Production and Absorption of Electromagnetic Waves from 3 cm to 6 mm in Length*

BY NEIL H. WILLIAMS

University of Michigan
Ann Arbor, Michigan

JUST what is meant by short electromagnetic waves depends upon one's point of view. The amateur radio operator thinks of 25 meter waves as short waves, and so, as it became possible to produce waves of one meter length, a new name was invented for them and they were called microwaves. There seems, therefore, no name left that will apply to waves whose lengths are measured in millimeters.

In 1919 Barkhausen and Kurtz described a method of producing radiation having a wave-length less than a meter. They used a three electrode tube with the grid at high potential and the plate at low potential. Work with oscillators of this kind now constitutes a standard experiment in courses on high frequency measurements in many universities. In 1921 A. W. Hull described the magnetron, a two-electrode tube with a magnetic field applied approximately parallel to the filament. He derived the value of the magnetic field which would cause the electrons from the filament to move in a spiral around the filament and just graze the surface of the cylindrical anode. This value is

$$H=(8m/e)^{\frac{1}{2}}V^{\frac{1}{2}}/R.$$

Putting in the value of m/e, this reduces to

$$H=6.72(V)^{\frac{1}{2}}/R,$$

in which V is the potential difference in volts between cathode and anode, and R is the radius of the anode. Hull's experiments showed a sharp cut-off of current when this field was applied. He did not use the tube as an oscillator but merely as a device in which a magnetic field controls the current. The expression for the magnetic field intensity is utilized in determining the approximate intensity of field that is applied to the oscillators which we are about to discuss.

In 1928 and the years immediately following, Yagi and Okabe and others used tubes like those of Hull's as oscillators, and were able to produce continuous radiations having wave-lengths as low as ten cm. These waves should be distinguished from those produced by Nichols and Tear by means of an oscillator using a spark gap. While these waves of Nichols and Tear were extremely short, having lengths as low as 1.8 mm, both the intensity and the wave-length were so variable that it was not possible to use them in researches requiring constant intensity and constant wave-length.

The tube as used at the present time has a split anode as shown in Fig. 1, the two halves of the anode being connected through a short Lecher frame. The anode is held at a potential with reference to the filament of from 500 to 1400 volts, depending upon the wave-length to be produced. The magnetic field is adjusted to very nearly the cut-off value. Any slight increase

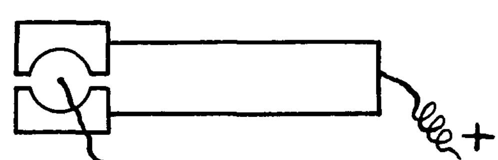

FIG. 1. Diagram of tube with split anode which is used at the present time.

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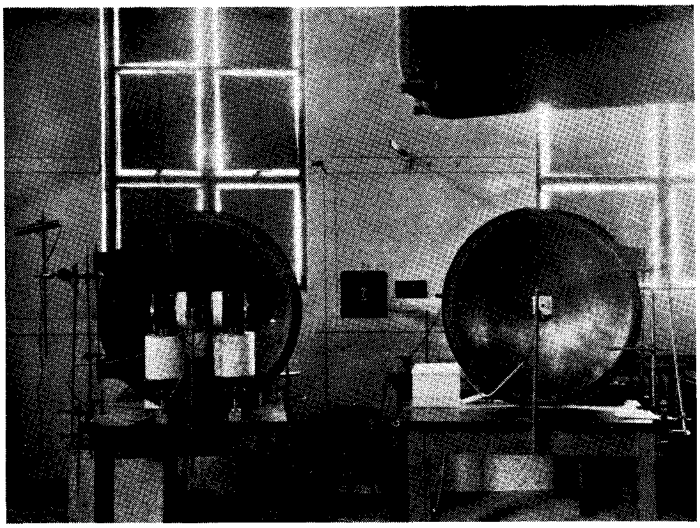

FIG. 2. Source and detector for 1.5 cm electromagnetic waves.

of potential of one-half of the anode will cause the electron stream to be deflected to that half. This lowers the potential of that half and the electrons are repelled to the other half. A surge in the frame connecting the two halves is thus set up. It will be evident that two items enter into the determination of the frequency of the oscillations, *viz.* the time of flight of the electron from one-half of the anode to the other and back, and the time determined by the LC product of the circuit. When these two values are equal, the conditions are right for producing a large amplitude. Okabe reported as the shortest wave that he produced by tubes of this kind, a length of 3.16 cm.

