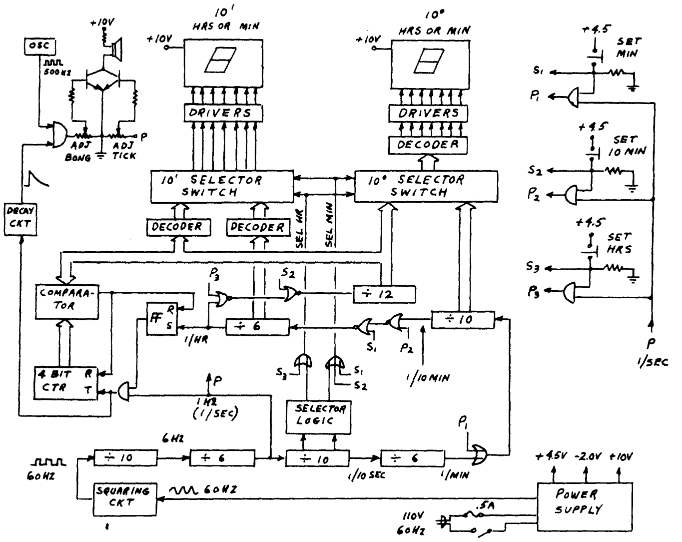

Fig. 4. Final system concept.

A Microwave-Circuits Laboratory with Multilevel Educational Objectives

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***Abstract*—A laboratory based upon circuit synthesis techniques applied to microwave-circuits structures is introduced into the U.S. educational system. This microwave-circuits laboratory serves several educational objectives including teaching, research, and professionalism functions.**

I. INTRODUCTION

The practice of engineering involves many aspects among which are theory, design, construction, testing, and professionalism. These are reflected in education at various levels in the teaching and research activities of our universities. In the U.S. some coupling between theory and experimentation occurs by way of satisfying the ECPD accreditation requirement of integration of analytic and experimental studies [1]. Although there seems to have been some doubt that further integration of the above mentioned engineering activities beyond this basic requirement will adequately satisfy educational objectives, experience in Europe [2] and Africa [3] indicates the possibility. Here we discuss our success in the U.S. where we have introduced the Microwave-Circuits Laboratory as a circuit synthesis based laboratory which simultaneously handles in a coupled manner, research, teaching, project, and professionalism activities.

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II. CHOICE OF TOPIC

Microwave-circuits was chosen for the orientation of the laboratory for several reasons. Among these are our own interests and those of nearby institutions of importance to the state of Maryland. But the primary reason for this choice of topic is the wide range of microwave-circuit applications in engineering such as are found in communications, radar, and biomedical systems. Many of these applications and the associated techniques are well established, but additional information has been and is still developing at a fast rate. Numerous new methods of microwave-circuit design and measurement are evolving continuously with the result that on the average, electrical engineering graduates have little or no knowledge and experience with modern theory and experimental technology applicable to microwave-circuits. It has previously been our experience that recently graduated electrical engineering students often find themselves with a handicap when they are exposed to these concepts and techniques in an industrial environment. Furthermore, senior level circuit synthesis courses have generally been taught with little or no introduction to distributed parameter networks, and with little or no interaction with practical implementations of such circuits in a laboratory. Also, in American university microwave engineering laboratories, swept frequency measurements are rarely introduced, and the concepts and practical use of many important instruments, such as microwave network analyzers, sweep oscillators, digital frequency counters, etc., are seldom made available.

With the above ideas in mind, under the chairmanship of Prof. N. DeClaris the concept was evolved for installing a microwave-circuits laboratory with modern equipment in the Electrical Engineering Department at the University of Maryland. Several purposes can be served by the facility, including:

1) Offering an advanced undergraduate laboratory course in microwave-circuits. A senior level course is being offered which is designed to familiarize the students with the modern methods of microwave-circuit design and measurements.

2) Providing a modern research facility in which both interested faculty and graduate students can perform experimental research work in the microwave-circuits area.

3) Utilizing the laboratory for undergraduate research under the department's unique "Apprenticeship Program."

