AMERICAN JOURNAL OF PHYSICS VOLUME 36, NUMBER 6 JUNE 1968

From Hertz to Gigahertz: An Undergraduate Physics–Electronics Laboratory Course*

JOHN E. DRUMHELLER
Department of Physics, Montana State University, Bozeman, Montana
(Received 6 November 1967)

This paper outlines the one-quarter laboratory course taught at Montana State University which offers a series of experimental "sessions" designed to give junior year students experience at all "electronic" frequencies, stressing those in the microwave region. Such a course offers the possibility of including experiments related to electromagnetic theory and optics in addition to teaching practical electronics. A review of recent literature and a list of advanced experiments using much of the same equipment as well as a discussion of the acquisition of equipment and instructors manuals is included.

INTRODUCTION

Described below is a one-quarter laboratory course which is taught in the last part of the junior-year physics curriculum at Montana State University in which the students gain laboratory experience at all practical electronic frequencies.[1] A feature of this course is that a considerable attempt is made throughout to bridge the gap between straight engineering electronics and meaningful physics.

The course is taught in a one-afternoon-per-week session (2-h credit) as the third quarter of a three-quarter "electronic" sequence designed to give adequate preparation for senior-year project or research-type modern physics experiments. The word *session* is used as in each laboratory period several experiments are available, all or some of which may be performed. This is based on the notion that there is no unique set of experiences necessary but that they should be determined to some extent by student interest and instructor desire. This procedure has been found successful in three years of attempt. Such a course, or variations on it, might find use in a wide range of college applications from the first introduction for an upperclass laboratory to providing a bridge between the Berkeley series[2] and advanced experiments. In this vein the notes below provide only an outline or suggestion of a group of experiments to be compatible in a given session. It is intended that the course use, as much as possible, the equipment available in most physics departments. However, the course leans heavily on microwave experiments and may therefore in some cases depend on additional equipment. Many of the components used can be purchased in "training kits" at reduced cost or can be fabricated in the laboratory, perhaps even as student projects. Some of these possibilities will be pointed out below. Many ideas for specific experiments with their proper procedures can be taken from the company equipment manuals or from their "training manual." A list of the companies that have such kits and manuals is included in Appendix I.

I. LABORATORY NOTES

The following notes are a brief outline of the sessions found to be convenient in an eight-week course. This course follows a rather standard introductory quarter in electrical measurements and a quarter of electrical circuits from which additional sessions could be drawn to extend the course to a semester.

Session 1: *Six cycles per second to radio frequency.* The first session is designed to introduce frequency and phase measuring techniques as well as to ensure some competence with oscilloscopes and related laboratory equipment. For example, using line voltage as a frequency reference and introducing Lissajous figures, frequencies from 6 to 600 cps (Hz) can be measured and, using that as a substandard, any laboratory audio oscillator can be calibrated. One may then progress to as high a frequency range as available oscillators or other standards allow. For higher-frequency standards there are many military frequency meters available on surplus such as the BC221. With a

* This material was presented as an invited paper to the Summer Meeting of the American Association of Physics Teachers, 16 June 1966; Am. J. Phys. **35**, 65 (1967).

[1] Another laboratory course that uses this idea has been described recently in a note by Arnold D. Pickar, Am. J. Phys. **35**, 283 (1967).

[2] A. M. Portis, Am. J. Phys. **32**, 458 (1964).

short-wave receiver experience can be gained using WWV as a reference. The most common reference of all, the time base of the oscilloscope, should be stressed.[3]

Session 2: *Harmonic analysis.* Postponing temporarily the advance to higher frequencies, this session provides a vehicle for understanding superposition and experience with Fourier analysis. Harmonic analysis can be accomplished in several ways.

(a) Graphically: A laboratory oscillator is used to overdrive an amplifier and the result is displayed on a slave scope made from a large TV tube so that the students can trace the curve and graphically compute the harmonics.[4]

(b) Electronic: A laboratory wave analyzer such as the Hewlett–Packard model 300A can be used to check the results from above. A modification of this is to sweep the oscillator circuit of any wave analyzer and display the results on a scope. This amounts in practice to building an electronic harmonic analyzer and is instructive for the students.[5]

(c) Computer: The graphical part above can be checked on a computer, providing an interesting computer problem for the enterprising student.