Our own interest in producing short wave radiation grew out of the prediction by Dennison of the Michigan laboratory that ammonia gas should absorb waves 1.5 cm long. Kilgore had worked with tubes at the Westinghouse laboratory that gave considerable power at a wave-length of 9 cm. It seemed reasonable to assume that smaller tubes, operating on higher voltages and with stronger magnetic fields, would oscillate at higher frequency. C. E. Cleeton, at that time a graduate student at Michigan, undertook to build the tubes. He became very expert in this work and finally carried out the research on ammonia gas. The wave-lengths were so near to those that had been used in infrared work that optical methods immediately suggested themselves. The tube was mounted at the focus of a mirror 3 feet in diameter. The radiation was directed across the room to an echelette grating 25 feet away. From there it was reflected to another large mirror and focused upon a crystal detector. Figs. 2 and 3 show this part of the apparatus. A crystal must be used that does not require a voltage bias. Iron pyrite-phosphor-bronze was found to be the best. The grating gave a very satisfactory measurement of the wave-length. The elements of the grating were strips of aluminum $7\frac{1}{2}$ by 70 cm, and there were 18 such strips in the grating. The elements of the grating were automatically adjusted to remain perpendicular to the bisector of the angle between the lines from the center of the grating to the centers of the mirrors. The spectrum was pure and as many as seven orders could be measured. The accuracy of the wave-length measurement was better than one percent. Fig. 4 shows the seven orders of spectra for a wave-

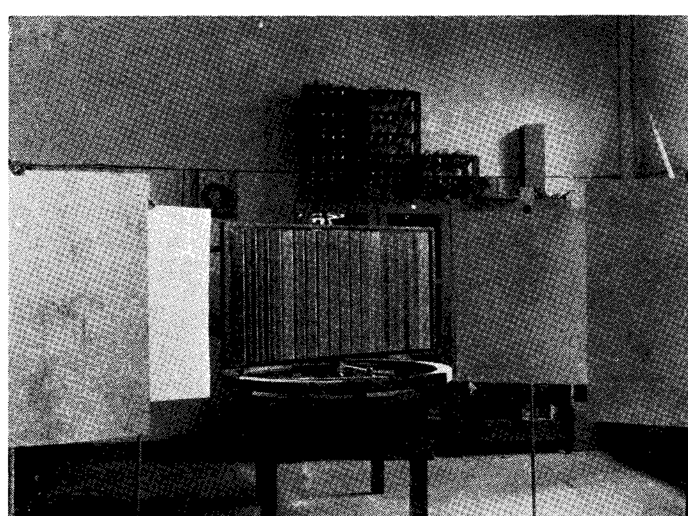

FIG. 3. Echelette grating for 1.5 cm electromagnetic waves.

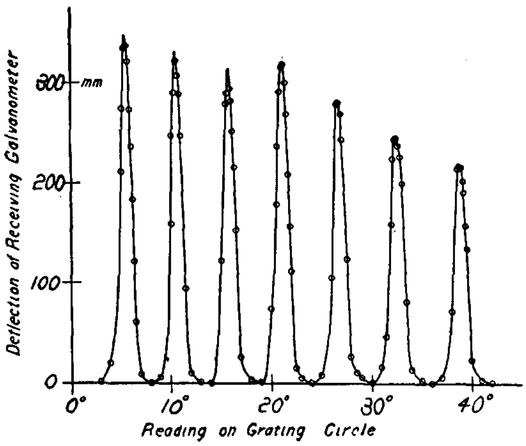

FIG. 4. Seven orders at 1.33 cm as given by the echelette grating.

length of 1.33 cm. This tube had an anode radius of 0.027 cm and required an anode potential of about 800 volts. The Lecher system had a length of about four mm. Each tube could be made to operate over a range covering about 30 percent of the mean frequency. Four tubes were used in making the absorption measurements between wave-lengths of 1.06 and 3.8 cm. To study the absorption due to ammonia gas, a cell somewhat larger than the mirrors and having a thickness of 16 inches was used. This could be lowered in front of the receiving mirror and the absorption observed. After a series of measurements with the ammonia, the cell was filled with air and the small absorption due to the rubber was measured. The ammonia absorption data were then cor-