4) Coupling the research and teaching activities to cross-fertilize and motivate each other.

III. BASIC LABORATORY

The basic equipment was chosen for its versatility and importance in design practice. In the microwave range, activities center around a complete network analyzer, sweep frequency oscillator, digital frequency counter, and spectrum analyzer with the other necessary components to make sweep frequency measurements such as directional couplers, attenuators, isolators, etc. A programmable calculator is included for on-line data reduction and computer-aided design considerations. The frequency range for the laboratory equipment presently installed was chosen initially to include dc through S-band (to 4 GHz). The initial choice of the S-band was made in order to accommodate various types of microwave-circuit technologies (e.g., coaxial, strip lines, microstrip, waveguide, etc.). The circuits designed can be constructed conveniently in the laboratory or in the nearby department workshop without requiring extraordinarily tight tolerances.

Because of the increasing importance of microwave integrated circuits, and biomedical engineering, the laboratory was located next to the integrated circuits and the clinical engineering laboratories. Compared to other research laboratories in the department, the laboratory is small, being 23 X 26 ft with two adjacent walls of the room being reserved for the research and teaching aspects, respectively. A ceiling drop screen accommodates seminar lectures, while reference materials and texts are included in the laboratory's library also housed in the room.

IV. TEACHING ASPECTS

A senior level undergraduate course (ENEE 407) has been initiated and is being offered. The course is organized so that the students get a clear understanding of the theory of operation and a good working knowledge of the equipment. Each experiment is performed after a lecture on its background theory. Some experiments are related and form a continuous sequence at the end of which students are asked to make a report which includes answers to several questions and problems, and the design of components similar to those used in the laboratory. Some circuits are completely designed, built, and tested by the students in the laboratory and then performances are compared to theory. Summary descriptions of some typical experiments are included in Section VI.

A graduate laboratory course (ENEE 609) has also been initiated explicitly for the laboratory as described in Section V.

V. RESEARCH ASPECTS

From the inception of the idea of the Microwave-Circuits Laboratory, research has been an integral part of the laboratory since it is our belief that the research and teaching aspects of such an operation go hand in hand; both being enhanced with a proper mixing. To accomplish this cross-fertilization, our research and project students carry out their experiments in the same room on a shared basis. This permits demonstrations and discussion on an informal basis among the graduate and the undergraduate students taking the ENEE 407 course. Typical research projects undertaken include tuning effects in multiple coupled cavity filters, VCO design, integrated transducers, nonlinear realizability in terms of traditor devices, and MOS clinical classification circuits. Some of the projects are undertaken in conjunction with internationally known experts, as that on neural lines undertaken through a joint American–Polish program.

Closely associated with the research operation is a graduate projects laboratory course, ENEE 609, in which any graduate student may enroll with instructor consent. This initially led to improvement of the undergraduate laboratory experiments, as many of the early projects were related to the efforts of installing the laboratory. But this has also led to thesis research, as for example in the case of new interdigital filter designs and the development of a class of phase-locked structures. In this way the experimentally oriented students have been quite motivated in their graduate studies through the presence of the laboratory; we can also safely say that their enthusiasm has contributed greatly to the success of the undertaking. Indeed this course has proven so popular that it has been taken up by all other areas of the department.

VI. LABORATORY EXPERIMENTS

Initially the experiments listed in Table I have been introduced for the undergraduate laboratory course ENEE 407. These experiments are concerned with passive microwave components and emphasize design aspects, practical construction, and measurements techniques, though with time active circuit experiments are being evolved for inclusion.

