The First Century of Microwaves—1886 to 1986

JOHN H. BRYANT, FELLOW, IEEE

(Invited Paper)

Abstract—The first century of microwaves began with the historic experiments of Heinrich Hertz, between 1886 and 1889, using what are now called microwave circuits and techniques. His remarkably thorough investigations validated the Faraday–Maxwell theory of electromagnetism, opened up the electromagnetic spectrum between dc and light for scientific and practical uses, and opened up a new line of investigation in the ultraviolet. Even so, his was a step-by-step learning process, alternating between experiments and analytical work.

Although Hertz's papers are a model of excellence in technical writing, they are extensive and are difficult to understand, due in part to the hazards of being a pioneer. Nomenclature and ideas that had meaning to him can create unforgiving pitfalls.

Hertz's work and his outlook were that of pure scientific inquiry. He never considered patents or products, yet the results of his work form the basis for a wide range of products and services represented in diverse industries and institutions today.

Hertz's immediate successors in at least nine different countries made advances in techniques and technology, scaling their apparatus to shorter (millimeter) wavelengths in scientific investigations.

The first practical use of Hertz's work in electromagnetics was the wireless telegraphy system. The high-power pulses of RF energy from the Hertzian oscillator could quite readily be formed into dots and dashes of Morse code for the transmitted signal in Marconi's wireless telegraph system (1896). With the need for transmitting increasing amounts of data and information to distant places not accessible to wire or cable, wireless telegraphy experienced rapid growth.

The advent of the triode electron tube, the DeForest audion (1906), led to continuous wave (CW) sources, amplifiers, and detectors by about 1914. This made voice communications possible and, equally important, far better use of the RF spectrum. Radio broadcasting started to replace wireless telegraphy.

Early microwave system applications, centered in communications and early radar experiments, were stimulated by the advent of CW microwave signal sources in the 1920's.

Examples of some of the ensuing advances described in this article are drawn from a search of historical records and from personal correspondence and interviews with some pioneers in microwave devices and applications.

This paper is in two parts. Two of the objectives of Part I are (1) to identify, and establish a uniform nomenclature for, the apparatus used by Hertz in his experiments, and (2) to serve as a guide to the understanding of the work of Hertz in electromagnetics, especially his experiments. Part II covers succeeding work to the early 1940's in outline, with some detail.

Part I: The Work of Hertz in Electromagnetics

I. Introduction

THE MICROWAVE REGION of the electromagnetic spectrum is characterized by the techniques employed and does not have precise wavelength limits. A distinguishing characteristic of microwave circuits is the use of distributed-constant circuits that are related to wavelength in size, in contrast to the use of lumped-constant circuit elements (coils and capacitors) at longer wavelengths.

By modern definition, the microwave range may be considered to be from 30 cm (frequency 1.0 GHz) to 1 mm (frequency 300 GHz). Waves shorter than 1 cm (frequency 30 GHz) are often referred to as millimeter waves, and below 1 mm as submillimeter waves. In modern practice, microwave circuits are usually enclosed within metal boundaries, except for elements intended to act as radiators (antennas).

One incentive to use high frequencies is to get more spectrum space. Beyond that, the principal attraction is the short wavelength. To obtain narrow beam directed radiation, use must be made of an antenna that is large in comparison to the wavelength.

Microwave energy, the propagation of which is practically line of sight, is both reflected and scattered from physical objects. Connected with narrow beams, this makes both directed-wave radio communication and radar feasible.

Although numerous investigators before him inadvertently generated and detected electromagnetic energy [1], Heinrich Hertz was the first to knowledgeably and

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The author is at 1505 Sheridan Drive, Ann Arbor, MI 48104.

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Title	Began Work(1)	Submitted Manuscript	Published(2)	Chapter Number(3)
On very rapid electric oscillations	13 Nov 86	23 Mar 87	15 May 87	2
On an effect of ultraviolet light upon the electric discharge	23 Mar 87	27 May 87	1 July 87	4
On the action of rectilinear electric oscillation upon a neighboring circuit		Feb 88	15 March 88	5
On electromagnetic effects produced by electrical disturbances in insulators	8 Sept 87	5 Nov 87	15 April 88	6
On the finite velocity of propagation of electromagnetic actions	7 Nov 87	21 Jan 88	15 May 88	7
On electromagnetic waves in air and their reflection	2 Mar 88	Apr 88	20 May 88	8
The forces of electric oscillations, treated according to Maxwell's theory	6 Apr 88	Nov 88	15 Dec 88	9
On electric radiation	10 Mar 87	Dec 88	15 Feb 89	11
On the propagation of electric waves by means of wires	7 Nov 87	Mar 89	15 June 89	10
On the relation between electricity and light			20 Sept 89	(4)
On the fundamental equations of electromagnetics for bodies at rest	11 Oct 89	Mar 90	15 July 90	13
On the fundamental equations of electromagnetics for bodies in motion	30 Mar 90	Sept 90	15 Oct 90	14
On the mechanical action of electric waves in wires	16 Feb 89	Jan 91	12 Feb 91	12
Introduction to the reprint book (Note 3)	1892	1892		1

Notes:

1 Dates estimated from entries in the book Memoirs, Letters and Dairies

2 Dates of publication in the periodical Annelen der Physik

3 Chapter numbers in the reprint book Untersuchungen uber die Ausbreitung der Elektrischen Kraft, 1892 English translation Electric Waves, 1893

4 Lecture delivered September 20, 1889 in Heidelberg Published by Emil Strauss in Bonn Reprinted in the book Miscellaneous Papers

Fig. 1. Chronological list of Hertz's experiments and published papers in electromagnetics, 1887–1892.

purposefully do so. He not only comprehended electromagnetic theory, but also found methods to both generate and detect electromagnetic energy. Hertz worked at the threshold of the microwave region, first at about 6 m (50 MHz frequency), then 70 cm wavelength (430 MHz) so that his apparatus would fit into the confines of his laboratory. Hertz's resonant circuits were distributed circuits (he termed them open circuits): the balanced half-wave dipole and the half-wavelength loop containing a small gap.

Hertz's experiments, interspersed with his analytical work, in the period from 1886 to 1889 resulted in no less than 14 published papers. This was a step-by-step discovery process which validated the Faraday/Maxwell theory of electromagnetism. Hertz's work opened up the entire radio spectrum from dc to light for scientific and practical uses and opened up a new line of investigation in the ultraviolet.

Fig. 1 lists 14 papers by Hertz, arranged in the order of their appearance. They are shown primarily for three significant sets of dates. Looking at the three columns on the right, *Began Work*, *Submitted Manuscript*, and *Published*, we can envy the fast turnaround in publication. We can't do that today, with our peer review system. Hertz could have used some peer review. He published a few mistakes, which are part and parcel of all development work. The important thing is that they did not impede his work.

The first significant date to note is 13 November 1886, when he started successful experiments in electromagnetics. The next date to note, 5 November 1887, paper #4, reports on work to experimentally demonstrate the validity of the Faraday/Maxwell theory of electromagnetism. This was done in response to the Berlin prize problem pointed out to him by Hermann von Helmholtz in 1879.

The year 1888 is highly significant due to the response to Hertz's paper #6, published 20 May 1888. With the expression "waves in air" in the title, this paper caught the attention of the technical public. Before that, almost no one read Hertz's papers and he had virtually no correspondence outside Germany. Two things happened after the publication of paper #6: (1) Hertz started correspondence with scientists outside of Germany (Oliver J. Lodge, George F. Fitzgerald and Oliver Heaviside in Great Britain, Edouard Sarasin and Lucien de la Rive in Switzerland, and J. H. Poincare in France), and (2) before the year 1888 was over Hertz's results had been verified by scientists in several countries (Lodge and Howard in England, Fitzgerald and F. T. Trouten in Ireland, and Sarasin and de la Rive in Switzerland).

1988 — A Hertz Centennial

The collection of apparatus shown in Fig. 2 is 100 years old. It includes signal sources, receivers, and other test apparatus built and used by Heinrich Hertz at the Technical Institute of Karlsruhe (now the University of Karlsruhe), along with items of laboratory apparatus, to experimentally validate the Faraday/Maxwell theory of electromagnetism. Hertz did that and much more.

At its 1988 International Microwave Symposium (May 25–27) in New York—100 years after the publication of Hertz's "waves in air" paper—the IEEE Microwave Theory and Techniques Society (MTT-S) is observing the centennial with an exhibit and a special session of five papers [2]–[6].

Hertz's original apparatus was donated to the Deutsches Museum in Munich, where it remains today. Around 1929 a model maker, Julius Orth, in Munich made three sets of replicas. One set went to the Science Museum in London, one to Berlin (present status unknown), and one to Chicago for showing at the 1933 World's Fair. After the fair, the Chicago set went to the Museum of Science and Industry in Chicago, where about half of the items remain today.

The set owned by the Science Museum (London) is intact and will be on loan to MTT-S. At the Symposium, both the exhibit and the Exhibit Catalog [7] will show the apparatus laid out in Hertz's step-by-step discovery process. Following the Symposium the exhibit will be moved to the MIT Museum in Cambridge, Massachusetts, where it will be shown through the summer and fall of 1988 before being returned to the Science Museum.