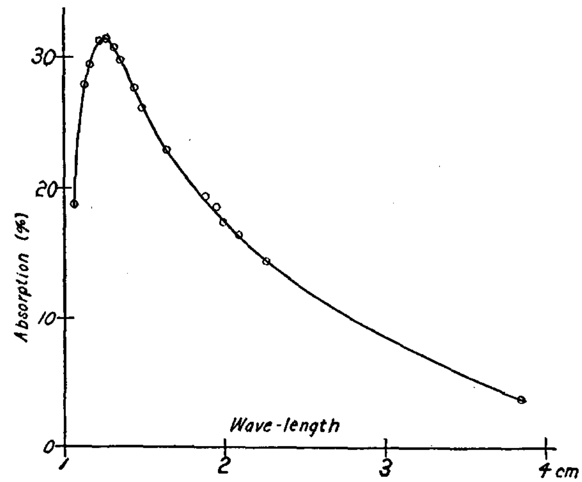

FIG. 6. The absorption band of NH_3 plotted on a wave-length scale.

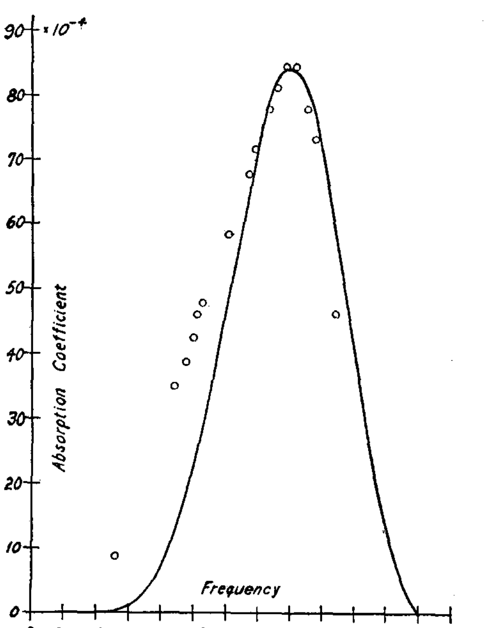

FIG. 5. The theoretical absorption curve for NH_3 and the observed experimental points plotted on a frequency scale.

rected for the absorption due to the cell. The absorption as a function of the frequency is shown in Fig. 5. The maximum absorption occurs very nearly at the point predicted by Dennison. Fig. 6 shows the percentage of absorption as a function of the wave-length.

Dr. Cleeton was still at the Michigan laboratory last summer, and we undertook, at that time, the problem of finding out the practical limit of frequency that may be produced by magnetron tubes. The tubes were already so small that they were difficult to build, but the limit had not been reached. Dr. Cleeton made a number of smaller tubes and the data for some of them are given in Table I. It will be observed that the radius of the anode for the tube giving the shortest wave-length is only 0.2 mm, and that the Lecher system is less than 4 mm in length. The tube was literally built under a microscope. The fact that the radiator is so small of course means that very little energy is radiated. This is sufficient to discourage one from trying to go farther.

TABLE I.

R_a	L	V	H	λ
0.045	0.99	830	6,600	1.87
0.035	0.75	1350	9,900	1.22
0.019	0.38	1200	24,000	0.64

R_a is the anode radius in cm, L is the distance from the filament to the end of the frame, V is the anode potential in volts, H is the magnetic field strength in oersteds, and λ is the wave-length in cm.

Several modifications of the apparatus already described have been made. For example, the magnet and the tube were put behind the mirror and the energy was conducted by concentric conductors through a hole in the mirror to its focus. This avoided covering a large portion of the mirror surface by the magnet, and thus increased the radiation. This apparatus was used in studying the possibilities of modulating the waves. Speech and music were successfully transmitted at a wave-length of a few cm.

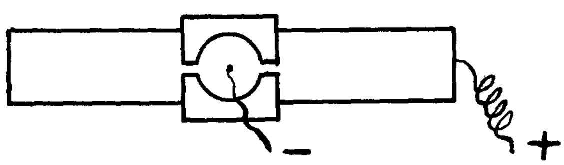

FIG. 7. Diagram of a tube with 2 Lecher systems connected to the halves of the anode.

A change in the design of the tube was also tried. Two Lecher systems were connected to the halves of the anode, so that the tube appeared as in Fig. 7. These tubes worked well but there was no marked improvement in the results.