Session 3: *"Almost" microwave.* This session uses frequencies of from 50 to 1000 MHz (GHz) and thus requires rather uncommon laboratory equipment. However, if generators and a slotted line are available in this range, the first physical measurement of wavelength can be made. With a more complete set of General Radio equipment which, for example, includes rf oscillators, coaxial cables, and terminations, one can, in addition, illustrate the physical ideas of impedance and propagation in coaxial transmission lines with the underlying idea that the so-called "electronic" frequencies are electromagnetic waves. The solution to the transmission line can be shown to be in one-to-one correspondence with the wave equation derived from Maxwell's equations. Also, the important technique of beating a local oscillator against the primary of signal oscillator and detecting and amplifying the difference frequency (superheterodyning) is learned.[6]

Session 4: *12-cm microwaves.* Here the range of frequencies more commonly considered microwaves begins and, in the first of these, we have used the standard laboratory CENCO 12-cm apparatus (3 GHz). This session is the most open-ended allowing the students to perform eight or 10 of the experiments in the CENCO laboratory manual—the same experiments that are delightfully described in C. L. Andrews' book.[7] The value here is the explicitness of E- and -M waves in space and the measurement of wavelength, diffraction, and the explicit determination of the phase relation for a reflected standing wave by using the two configurations of diode detectors. With such a wealth of experiments available, it would be easy to add an additional week here in a semester course, perhaps stressing optics experiments only, and possibly eliminating a separate laboratory course in geometrical optics.

Session 5: *Reflex klystron.* From here on the course concentrates entirely on experiments at about 9 GHz (X band), so it is worthwhile concentrating an entire session on the characteristics of a reflex klystron. There are other microwave sources available, but they are impractical or expensive where a suitable 2K25 klystron may be purchased for a few dollars. The procedures may be taken directly from the excellent instruction manuals available from the microwave companies.[8] The larger problem is the power supply. This can be easily fabricated in the laboratory with two standard 300-V dc supplies and the simple control circuit shown in Fig. 1. Modulation may be provided by any laboratory oscillator or by the

[3] See, for example, *The Taylor Manual,* T. B. Brown, Editor-in-Chief (Addison-Wesley Publ. Co., Inc., Reading, Mass., 1961), Secs. 6–20.

[4] An example of this is given in R. S. Sokolnikoff and E. S. Sokolnikoff, *Higher Mathematics for Engineers and Physicists* (McGraw-Hill Book Co., New York, 1941), p. 545; or C. R. Wylie, Jr., *Advanced Engineering Mathematics* (McGraw-Hill Book Co., New York, 1951), p. 542.

[5] The circuit for this is given in "Apparatus Notes," F. J. Blankenburg, Am. J. Phys. **35,** No. 8, v (1967).

[6] Particularly helpful in the rf region as well as later in the microwave measurements is the book by A. L. Lance, *Introduction to Microwave Theory and Measurement* (McGraw-Hill Book Co., New York, 1964).

[7] C. L. Andrews, *Optics of the Electromagnetic Spectrum* (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1960).

[8] A particularly useful manual is that published for the Hewlett-Packard Company: *Microwave Theory and Measurements,* I. L. Kosow, Ed., (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1964).

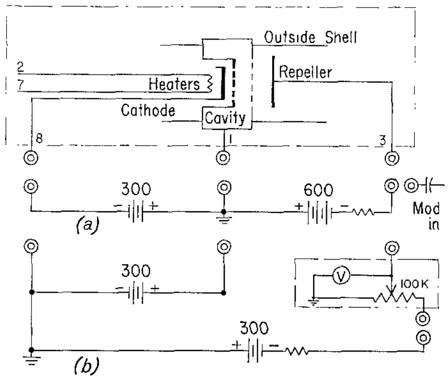

FIG. 1. Schematic of a typical reflex klystron showing: (a) the usual voltages necessary for the operation of many klystrons and (b) a simple arrangement requiring only 300 V dc power supplies. Also shown is a schematic of a simple repeller voltage divider for electronic tuning. The pin numbers on the klystron refer to a 2K25 octal base. Note that in case (b) the outside shell is 300 V above ground and should be carefully shielded.

−175-V sawtooth output from a Tektronix oscilloscope.