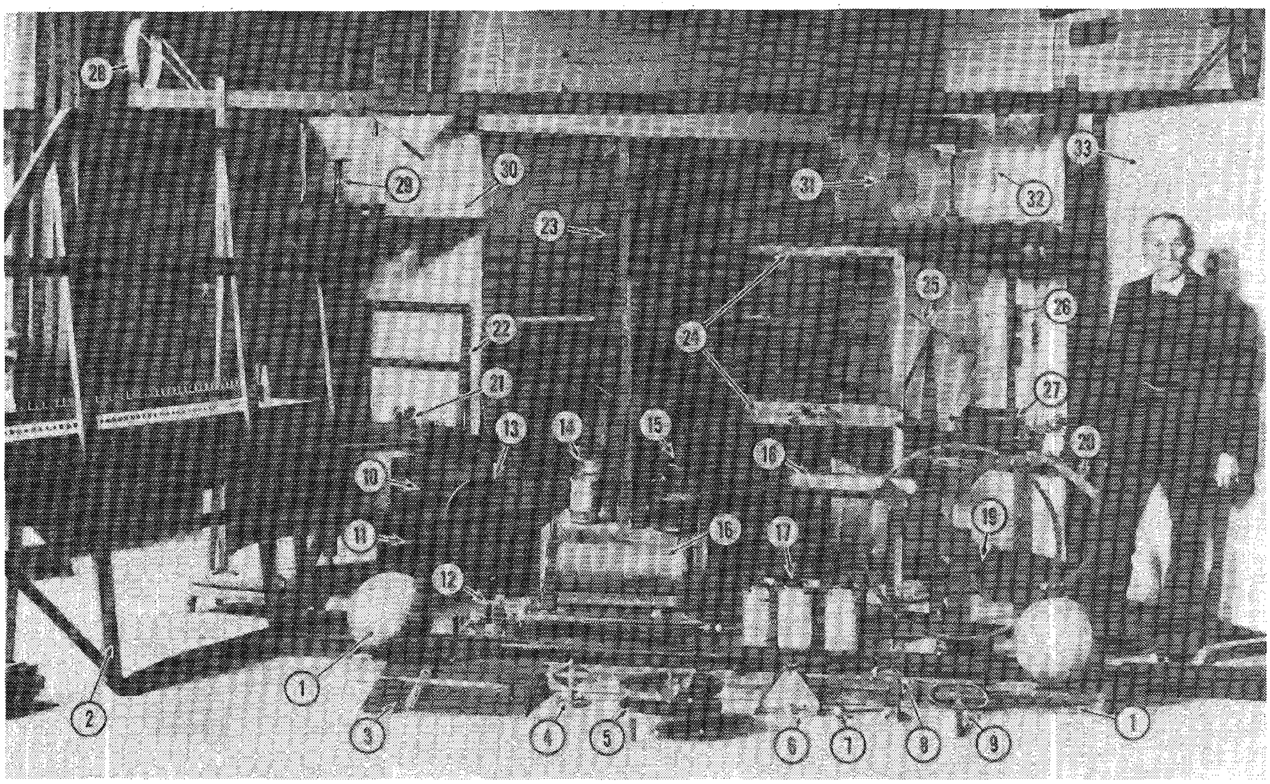

Fig. 2. Photograph of originals of apparatus built by Heinrich Hertz for his electromagnetics experiments, along with items of laboratory apparatus: *1* First oscillator/radiator transmitter, signal source, 6 m wavelength. *2* Wooden frame and parallel wires for polarization demonstration, both transmission and reflection. *3* Possibly a demountable vacuum apparatus for cathode-ray experiments. *4* Hot-wire galvanometer. *5* A pair of Reiss or Knochenhauer spirals. *6* Rolled-paper electroscope. *7* Metal sphere with insulated handle. *8* Reiss's spark micrometer. *9* Receiver/detector used with coaxial line, 6 m wavelength. *10*, *11*, & *13* Apparatus to demonstrate dielectric polarization effects in insulators, 3 m wavelength. *12* Mercury interrupter. *14* Meidinger cell (primary battery), same chemistry as the Daniell cell. *15* Bell jar, photoelectric effect experiments. *16* Induction coil. *17* Bunsen cells (primary batteries). *18* Large-area conductor, insulated for high voltage, used for storing electric charge; variously referred to as the "primary" conductor of a high-voltage electrostatic machine, or as a "capacitor." *19* Circular-loop receiver/detector, 6 m wavelength. *20* Receiver/detector, not otherwise identified. *21* Rotating mirror and mercury interrupter assembly. *22* Square-loop receiver/detector, 6 m wavelength. *23* Stack of three wedge-shaped wooden boxes to hold dielectric material for refraction demonstration and dielectric constant measurement. *24* An assembly of two square-loop receiver/detectors, 6 m wavelength. *25* Square-loop receiver/detector, 6 m wavelength. *26* Transmitter dipole, 70 cm wavelength. *27* Induction coil. *28* Coaxial line. *29* Discharging table similar to a Henley's discharger. 30 Cylindrical parabolic reflector, receiver/detector, 70 cm wavelength. *31* Cylindrical parabolic reflector, transmitter, 70 cm wavelength. *32* Circular-loop receiver/detector, 3 m wavelength. *33* Plane metal reflector. Photograph taken on 1 October 1913 in the auditory of the Bavarian Academy of Science, in Munich (Courtesy of the Museum of Science and Industry, Chicago). The individual in the photograph is not identified, but possibly he was an employee of the Deutsches Museum.

Hertz's unusual grasp of theory, added to his insight, enabled him to translate theory into concepts. With equally unusual abilities as an experimenter, Hertz transformed concepts into apparatus and conducted some of the most important experiments in the history of science. Hertz's experiments were the first knowledgeable and purposeful use of the RF spectrum. He first had to learn how to generate and detect electric waves. His progress led him to use distributed circuits, at 50 MHz (6 m wavelength), 100 MHz (3 m wavelength), and later at 430 MHz (70 cm wavelength).

The items of apparatus designed by Hertz and built by an assistant and himself are notably elegant in their simplicity and functional capability. For the most part they were built of inexpensive materials: metal sheet and wire, wood, glass, string, and sealing wax. A comparison of the replicas with the originals speaks for the replicas as representative of the original pieces in size, shape, construction, and therefore in functional detail.

II. Background

In 1864 James Clerk Maxwell (1831–1879) produced a thoroughly new way of thinking about electricity and magnetism. It incorporated almost all prior results and placed them in a novel context, in the universal language of mathematics—in the form of equations—Maxwell's equations. A solution to the equations is periodic in space and in time, in other words, a wave. The velocity of the wave is given by the product of wavelength times frequency. A numerical value for the velocity also comes from the solution: 3×10^8 meters per second. It was recognized that this was close to the velocity of light, which had been measured to within a few percent of the value accepted today.

There was a 22-year interval between the delivery of the paper "On a Dynamical Theory of the Electromagnetic Field" by Maxwell in 1864 [8] and the start of successful experiments in November 1886 by Heinrich Hertz

(1857–1894) to validate the theory [9]. Public recognition of Hertz's results came in mid-1888 on publication of his paper with "waves in air" in the title [10].

Maxwell's theory says that energy can be transported through dielectrics, including empty space, at a finite velocity by electric and magnetic fields traveling together in space at right angles to each other and both at right angles to the direction of travel. Maxwell never published a proposed experiment to validate his radical theory, opposed by most scientists. According to Maxwell what happened in space far from conductors was a key to his theory, in direct opposition to the generally accepted theory of action-at-a-distance with infinite velocity of propagation. A few scientists tried to understand Maxwell but had difficulty understanding what he said, much less comprehending what the equations implied.

Hertz's Career

Hertz started out to be an engineer. On graduation from the gymnasium (high school) in 1875 he went to Frankfurt to work for an engineering firm. In April 1876 he enrolled in engineering at the Technical University of Dresden, but left on 30 September 1876 for his year of mandatory military service—with the First Railway Guards Regiment in Berlin.

He went to Munich in October 1877 to enroll in engineering at the Technical University, but quickly decided that he preferred the natural sciences to the engineering sciences. He enrolled in physics at the University of Munich, and also took courses at the Technical University. In October 1878 Hertz transferred to the University of Berlin and studied under Hermann von Helmholtz and Gustav Kirchhoff.

Paving the Way to Understanding and Using Maxwell's Work: The Berlin Prize Problem

Helmholtz had been trying to understand Maxwell's theory of electromagnetism and to compare it with a theory, based mostly on Newtonian mechanics, attributed especially to Fritz Neumann and Wilhelm E. Weber in Germany. In 1879 Helmholtz called for an experimental validation of Maxwell's theory and had it published as a prize problem of the Prussian Academy of Science (Berlin) in 1879 [11], often referred to as the *Berlin prize*. The translated full text is as follows:

> Mr. Mommsen, the presiding secretary for the day, opened the meeting with the speech of the day. He spoke on Leibniz's importance as a historian and on his achievements in the publication of source material and in historiography. Mr. du Bois-Reymond gave a report on the prize in the physical-mathematical class which is to be paid out of the Ellert legacy. The Academy poses the following question for the 1882 prize: The theory of electrodynamics which was brought forth by Faraday and was mathematically executed by Mr. Cl. Maxwell presupposed that the formation and disappearance of the dielectric polarization in insulating media—as well as in space—is a process that has the same electrodynamic effects as an electrical current and that this process, just like a current, can be excited by electrodynamically induced forces. According to that theory, the intensity of the mentioned current would have to be assumed equal to the intensity of the current that charges the contact surfaces of the conductor. The Academy demands that decisive experimental proof be supplied either
>
> > for or against the existence of electrodynamic effects of forming or disappearing dielectric polarization in the intensity as assumed by Maxwell
>
> or
>
> > for or against the excitation of dielectric polarization in insulating media by magnetically or electrodynamically induced electromotive forces.
>
> Answers to this question have to be submitted by March 1, 1882. Submissions may, at the author's discretion, be written in German, Latin, French, or English. Each submission has to bear a motto which must be repeated outside of a sealed envelope containing the author's name. The prize of 100 ducats = 955 marks will be awarded at the public meeting of the Academy on the Leibniz anniversary in July 1882.