The necessary background required for students to take ENEE 407 include basic circuit theory, basic electromagnetic

TABLE I
ENEE 407
LABORATORY EXPERIMENTS

1) Familiarity with sources and equipment:
    a) Signal source;
    b) Sweep oscillator;
    c) Power and SWR meter.
2) Scattering parameter measurement using swept frequency techniques.
3) Horn antenna:
    a) Design;
    b) Construction and testing.
4) Measurement of the equivalent circuit parameters of a microwave cavity resonator.
5) Narrowband waveguide coupled cavity filter:
    a) Theory and design;
    b) Method of tuning;
    c) Measurements of return loss and insertion loss characteristics.
6) Low pass microstrip filter:
    a) Theory and design;
    b) Construction techniques and measurements;
    c) Testing.
7) Interdigital filter:
    a) Theory and design;
    b) Construction techniques;
    c) Testing.
8) Programmable calculator in design:
    a) Computer aided circuit design using the programmable calculator;
    b) Response plots;
    c) Optimization.
9) Use of circulators and isolators in microwave circuit design.

field theory, and electronic circuits. It is preferable that the students taking the course be exposed either previously or concurrently to circuit synthesis which is available at the University as an undergraduate elective. In concluding the experiments students will be asked to look at various professional aspects including ethical and design product liability considerations.

Some of the experiments are interrelated to form a group, since it is felt that a detailed study is important within a particular subject. In the following sections a brief description and discussion of two typical experiments are presented to give a general idea of the nature of the course.

A. Waveguide Cavity Bandpass Filters

Two experiments covering the synthesis and design of waveguide bandpass filters are available. The first experiment considers the basic resonant cavity building block, its characteristics, construction, and measurements. Development of the equivalent circuit model for a certain cavity made from the basic resonator electromagnetic field equations is carried out and the various approximations involved in this development are carefully examined. Then the students experimentally verify the circuit model. Various practical methods of coupling system parameters based on amplitude and on phase measurements [4] are used to characterize the cavity and to obtain practical design curves relating the physical dimensions of the coupling system to its electrical equivalent circuit properties. The cavity used for the experiment is a circular waveguide cavity resonating at about 3 GHz which can be excited in the fundamental TE_{111} resonant mode. A coupling system consisting of a coaxial probe at the center of the cavity length is used. Here some research aspects are introduced since practical measured data on such a coupling system is performed and students are asked to investigate (or develop) a theory with which to compare the measurements.

Once the properties of the basic element (the cavity resonator) are understood, the students are prepared to proceed to the second experiment which provides insight in synthesis and design methods of bandpass filters using resonant cavities. The theoretical part of the experiment begins by studying various realizable filter transfer functions, e.g., the Butterworth, Chebyshev, and the elliptic function types. The methods of realization of these transfer functions using coupled cavities are studied. Both the conventional direct coupled [5] cascaded structures and the more recently introduced multiple coupled structures [6], [7] are analyzed while physical realizations in dual mode waveguide cavities of circular or square cross-sections are considered. Also, realizations in single mode rectangular waveguide cavities are explained [8]. Methods of practical design of these types of filters (e.g., calculations of cavity and coupling slot dimensions) are introduced. Finally, methods of measurement of coupling among certain cavities within the assembled filters are investigated [9]. All of the above concepts are demonstrated experimentally on a dual mode four cavity elliptic function filter previously constructed from circular waveguide resonators. Then the filter is tuned using the measurement technique of [9]. The students finally make swept frequency measurements of the filter response and compare these with the theoretical results.

B. Filters Using Semilumped Elements

Design techniques for filters using semilumped element approximations of distributed transmission lines are considered in an experiment on a low-pass filter constructed in TEM line configurations (coaxial, strip-line, and microstrips). The emphasis in this experiment is on the generality of using the semilumped approximations of the transmission lines to construct microwave components. Effects of the discontinuities in TEM transmission lines due to changes in cross section and the calculation of the equivalent circuit parameters of such discontinuities is an important subject which is introduced at this point and used in presenting practical design considerations [10]. An eight-section Chebyshev low-pass filter previously built in a microstrip configuration is used in this experiment. Swept frequency measurements of the insertion loss and input reflection coefficient (return loss) determine the parameters of primary interest for the designs from which the students are asked to correlate measurements with theory. In addition, designs of other filters with different types of realization are required of the students.

In a like manner descriptions can be given for the other experiments listed in Table I for which the procedures are similar. Other experiments continue to be considered and those presently under development for future incorporation involve active systems and design in the presence of noise. In order to introduce professional considerations into the laboratory we are planning to insert ethical and similar type questions into the design considerations following a philosophy of professionalism discussed in [11].