One of the significant features of the work on short electromagnetic waves is that it opens a new region of the spectrum for quantitative study. Possibly it will not be a very exciting region, since it forms the link between the shorter electric waves and the longer heat radiation, and hence its properties may be estimated by interpolation. Nevertheless, it does allow us to investigate the behavior of matter to a band of frequencies which up until now have been inaccessible. In fact, as has already been mentioned, the strong initial motive for attempting to produce short waves was the desire to test a hypothesis concerning the structure of the ammonia molecule. It had been pointed out by Dennison that there was spectroscopic evidence which indicated that the normal energy state of ammonia might be double. The separation between these levels was about 0.7 cm^{-1} and hence the gas should strongly absorb radiation of 1.4 cm wave-length. As you know, this prediction was beautifully and completely verified by experiment. A cell six times as thick as the ammonia cell was filled with saturated water vapor and put into the path of the rays. Theory would lead us to expect no absorption in this case and none was found. It is now interesting to enquire whether other gases may be expected to absorb in this region. The two energy levels which exist in ammonia are a consequence of the fact that there are two entirely equivalent equilibrium positions for the nitrogen atom separated by a low potential barrier. If we think of the hydrogen atoms as forming an equilateral triangle, the nitrogen atom is not at the center of this triangle but is displaced from the plane of the hydrogen atoms, thus giving the molecule the shape of a pyramid. The equilibrium positions referred to are on opposite sides of this plane. The frequency of the transition is closely related to the ease with which the nitrogen atom can penetrate the barrier, and is a very sensitive function of the molecular dimensions. Thus if the height of the pyramid which represents the ammonia molecule should be decreased by 20 percent, the wave-length corresponding to absorption would change from 1.4 cm to 0.07 cm, which is quite outside the present experimental range. If the height of the pyramid were increased by 20 percent, the absorption wave-length would become 42 cm, which would appear to be easily observable. However, a simple calculation shows that for this type of transition, the absorption is inversely proportional to the square of the wave-length. Thus an absorbing column of gas 1000 or more meters long would be required. The conclusion which we reach is that the molecule of ammonia is ideally designed for an initial experiment on the absorption of short waves. We know of no other molecule which possesses these properties, and it is unlikely that one exists. Even the molecule ND_3 would have too long a wave-length, although possibly NH_2D might fall within the range of observability.

There are, however, other classes of transitions between the energy states of molecules which may be studied. One which suggests itself first results in rotational frequencies. Molecules which are only moderately large, as for example, the methyl halides, will possess rotational frequencies in the region of one cm waves. A knowledge of these would be very useful, since it fixes one of the moments of inertia of the molecule. Professor Dennison has calculated the length of path in the gas which is necessary in order to insure an absorption of 50 percent at the center of the line. He informs me that he finds

$$l=2000(\lambda^3/(M_0)^2),$$

where λ is the wave-length in cm and M_0 is the permanent electric moment of the molecule in units of 10^{-18}. For the methyl halides, $M_0 \simeq 1.5$ and consequently at $\lambda=1$ cm, we should need a path length of 9 meters, while at $\lambda=2$ cm, $l=72$ meters. It is quite evident that no ordinary absorption cell can be used. At the University of Michigan we are now attempting this experiment. We propose to use guided waves where the wave guide will be a conducting tube which will serve as the absorption cell. Clearly the success of our attempt will depend upon just such studies of guided waves as are to be discussed here today.

A second and an interesting field for the application of short waves is the investigation of the absorption and refraction of waves by liquids and solids. Last year Dr. Knerr, working with the apparatus just described, measured the refractive index of water in the region from 4 to 20 cm wave-length. He found that for these waves water shows no measurable dispersion, the index remaining constant at 8. The absorption coefficient, however, increases rapidly as the wave-length decreases. Obviously this research has a bearing upon the theory of liquids, in particular upon Debye's dipole theory. It will be desirable to extend this work to electrolytes and to other liquids which possess dipoles.

In conclusion we may say that the work already done on short waves has been fruitful and it bears promise of becoming increasingly so. A study of the production of the waves sheds light upon phases of the problems of electronics and vacuum tubes. Many interesting questions must be answered before still shorter waves can be obtained. On the other hand we may expect that the waves will furnish us with useful information concerning the structure of molecules as well as concerning molecular aggregates as they occur in liquids and solids.

It is also probable that these very short waves will make important contributions to certain practical problems. They may be used in communication over short distances by means of a directed beam. The frequency band which they represent is so broad that many channels are possible in a narrow range of wave-lengths. Again as a directed beam they may play a role in solving the problem of seeing through fog. However, these are mere speculations and much arduous research would be necessary before results could be realized.

This new ability of man to create, and the new vision it has given us, in turn is creating a new economy—an economy that is putting wealth, in the true sense of greater enjoyment of life, within the reach of millions who never before knew it, that is creating new opportunities for work, new leisure, new health. Above all it is creating new knowledge in the light of which almost nothing stands as impossible.

—C. M. A. Stein