Helmholtz thought that one of his students, Heinrich Hertz, would be the most likely to succeed in experimentation. In 1892 Hertz wrote:

> As I was at the time [1879] engaged upon electromagnetic researches at the Physical Institute in Berlin, Herr von Helmholtz drew my attention to this problem, and promised that I should have the assistance of the Institute in case I decided to take up the work. I reflected on the problem, and considered what results might be expected under favorable conditions by using the oscillations of Leyden jars or of open induction coils. The conclusion at which I arrived was certainly not what I had wished for; it appeared that any decided effect could scarcely be hoped for, but only an action lying just within the limits of observation. I therefore gave up the idea of working at the problem; nor am I aware that it has been attacked by anyone else. But in spite of having abandoned the solution at that time, I still felt ambitious to discover it by some other method; and my interest in everything connected with electric oscillations had become keener. It was scarcely possible that I should overlook any new form of such oscillations, in case a happy chance should bring such to my notice [12].

Hertz did an analytical thesis on the induced currents in a rotating metal sphere in a magnetic field [13] and obtained his doctorate in 1880. Numerous entries in his diary [14] show that he did in fact give a great deal of thought to electromagnetics in the intervening years to 1886.

After graduation in 1880, Hertz stayed on as an assistant to Helmholtz for three years, then went to the University of Kiel as an instructor in theoretical physics. At Kiel, Hertz had no laboratory, and was very impatient working only in theoretical physics. Even as a boy he had had his own home workshop. Hertz built instruments and was very interested in experimentation, remaining equally skilled at both experimentation and analytical work.

In 1884, at Kiel, Hertz published a significant paper, "On the Relations between Maxwell's Fundamental Electromagnetic Equations and the Fundamental Equations of the Opposing Electromagnetics." It led him to believe more strongly in Maxwell's theory, and gained recognition from his superiors. In the 1884 paper, he concluded that if he had to make a choice, he would choose Maxwell's theory: "I have attempted to demonstrate the truth of Maxwell's equations by starting from premises which are generally admitted in the opposing system of electromagnetics, and by using propositions which are familiar in it. Consequently I have made use of conceptions of [the opposing theory]; but, excepting in this connection, the deduction given is in no sense to be regarded as a rigid proof that Maxwell's system is the only possible one. It does not seem possible to deduce such a proof from our premises.... I think, however, that from the preceding we may infer without error that if the choice rests only between the usual system of electromagnetics and Maxwell's, the latter is certainly to be preferred...." He went on to give reasons [15]. This paper helped him get his next and most important appointment, at Karlsruhe in 1885.

On 29 March 1885 Hertz moved to Karlsruhe as a professor. Here his life changed. He had his own department, including a laboratory, shop, and some staff [16]. On 31 July 1886 he married Elizabeth Doll, the daughter of a faculty colleague, and started successful electromagnetic experiments later that year.

III. Discovery by Hertz of Method to Both Generate and Detect Electromagnetic Energy (Electric Waves)

Among the equipment in the laboratory at Karlsruhe was a set of Knochenauer spirals (Fig. 3). They are flat spiral coils of copper wire, with no iron present. While experimenting with this apparatus, Hertz discovered how to generate and detect electromagnetic energy.

At each end of these two coils are spherical balls. If a battery is connected across the top terminals and then the circuit is opened, a spark occurs. The eye sees and the ear hears a spark, but human senses are not fast enough to know that the discharge is oscillatory. However, each time that a spark was drawn at the top coil, which Hertz referred to as the *primary*, a spark simultaneously occurred across the close-spaced terminals of the bottom coil, the *secondary*. A further observation convinced him that he was on the right track: "At first I thought the electrical disturbances would be too turbulent and irregular to be of any further use; but when I discovered the existence of a neutral point in the middle of a side-conductor, and therefore of a clear and orderly phenomenon, I felt convinced that the problem of the Berlin Academy was now capable of solution" [17].

According to Hertz [18], the typical frequency of oscillation of a laboratory coil is around 10 kHz (wavelength 3 km), and for a typical laboratory capacitor (Fig. 4), known as a Leyden jar, about 1 MHz (300 m wavelength). Even the latter wavelength was much too long for apparatus to be used in the laboratory. Hertz needed a signal source and detector operating at a much higher frequency.

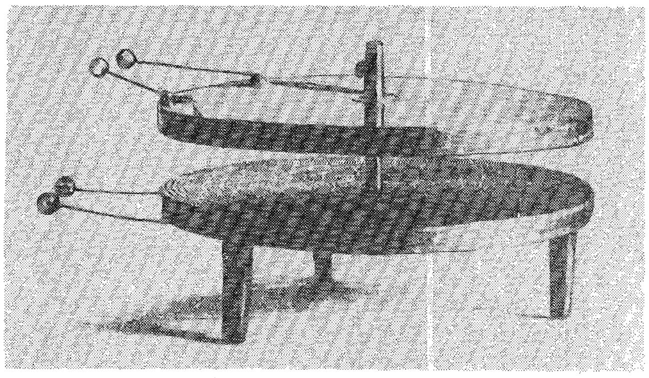

Fig. 3. A set of Knochenauer or Reis spirals, typical.

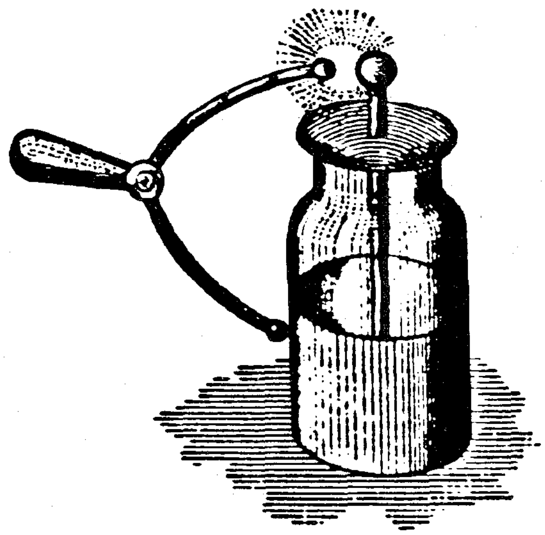

Fig. 4. Discharge of a Leyden jar capacitor.

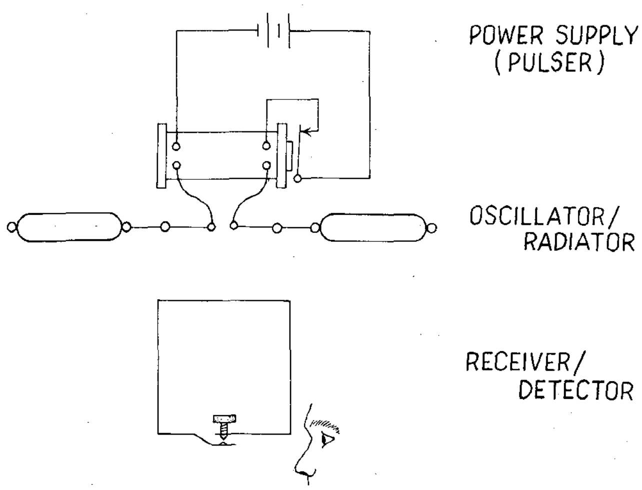

Fig. 5. Schematic of Hertz's transmitter and receiver, using distributed or *open circuits*. (Adapted from Hertz.)

First RF Circuits and Their Use, Concept

For his high-frequency apparatus, Hertz invented "open" or distributed (microwave) resonant circuits (Fig. 5) [19]. He referred to the RF circuit arrangement as a transformer, reminiscent of the two flat spirals. The oscillator/radiator, or signal source, which he termed the *primary*, is

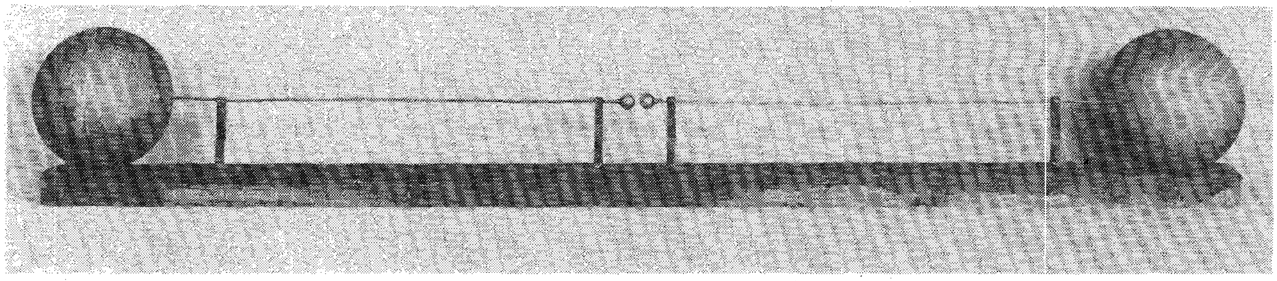

Fig. 6. Hertz's first oscillator/transmitter. The frequency of this oscillator can be tuned somewhat by sliding the spheres in or out along the rods. (Courtesy of the Deutsches Museum, Munich—original.)

a balanced half-wave dipole. In the center of the dipole is a spark gap that functions only as a very fast acting switch. Above the dipole is an induction coil and battery. These supply high-voltage pulses of dc potential energy which are converted to RF energy by the oscillatory motion of current flowing on the surface of the dipole.