VII. LABORATORY INITIATION

In order to install the laboratory a special seminar was held during the 1974 Fall term as part of the departmental circuits-area seminar activities. Besides ourselves, all of the interested graduate students as well as some participants from local industry were involved in this seminar. Because of the general unfamiliarity with modern equipment in the GHz range, a student was assigned to each primary piece of equipment at the beginning of the semester. This student then presented the principles of operation and typical uses to the seminar. Since we often found the manuals to be overdetailed and not academically oriented for a first knowledge, these students assisted in preparing educational descriptions of the equipment on which they had become our experts.

With this familiarity available, several students were assigned, as part of independent study, ENEE 609, or their graduate assistantship duties, to help create several of the experiments listed in Table I. In addition, the industrial assistance so far received has been particularly valuable in achieving a practical outlook. Industry and Government research centers have contributed through equipment donation, invited seminar talks in the laboratory on recent advances in microwave-circuits, as well as through consulting with some nearby institutions.

VIII. Discussion and Conclusion

The Microwave-Circuits Laboratory presented in this paper is a unique facility which, by fulfilling several purposes in an integrated manner, demonstrates the feasibility of the multifaceted laboratory concept in the U.S. educational environment. Through close cooperation with industry, the laboratory has been set up to give the students an opportunity to gain important practical design knowledge and experience in a field of considerable engineering significance. It also is a facility which opens up fertile fields for graduate students to generate new ideas and subjects of research. The laboratory has been received with great interest and enthusiam from all the students who have enrolled in it [12]. One of the areas of significant achievements of the laboratory has been to demonstrate that circuit synthesis, which is often considered by most students as a purely theoretical subject, has great value in practical designs.

Nevertheless, as is frequently the case with new concepts, this laboratory has not had enthusiastic reception from the faculty. However, the idea of the multifaceted laboratory is proving to be a useful and successful one and, given the chance, we believe this will be even more so in the future.

Finally we would point out that the original idea for this type of laboratory came after an ECPD evaluation of the curriculum at the University of Maryland showed that more design and integration courses were needed. Certainly we and our students feel this has been a valuable result of the accreditation process and that the Microwave-Circuits Laboratory has become one of the show cases of the department.

Acknowledgment

With pleasure, the authors acknowledge their colleagues and students who have assisted them so much in establishing the Microwave-Circuits Laboratory. They especially wish to point out the assistance of Dr. A. Atia on technical aspects and Prof. N. DeClaris for the administrative drive to implement the educational philosophy.

References

[1] ECPD, 38th Annu. Rep., 1970, p. 66.
[2] T. K. Gaylord, "An economical microelectronics laboratory," *Microelectron.*, vol. 5, no. 1, pp. 3-11, 1973.
[3] "Microwaves flourishing at Stellenbosch," *Pulse*, July 1975.
[4] C. G. Montgomery, "Technique of microwave measurements" (Radiation Laboratory Series, Vol. 11). New York: McGraw-Hill, 1947.
[5] C. B. Cohen, "Direct-coupled-resonator filters," *Proc. IRE*, vol. 45, pp. 187-196, Feb. 1957.
[6] A. E. Atia and A. E. Williams, "Narrow band-pass waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 258-265, Apr. 1972.
[7] A. E. Atia, A. E. Williams, and R. W. Newcomb, "Narrow-band multiple-coupled cavity synthesis," *IEEE Trans. Circuits and Systems*, vol. CAS-21, pp. 649-655, Sept. 1974.
[8] A. E. Atia and A. E. Williams, "Nonminimum phase optimum amplitude band-pass waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 425-431, Apr. 1974.
[9] ——, "Measurements of intercavity couplings," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 519-522, June 1975.
[10] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks and Coupling Structures*. New York: McGraw-Hill, 1964, ch. 7.
[11] R. W. Newcomb and N. DeClaris, "Professional ethics: An engineering educational obligation," to be published.
[12] *Electrical Engineering Department Student Evaluation*, Univ. Maryland, College Park, Spring and Fall 1975.