Session 6: *X Band I, physics in a waveguide.* The remaining sessions concentrate on the physics and "electronics" at *X* band. Again there are many experiments from which one may draw; electronics-type experiments can be taken from the microwave company manuals mentioned above or from a textbook on microwaves, and the "physics" experiments can be drawn from the literature or from one's own experience. Appendix I gives a list of some suitable experiments that have appeared recently in the *American Journal of Physics.* In our laboratory, the sixth week includes: microwave attenuation in waveguides and coaxial cable, wavelength and standing-wave ratios of several microwave components. In addition, for a laboratory emphasizing electronics, the Smith chart can be introduced as a graphical method of measuring impedance. A particularly interesting side experiment in this session involves the magic tee. Measurements quickly show the student the properties of a hybrid (magic) tee, and it can be demonstrated how the voltage of an incoming wave into any port can be expanded in terms of all the outgoing voltages, introducing the useful idea of a scattering matrix. The student can now experimentally determine the scattering matrix of a simple *H* plane tee, a directional coupler, or any multiport system.

Session 7: *X Band II.* This session contains power measurement, cavity *Q*, and a waveguide cutoff experiment. It is convenient to mount the sides of the split waveguide of the latter on a standard optical bench with a scale on the side so the student can make quantitative measurements. With the preparation in the electromagnetic-theory course, the boundary conditions at the wall of a conductor and the description of the group velocity or waveguide velocity, phase velocity, waveguide wavelength, and the comparison to free space wavelength is very instructive.

Session 8: *Interference.* The last group of experiments is perhaps the most fun for students. This session is reserved for interference phenomena and contains: the Doppler effect, the Michelson interferometer, thin films, Wiener's or similar experiments. The Michelson interferometer also is mounted on an optical bench. The free-space wavelength can now be measured easily and serves as a nice introduction to interferometry. The grid (half-silvered) mirror was made by following the formula given in the CENCO manual and scaling it to 3 cm.[9] The Doppler shift is more popularly received as the "police radar" experiment and is a direct copy that was published recently by Manchester.[10] The Fletcher's trolley was student made and the whole experiment assembled as a project experiment for a graduate lab, but is done with apparent pleasure by the juniors. We were able to improve on Manchester's data by running the trolley much slower and using a scope camera. A stopwatch and meter stick were used as the independent measure of velocity. It is not coincidental that with a trolley velocity of about 10 cm/sec the interference is in the range of 6 cps—just the frequency at which the course was begun eight weeks earlier.

II. APPARATUS

There is almost no limit to the equipment that one could ultimately have in such an undergraduate lab; but a surprising number of electronic and optics experiments can be done on a very modest beginning. As for microwave components, a good beginning is with the inexpensive "kit"

[9] CENCO, "Microwave Optics Demonstration Apparatus," manual prepared by C. L. Andrews.

[10] F. D. Manchester, Am. J. Phys. **33**, 499 (1965).

that has many of the necessary components and with which, of course, the entire X-band portion above can be accomplished. An example of this is CENCO's 3-cm microwave apparatus, which sells for about $375.00.[11] An advantage of such a kit is that it serves as an easy way to get started. A serious disadvantage is that it is often very difficult to get good quantitative results, a problem in many undergraduate laboratories.

The most desirable equipment is that which is of research quality and is nearly a must if the course stresses electronics. In this category are the "microwave training kits" sold by the larger companies. This kind of kit can be purchased in part or, in some cases, as a unit at a reduced price and will include everything necessary except a klystron. Most useful for Sessions 6 and 7 above would be a good slotted line, a standing-wave meter, and a calibrated attenuator. The price tag here is up to $3000.00, but for the most desired items mentioned is about $850.00.

There are a number of components which can be homemade. These include the standard power supplies, or fabricating microwave horns, cavities, or tee joints. This is the cheapest way to supplement and has the additional feature of being more interesting and perhaps providing projects for interested students.[12] Standard waveguide and flanges can be inexpensively purchased from many of the electronic clearing houses or from manufacturers.

III. DISCUSSION

It was found that since there was no specific accompanying lecture course it was necessary to give 30 min or so in each laboratory session to introductory comments. This time was largely spent in attempts to connect the laboratory material to that of the regular lecture courses and, where appropriate, to discuss and demonstrate special experimental details such as the operation of a klystron. Efforts were made to emphasize laboratory techniques and to avoid strictly engineering electronics. It is not clear that these goals were always met, but student response seemed encouraging.

Our own laboratory was fortunate to have rf equipment available which permitted experience with a broad electronic spectrum. This is not necessary, as the microwave portion can stand on its own merits, and there are many ways that any of the sessions can be expanded to fill other sessions if desired. An inexpensive kit is all that is necessary for one group of two or three students to work. With the addition of a klystron and power supply and a few homemade or surplus components, more than one group can work simultaneously on different experiments. Any further addition of equipment, particularly the quality items, very quickly expands the possible sophistication of the course and the number of students a section can accommodate. In fact, with the above equipment available and with the experience gained in such a junior-year course, a wide variety of senior or graduate-level experiments could be performed. Some of these are listed in the Appendix.