Hertz called the receiver/detector the *secondary*, and sometimes the *resonator*. It is a half-wavelength resonant loop, fitted with a tiny adjustable spark gap to detect the presence and the magnitude of RF energy radiated by the primary. The primary and the secondary are linked by the electromagnetic fields in the free space.

IV. The Hertzian Oscillator/Radiator Transmitter [20]

Hertz's first oscillator/transmitter (Fig. 6) makes use of a resonant circuit that consists of a blanced half-wavelength dipole, capacitively loaded by the rather large (30 cm diam.) spheres made of zinc sheet. The frequency is about 50 MHz, the wavelength 6 m, and the half-wavelength 3 m. The overall length is about 2 m, with the shortening from 3 m to 2 m accounted for by the capacitive loading of the conducting spheres. The spherical balls in the center, which divide the dipole in half, are used as a very fast acting switch.

Power Supply

For a power supply to furnish electrical energy to be converted into radio frequency (RF) energy, Hertz used available technology. The principle of the transformer had been known for about 50 years—from the work of Michael Faraday and Joseph Henry. The induction coil, a transformer with a primary of a few turns of heavy wire and secondary of many turns of smaller wire, was a common piece of laboratory apparatus. Electrical energy from the battery is transformed into a high-voltage dc pulse at the output terminals of the induction coil each time the interrupter breaks the circuit of the induction coil primary. Some induction coils are fitted with an electromechanical vibrator to interrupt the current. Another common form of interrupter used was a solenoid-operated mercury switch, referred to as a mercury interrupter. The output terminals of the induction coil are connected across the dipole.

Operating Mechanism of the Hertzian Oscillator

When current flowing in the primary of the induction coil is interrupted, the resulting dc voltage pulse across the secondary rises, charging the capacitance of the dipole until voltage breakdown occurs across the central spark gap. The resulting arc connects the two parts of the dipole. If the arc develops fast enough (in a very small fraction of a cycle), the opposite ends of the dipole are momentarily of opposite charge (+ and −), and the electric field between the two ends of the dipole is maximum. When the gap breaks down, the arc has very low resistance. The quantity of stored energy at that point is the product of the voltage squared at breakdown and the capacitance of the resonant circuit (the dipole). The charge starts to redistribute itself, but cannot do so immediately owing to inductive forces on the resulting current flow. At the end of one quarter-cycle the charge has redistributed to zero, the current flow has reached maximum, and the energy is in the surrounding magnetic field. The electric field has gone to zero.

The magnetic field starts to collapse, further driving the current in the same direction as before and charging the dipole in the opposite direction until the end of one half-cycle. The energy is again in the electric field. The voltage between the dipole halves again breaks down the central spark gap, but in the opposite direction to that of a half-cycle before, and current flows. The charge thus flows back and forth in simple harmonic motion as the energy alternates between electric and magnetic—except that during each half-cycle a *percentage* of the energy present is radiated as RF energy. The percentage radiated each half-cycle depends on the configuration of the radiating element. For a dipole it is about 15 percent. One therefore gets about five half-cycles of detectable RF energy from each pulse.

For a given wavelength, the only means for increasing the input power is to increase the voltage of the pulse (up to a certain point, by widening of the spark gap so that it will break down at a higher voltage). In practice, the switching arc pits the spark gap electrodes, necessitating frequent polishing. The sharp edges of the pits result in high fields that leak off the charge prematurely, causing erratic operation or failure of the transmitter to operate.

In subsequent experiments Hertz used apparatus operating at 3 m wavelength, and at 70 cm.

Output Waveform

The typical output voltage waveform of a Hertzian oscillator is a damped sine wave. The damping is due mostly to radiation, since radiation losses are much greater than circuit losses. The resulting pulse of RF energy is very short.

Frequency Spectrum of RF Pulses

The relation of amplitude in time and amplitude in frequency is defined mathematically by the Fourier transform. A very short pulse of RF energy results in a very wide RF frequency spectrum, a long pulse in a narrow spectrum.

V. The Hertzian Receiver/Detector [21]

Hertz's first receiver (Fig. 7) for use with the 6 m transmitter makes use of a resonant circuit consisting of a rectangular loop of wire with a small gap. At resonance the loop is electrically one half-wavelength long and the voltage across the ends of the loop is maximum.

For a detector, Hertz fitted a tiny, adjustable spark gap across the ends of the loop to act as a voltmeter to detect the presence (and indicate the magnitude) of electromagnetic fields. The loop is polarized, with the plane of polarization in line with the gap. It is therefore a vector voltmeter, since the loop has direction sense and the length of the gap that will just break down is a measure of the RF voltage across the gap and therefore of the field strength. Note the mounting for optics used for observing the small spark gap. The breakdown voltage for even a tiny gap is at least 300 volts, so that a great deal of power is involved in producing even the tiniest visible sparks.

Hertz tried a classic detector, first used by Galvani in 1800, but got no result: "Acting on friendly advice, I have tried to replace the spark gap...by a frog's leg prepared for detecting [dc] currents; but this arrangement which is so delicate under other conditions does not seem to be adapted for these purposes" [22]. In his earliest experiments, Hertz had noted: "No physiological effects...could be detected; the secondary [receiver] circuit could be touched or completed through the body without experiencing any shock" [23].

Fig. 8 shows a 6 m wavelength circular configuration of his receiver, as used in the "waves in air" experiments. Hertz later used circular configurations of his receiver at 3 m and 70 cm wavelengths, and used a dipole at 70 cm wavelength.

VI. Experiments in Resonance, Coupled Circuits [24]

Fig. 9 illustrates an experiment in resonance. Keeping the signal source configuration constant, thus fixing the frequency, Hertz tuned the receiver over a wide range in wavelength by changing the overall length of the detector loop. He measured the maximum detector gap spacing that would just break down, a measure of the RF voltage across the gap. The shape of the curve is probably somewhat distorted due to frequency pulling of the source as the receiver was tuned. At resonance Hertz was able to get a 3 mm spark gap to break down. He could detect spacing down to 3/10 mm—a voltage ratio of 10 to 1, or 20 dB.

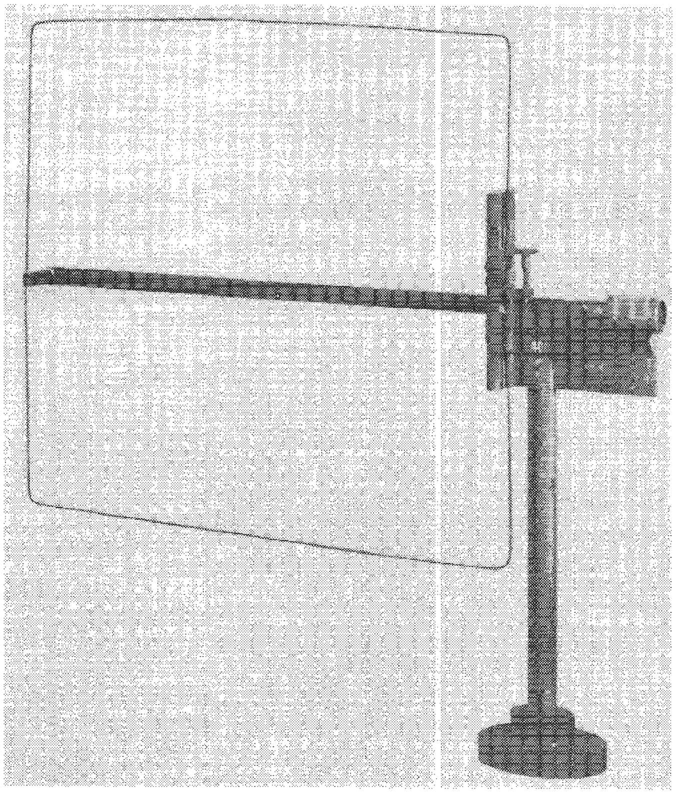

Fig. 7. Hertz's first receiver/detector. When the loop is electrically one half-wavelength long, the voltage across the tiny spark gap is maximum. The maximum length of the detector spark gap that will just break down is a measure of the RF voltage across the gap, and therefore of the RF field strength. The loop is polarized, with the plane of polarization in line with the gap. The peripheral length of the loop is about 240 cm. (Courtesy of the Deutsches Museum—original.)

Transmitter and Two Coupled Circuits (Receivers)

Fig. 10 is a photograph taken in a laboratory of Hertz's Physical Institute at Karlsruhe, circa 1887 [25]. On the table at the left may be seen the induction coil, used to produce pulses of dc potential energy that is converted into RF energy by the transmitter, and the manner in which it is connected to the transmitter. On the near table is the transmitter and two rectangular-loop receivers.

In the middle of the loop on the right notice the metal sphere mounted on an insulated handle, used to probe (disturb) the fields on each loop and demonstrate resonance. At the nodal points on *cd* and *gh* (Fig. 11) there is no disturbance when the sphere touches the wire. Continuing around the loop, sparks can be drawn from the wire and simultaneously sparks in the detector gap are diminished. The effect increases and is maximum by the detector gaps *1–2* or *3–4*.

VII. Discovery of the Photoelectric Effect [26]

From the start of his experiments, Hertz had been bothered by a phenomenon that gave an erratic effect on the detector spark gap. Whenever it was exposed to direct view of the transmitter spark the maximum spark length was always increased. This was especially a problem in the experiment on resonance in which he needed to measure

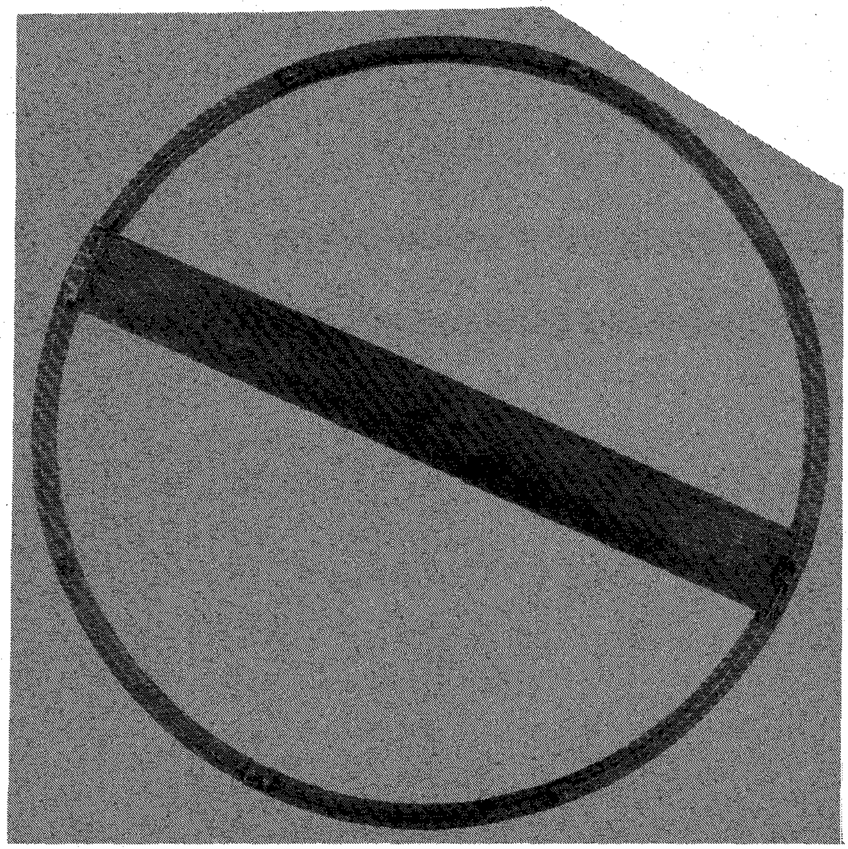

Fig. 8. A circular loop configuration of the Hertzian receiver/detector, 70 cm diameter. Note the small plates soldered to the loop near the gap, supposedly for the purpose of bringing the receiver into tune with the transmitter. Used in "waves in air" experiment (Fig. 18). (Courtesy of the Science Museum, London—replica.)

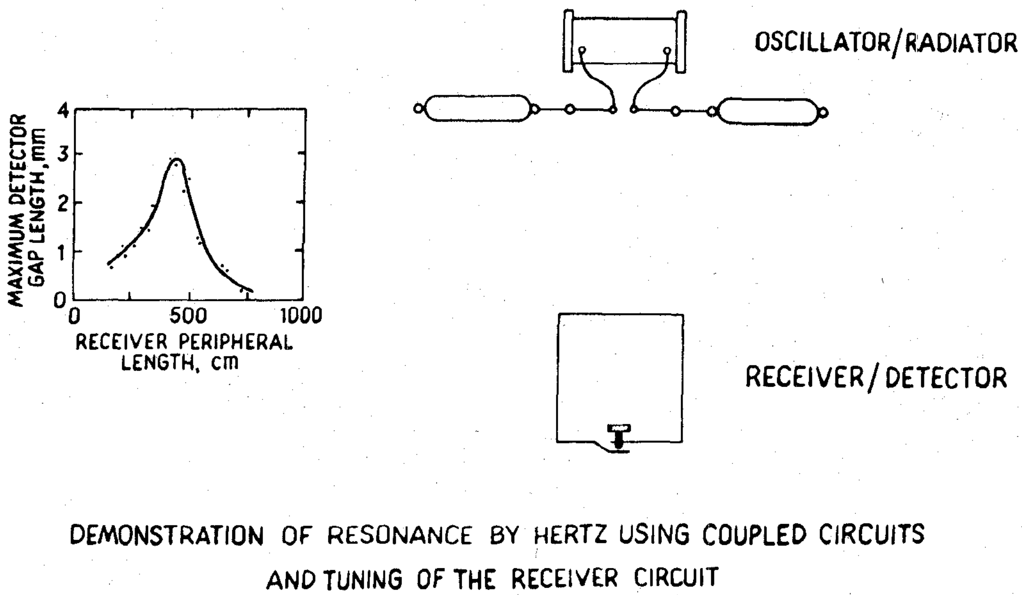

Fig. 9. An experiment in resonance, using a signal source (transmitter) and a coupled circuit (receiver). Hertz referred to such a coupled circuit as the secondary, and as a side circuit. Keeping the signal source configuration constant, thus fixing the frequency, Hertz tuned the receiver over a wide range in wavelength by changing the overall length of the receiver loop. The maximum detector gap length that would just break down, a measure of the RF voltage across the gap, is plotted against the peripheral length of the receiver loop. (Adapted from Hertz.)

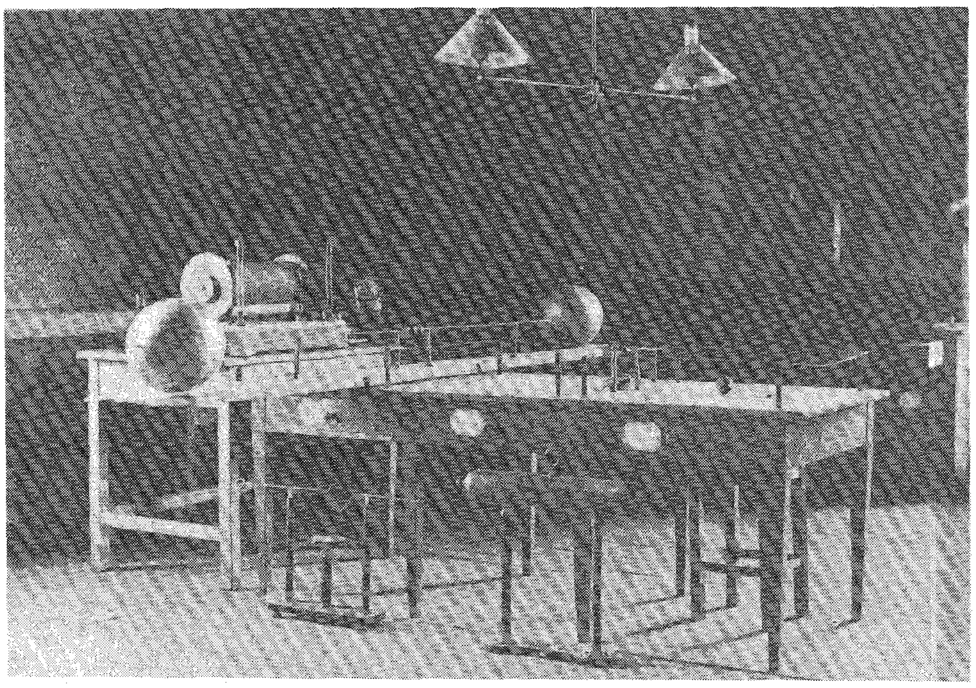

Fig. 10. Transmitter and two coupled circuits (receivers), in a laboratory of Hertz's Physical Institute at Karlsruhe, circa 1887. To the left may be seen the induction coil used to produce pulses of dc potential energy that is converted into RF energy by the transmitter. On the near table toward the right notice the metal sphere mounted on an insulated handle, used to probe (disturb) the fields on each lop and demonstrate resonance. At the nodal points on *cd* and *gh* (Fig. 11), there is no disturbance when the sphere touches the wire. Continuing around the loop, sparks can be drawn from the wire and simultaneously sparks in the detector gap are diminished: the effect increases and is maximum at the detector gaps *1–2* or *3–4*. (From [25]—originals.)