[11] Also available from electronic supply houses such as Lectronic Research Laboratories, Philadelphia, Pa.

[12] Recently we purchased a surplus radar set from which we retrieved power supplies, klystron, and sundry waveguide from which a junior laboratory setup was built.

ACKNOWLEDGMENTS

The author is grateful to many colleagues, particularly Professor I. E. Dayton, for many helpful suggestions and criticisms; and to the National Science Foundation for help with equipping the laboratory with the quality equipment through an instructional equipment grant.

APPENDIX

The recent literature, specifically the *American Journal of Physics*, has shown a considerable number of articles and contributed papers in the last few years regarding microwave and related experiments that can be performed in the laboratory by students. These articles listed below are divided into introductory and advanced categories and in addition a list of manuals available from microwave companies is included.

A. References Pertinent to Introductory Microwave Course

A. D. Pickar, "Adaption of Microwave Optic Apparatus," Am. J. Phys. **35**, 283 (1967).

C. L. Andrews, "Demonstration Microwave Interferometers," Am. J. Phys. **33**, 924 (1966).

F. D. Manchester, "Simple Doppler-Shift Apparatus Using Microwave," Am. J. Phys. **33**, 499 (1965).

A. M. Portis, "The Berkeley Physics Laboratory," Am. J. Phys. **32**, 458 (1964).

CENCO, "Apparatus Notes," Am. J. Phys. **32**, No. 3, xix (1964).

B. F. Plybon, "Demonstration of the New Budd–Stanley Microwave Apparatus," Am. J. Phys. **31**, 231 (1963).

J. H. Haynesworth, "Optics Demonstrations with 3-cm Microwaves," Am. J. Phys. **30**, 781 (1962).

C. L. Andrews, "Microwave Doppler Demonstration," Am. J. Phys. **30**, 549 (1962).

T. Brown, "Microwave Zone Plates," Am. J. Phys. **30**, 55 (1962).

E. S. Gravlin and J. A. Cowen, "Simple Microwave Resonance Spectrometer," Am. J. Phys. **27**, 566 (1959).

C. L. Carpenter, "Gouy Phase Advance with Microwaves," Am. J. Phys. **27**, 98 (1959).

R. E. Comely and R. J. Talhaus, "Universal Microwave Probe," Am. J. Phys. **25**, 568 (1957).

C. L. Andrews, "Demonstration of Electromagnetic Waves in Helices," Am. J. Phys. **24**, 11 (1956).

B. References Pertinent to Advanced Experiments with Microwaves

M. Campi and M. Harrison, "Waveguide Analog of Tunneling Through Quantum Potential Barrier," Am. J. Phys. **35**, 133 (1967).

H. N. Rexroad, "A Brown–Twiss Interferometer Experiment at Microwave Frequency," Am. J. Phys. **34**, 285 (1966).

J. A. Guinn and W. L. Kruer, "Interaction of 3-cm Microwaves with a Mercury Plasma," Am. J. Phys. **34**, 286 (1966).

P. L. Hartman, "Laboratory Course at Cornell," Am. J. Phys. **33**, 776 (1965).

J. J. Huppert and G. Ott, "Electromagnetic Analog of the Quantum-Mechanical Tunnel Effect," Am. J. Phys. **34**, 260 (1966). Am. J. Phys. **33**, No. 10, xiii (1965).

J. E. Lawson, "Analogous Behavior of Elementary Particles and Some Microwave and Cavity Systems," Am. J. Phys. **33**, 773 (1965).

R. E. Norberg, "Resource Letter NMR-EPR-1," Am. J. Phys. **33**, 71 (1965).

R. A. Kamper, "Paramagnetic Resonance," Am. J. Phys. **28**, 249 (1960).

C. Manuals

Microwave Theory and Measurement, Hewlett–Packard, 1964, Prentice-Hall, Inc., Englewood Cliffs, N.J.

Microwave Training Kit Manual, Microlab/FXR, 10 Microlab Road, Livingston, N.J. 07039.

Microwave Measurements Manual, Narda Microwave Corp., 1963, Plainview, L. I., N.Y.

PRD Reports, Vols. 1–7, PRD Electronics, 1964, 202 Tillary Street, Brooklyn, N.Y. 11201.

Microwave Optics Demonstration Apparatus, Central Scientific Co., 1700 Irving Park Road, Chicago, Ill.