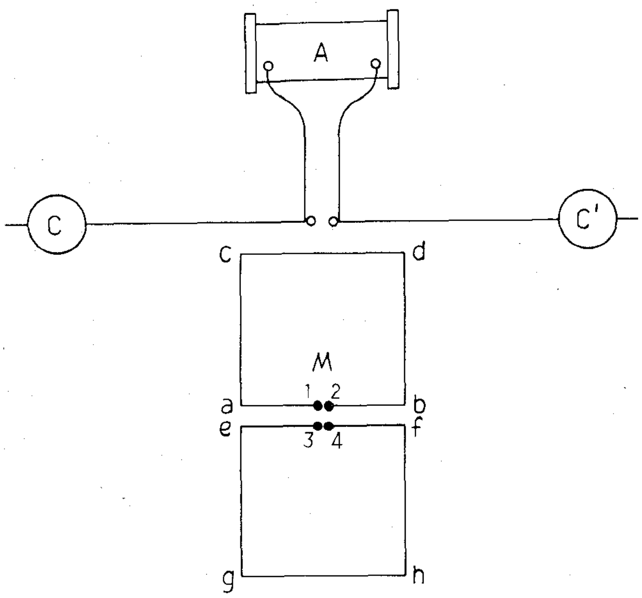

Fig. 11. Transmitter and two coupled circuits, schematic. (After Hertz.) See Fig. 10.

accurately the maximum length of the gap that would just break down. He also noted erratic performance of his transmitter when a corona discharge developed between the high-voltage leads from the induction coil and the metal reflector of the 70 cm apparatus. Hertz found that simple shielding sufficed in both cases, and could have left it at that.

Scientist that he was, however, Hertz realized that he was observing an important phenomenon: "A phenomenon so remarkable called for closer investigation." Hertz stopped his electromagnetic experiments to investigate and performed extensive experiments. All metals were opaque to the radiation. Various gases, liquids, and solid dielectrics were transparent, some were partially so, and some opaque. Quartz and rock crystal, for example, were transparent. Other light sources gave the effect in varying degree.

Hertz then used an optical spectroscope (developed in 1860 by Robert Bunsen and Gustav Kirchhoff). He identified the phenomenon as being clearly associated with the ultraviolet portion of the spectrum.

Hertz had discovered the surface photoelectric effect, but he had no way of understanding it. The electron had not been discovered. Later investigators came to understand that a photon (quantum of energy) at ultraviolet wavelength has enough energy to free an electron from the surface of the metallic spark gap electrode, and the presence of free electrons lowers the threshold of voltage breakdown. In his paper, "On an Effect of Ultraviolet Light upon the Electrical Discharge," Hertz concluded: "...I confine myself at present to communicating the results obtained, without attempting any theory respecting the manner in which the observed phenomena are brought about." Hertz's keen observation and skill as an experimentalist and communicator show through in this paper, which set off a new activity in physics and was the start of quantum physics.

VIII. Dielectric Polarization Effects in Insulators: The Berlin Prize Problem

Hertz now had the apparatus and techniques to tackle the Berlin prize problem proposed to him by Helmholtz eight years earlier. The work is described in his paper "On Electromagnetic Effects Produced by Electrical Disturbances in Insulators" [27]. A diagram of the apparatus is shown in Fig. 12. The dimensions shown are in centimeters. In the center is an assembly of an oscillator and a circular detector (Fig. 13). Referring to Fig. 12, the oscillator dipole $A-A'$ uses flat plates for loading instead of spheres. The detector loop B is mounted on a spindle so that it can rotate. At C is a metal sheet and at D a wooden box for holding dielectric material.

Since the apparatus bears no resemblance to present-day apparatus, and the experiments themselves are not easy to interpret, it seems best that the experiments be described in Hertz's own words:

> When the spark-gap lies in the horizontal plane AA', i.e., at a or a' [o or o' in Fig. 14(a)], it is entirely free from sparks. When the circle is rotated a few degrees in either direction from this position, minute sparks arise. These small sparks increase in length and strength as the spark-gap is removed farther from the position of equilibrium and reach maximum length of about 3 mm when f is at the highest and lowest points, b and b' respectively, of the circle....
>
> It will assist us in what follows if we also consider here the phenomena which occur when we shift the circle B a little downwards, parallel to itself and without moving it out of its plane. When this is done the sparking distance increases at the highest point and diminishes at the lowest point; the points which are free from sparks—the null-points as we may call them—no longer lie on the horizontal line through the axis, but appear to be rotated downwards through a certain angle on either side....
>
> Hitherto it has been assumed that the conductors AA' and B are set in a large room as far away as possible from all objects which might disturb the action. Such an arrangement is necessary if we wish to secure an actual disappearance of the sparks at a and a'.... We have now to choose a conductor which will produce a moderately large effect, and of which we may assume the oscillation period to be smaller than that of our primary oscillation. These conditions are fulfilled by the conductor made of sheet metal, which is shown at C in our illustration. When it is lowered towards the primary conductor AA', we observe the following effects:—The spark length has decreased at the highest point b and has increased at the lowest point b'; the null-points have moved upwards, i.e., towards the conductor C [Fig. 14(b)], whereas there is now noticeable sparking where the null-points originally were....
>
> A very rough estimate shows that if large masses of insulating substances are brought near the apparatus, the quantities of electricity displaced by dielectric polarization must be at least as great as those which are set in motion by [conductors]. The approach of the latter has been found to produce a very noticeable effect in our apparatus; if, therefore, the approach of large insulating masses produced no similar effect, we should naturally conclude that the electricity displaced by dielectric polarization did not exert a corresponding electromagnetic action. But if the views of Faraday and Maxwell are correct, we should expect that a noticeable effect would be produced, and, further, that the approach of a non-conductor would act in the same way as that of a conductor having a very short period of oscillation. Experiment fully confirms this expectation; and the only difficulty in carrying out the experiments is that of procuring sufficiently large masses of insulating material.

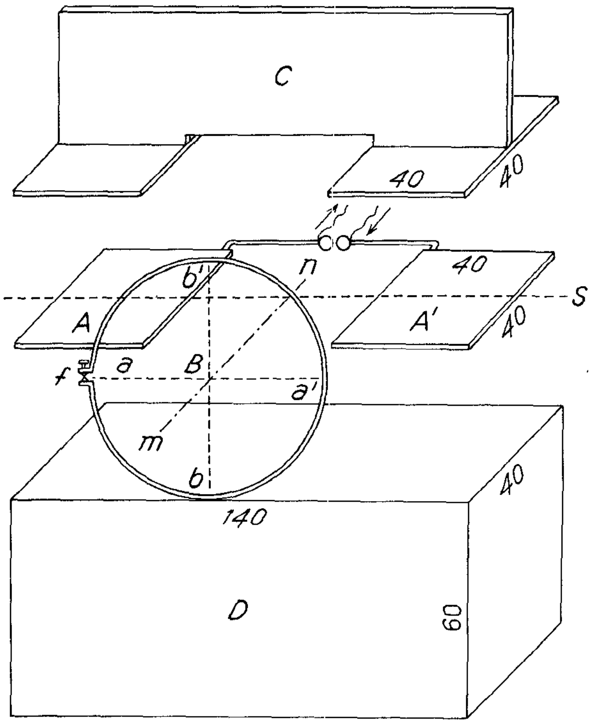

Fig. 12. Diagram of the apparatus used by Hertz to "...establish experimentally any relation between electromagnetic forces and the dielectric polarization of insulators—that is to say, either an electromagnetic force exerted by polarization in non-conductors, or the polarization of a non-conductor as an effect of electromagnetic induction." The dimensions are given in cm, for 6 m wavelength operation. In the course of experiments Hertz switched to apparatus operating at 3 m wavelength by reducing each dimension by one-half. (After Hertz.)

Hertz first experimented with a pile of books and observed expected effects. He next had a block of unmixed asphalt cast in the dimensions shown.

> The apparatus was removed on to this [block of asphalt], the plates being laid upon the block. The effect could immediately be recognized.... The spark at the highest point of the circle was now considerably stronger than at the lowest point (that nearest the asphalt). The null-points were displaced downwards, i.e., towards the insulator [Fig. 14(c)], and when the plates were laid right upon it the angle of displacement (which could be measured with fair accuracy) was 23°. But the sparking no longer ceased completely at these points. At the original zero-points there was now vigorous sparking.... If the apparatus was gradually removed in any direction away from the asphalt block the effect continually diminished, without experiencing any qualitative change....
>
> The accordance between the mode of action of the insulator and of a conductor is further shown by the fact that one can be compensated by the opposing action of the other. Thus, if the apparatus lay upon the asphalt, and the conductor C was brought near it from above, the null-points shifted backwards towards their original positions, and they again coincided with

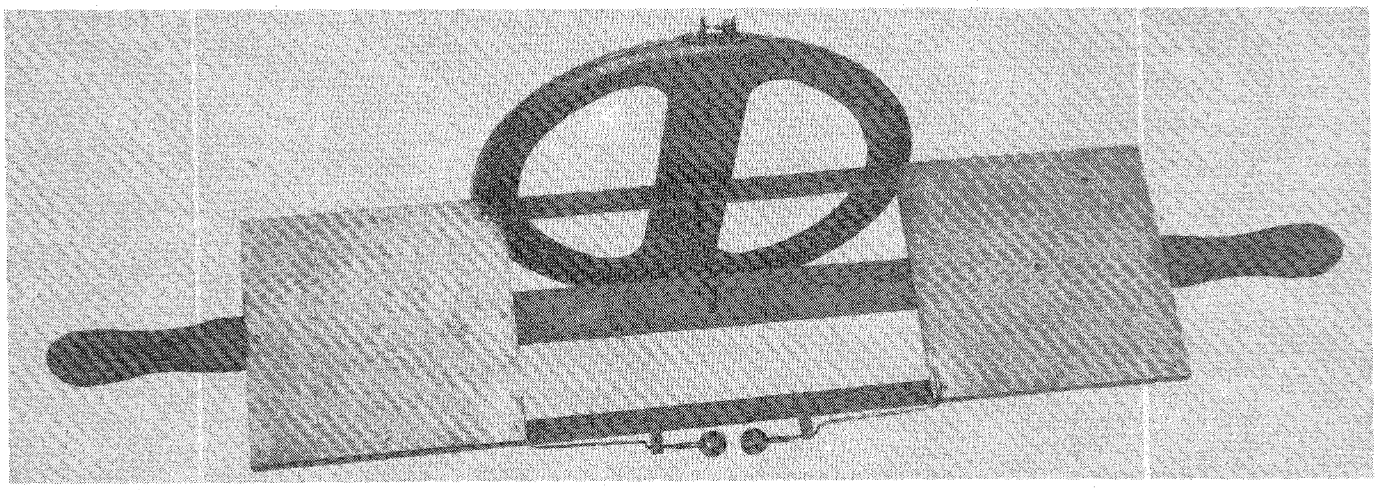

Fig. 13. An assembly consisting of a Hertzian oscillator and circular-loop receiver, for 3 m wavelength operation (see text). The receiver is mounted so that it can be rotated around its axis. (Courtesy of the Science Museum, London—replica.)

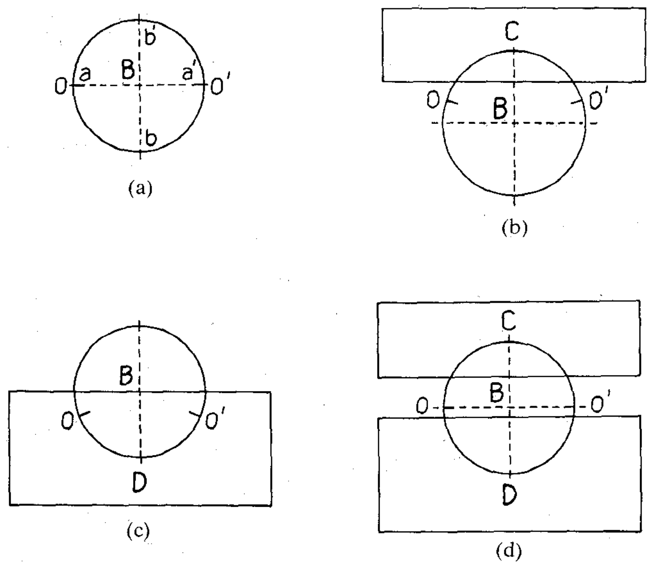

Fig. 14. Illustration of the shift in position of the null points of the detector: (a) free space, (b) metal plate above, (c) dielectric material below, and (d) both.

the points a and a' when the conductor C was brought within about 11 cm of the conductor AA'. If the upper surface of the asphalt lay 5 cm beneath the plates A and A', compensation was attained as soon as C was brought within about 17 cm of AA'." [Fig. 14(d)].

Wanting to be certain that impurities were not responsible for the observed effects, Hertz got a colleague to do an analysis. Indeed the asphalt did contain a large amount of mineral matter. Since the expense of undertaking further investigations on the same large scale with pure substances was prohibitive, Hertz had another transmitter AA' and receiver B built to exactly one half the linear dimensions. He thus shifted from experimenting at approximately 6 m wavelength to 3 m (frequency 100 MHz), which required blocks of dielectric material only one eighth the size in volume and weight. [Note: the existing original apparatus at Munich as well as the replicas at London and Chicago are of this smaller size.]

Hertz then investigated eight substances with the smaller apparatus. For asphalt the angle of rotation of the null-point was 31°, but, as noted above, it contained a large amount of mineral matter. For artificial pitch obtained from coal it was 21°, but this artificial pitch contained not only hydrocarbons but also free carbon in a fine state of division, which would have some conductivity. The six other substances investigated were paper, dense dry wood, sandstone, sulfur, paraffin, and petroleum. The corresponding angles of rotation of the null-point were 8°, 10°, 20°, 13–14°, 7°, and 7°, respectively. Hertz noted:

> The concordance between the observations made upon so many substances, some of which were pure, scarcely leaves any doubt that the action is a real one, and that it must be attributed to the substances themselves, and not to impurities in them.... At present it does not appear possible to give any discussion of the quantitative relations of the experiments that would be of interest.

Hertz considered that his results had fulfilled the experimental goal of the Berlin prize. He sent the manuscript to Helmholtz with a request: "Once again I am taking the liberty of sending you a paper with the respectful request to present it to the Academy [28], and if possible, to let it be printed in the proceedings..." [29]. Presumably, Hertz did not collect the prize money, the time limit having expired in 1882. No one else had entered the contest. Perhaps he was the only individual besides Helmholtz who had given it any thought.

IX. Transmission Experiments: Guided Electromagnetic Waves

Waves in Wire-over-Ground-Plane Transmission Line

In the paper "On the Finite Velocity of Propagation of Electromagnetic Actions" [30] Hertz describes his first experiment to measure the velocity of propagation of electromagnetic waves (Fig. 15). The signal source is a variation on the Hertzian 6 m oscillator. Square plates instead of spheres are used for loading. The transmission

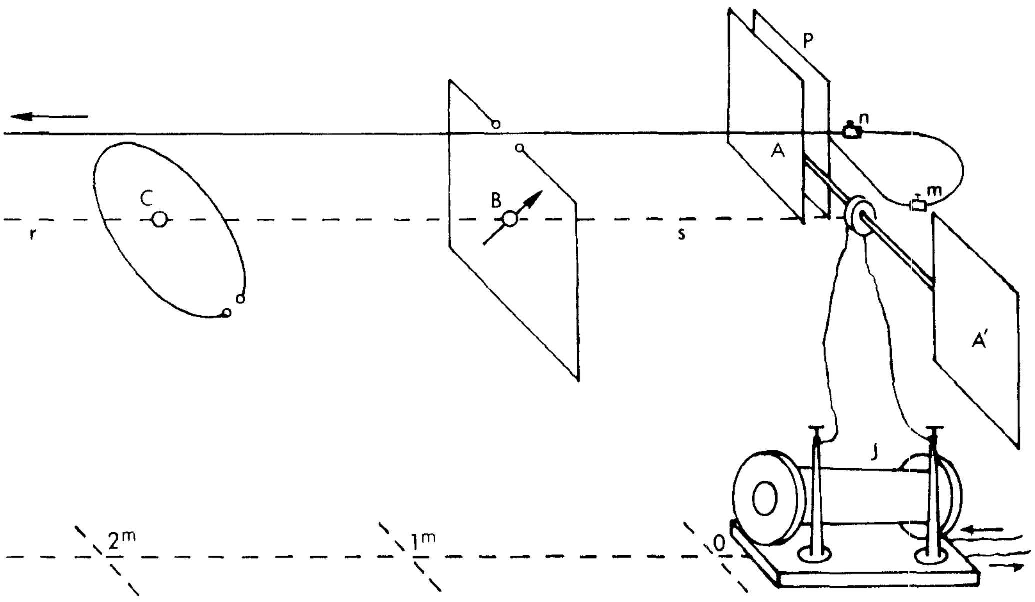

Fig. 15. Schematic of the wire-over-ground-plane transmission line experiment. (After Hertz.)

line is wire-over-ground-plane construction, with the wire 1.5 m above the floor. The polarization is vertical. Coupling off some of the energy capacitively, with a plate, keeps the high-voltage pulses off the transmission line. With the transmission line open-ended on the left, standing waves result. As one moves the detector along the line, the distance between nulls is one half-wavelength. Hertz obtained 2.8 m for the half-wavelength. According to Maxwell's theory, and as we know to be true, the product of frequency and wavelength gives the velocity of propagation, in this case the velocity of light in air.

Hertz had two objectives: (1) to demonstrate a finite velocity of propagation, a major distinction between Maxwell's theory and older theories, and (2) to determine the velocity and compare it with Maxwell's prediction of 3×10^8 m per second. Hertz calculated the frequency of his source from an estimate of the capacitance and the inductance of the dipole resonator [31]. For the velocity, the product of wavelength × frequency, he arrived at 2×10^8 m per second, not knowing of a computational error by a factor of $(2)^{1/2}$ in estimating the frequency. His correct result, without the error, would have been 2.8×10^8—within 7 percent of the correct value, a truly remarkable achievement. Hertz thus clearly succeeded in his first objective, and did not know how truly successful he had been in the second. Hertz published promptly, and the error in computation was pointed out to him about 18 months later in a letter from Poincare in France.

Skin Effect [32]

Maxwell explicitly suggested the phenomenon of *skin effect*, the tendency of high-frequency alternating currents and magnetic flux to penetrate the surface of a conductor only to a limited depth. As frequency is increased, RF currents penetrate conductors to a smaller and smaller depth, so that finally most of the energy of waves travels in the space outside and between conductors.

To investigate, Hertz conducted experiments by completely enclosing his detector in a box of thin metallic sheets of various thicknesses estimated to be no more than 1/20 mm. He obtained complete shielding. Using the same sheet material to form the outer conductor of a coaxial line, he obtained similar shielding. For an even thinner outer conductor, glass tubes that had been chemically silvered were used as the outer conductor. Electromagnetic energy only appeared in his external detector "when the film of silver was so thin it was no longer quite opaque to light, and certainly was thinner than 1/1000 mm."

Coaxial Transmission Line

Hertz wanted to conduct experiments in a uniform transmission line, free of interfering obstacles. He stated: "If our waves have their seat in the space surrounding [conductors], then a wave gliding along a single wire will not be propagated through the air alone; but, inasmuch as its action extends to a considerable distance, it will be propagated in the neighboring walls, the floor, etc., and will develop into a complicated phenomenon....We can thus take measures to secure that propagation occurs only through air or another insulator..." [33].

A coaxial transmission line section (Fig. 16) 5 m (17 ft) long and 30 cm (1.2 ft) in diameter was built. The outer conductor is not made of solid metal, since that would have made the interior of the line inaccessible. It is built up of 24 copper wires stretched parallel to one another along the generating surface of seven equidistant circular rings of stout wire. At the center of each large ring is a small ring supported by spokes of cotton cord. Running a wire through the center rings yielded a coaxial transmission-line section. When the 6 m wavelength (frequency 50 MHz) signal was sent through the line, there was no detectable signal outside the line. The parallel wires were thus close enough together to provide screening.

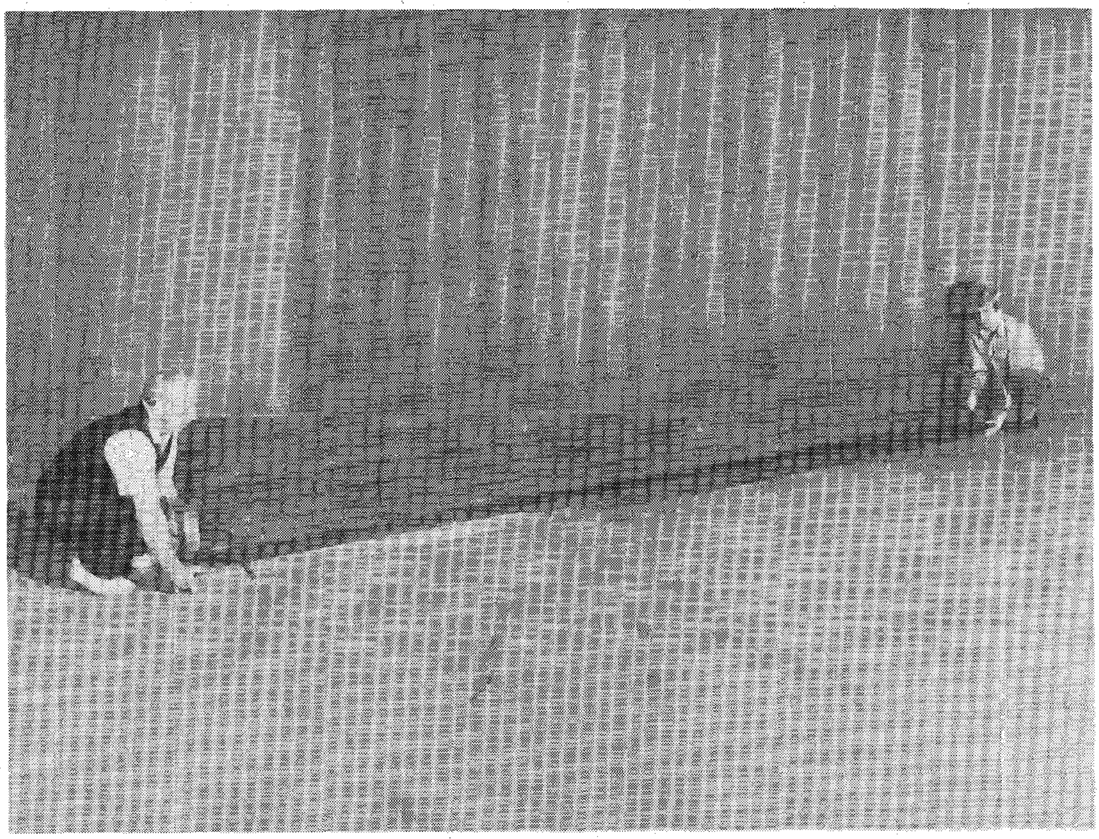

Fig. 16. Coaxial line section. In the photograph (1987), two employees of the Science Museum. The length is 5 m; diam. 30 cm. Used at 6 m wavelength. (Courtesy of the Science Museum, London—replica.)

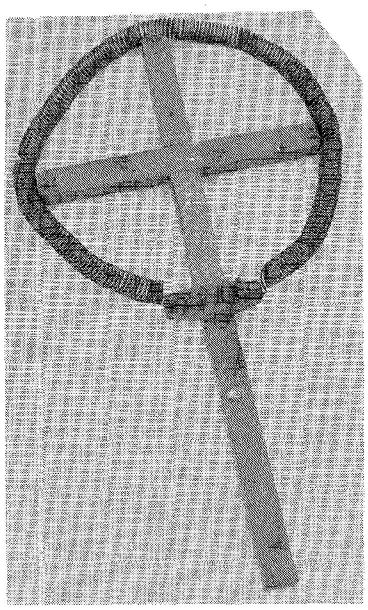

Fig. 17. Receiver/detector for use inside the coaxial line. The detector is small enough to be inserted between the longitudinal wires and turned as desired and moved along the line to probe the fields. The mean diameter of the helical coil is 12 cm. (Courtesy of the Science Museum, London—replica.)

The resonant circuit for the small receiver/detector (Fig. 17) to go inside the coaxial line consists of about 125 turns of 1 mm copper wire wound in a tight helix 1 cm in diameter, pulled out a little, and bent into a circle of 12 cm diameter. "Special experiments had shown that this circle was in resonance with the waves of 3 meters [34] length in the wire, yet it was sufficiently small to be introduced between the central wire and the tube."

This detector could be inserted between the outer wires, positioned, and moved along the line to measure the fields inside the line. It was thus the first slotted line. With it Hertz demonstrated standing waves, with nodes half a wavelength from a short circuit and a quarter wavelength from an open circuit. He also showed that the wavelength inside the line was the same as for a corresponding wave in free space (with the same dielectric, in this case air). The first practical use of coaxial line came more than four decades later.

X. Waves in Air

In Hertz's experiment to measure the velocity of waves in air (Fig. 18) [35] the transmitter is on the right, not shown. The polarization is vertical. On the left is the cross section of a sheet of metal used as a reflector. Waves reflected back toward the transmitter set up standing waves. The solid lines denote voltage standing waves. Hertz visualized the dotted lines as magnetic standing waves. The circles denote positions where Hertz used a receiver of circular configuration to measure the amplitude of the voltage standing waves. In use, the receiver was mounted so that it could be rotated about its axis. At position *I*, by rotating the receiver to two horizontal positions 180° apart, he noted decreasing amplitude toward the reflector. At *II* and *IV* he noted decreasing amplitude toward null points, and at *III* increasing ampli-

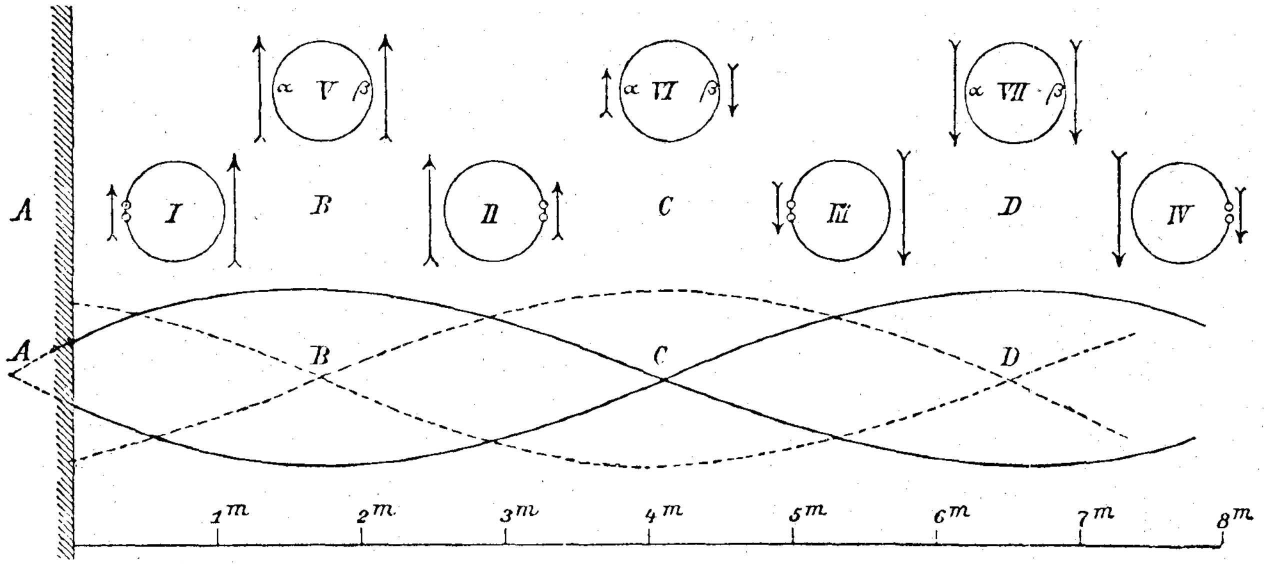

Fig. 18. Experiment to measure the wavelength of waves in air. (After Hertz.)

tude away from a null. At *V* and *VII* there was equal amplitude on each side of an antinode, and at *VI* there was equal amplitude on each side of a null. The distance between nulls was reckoned to be one half-wavelength.

Hertz projected a voltage null beyond the reflector, not in the plane of the reflecting surface as expected. He reasoned that this might be due to the finite conductivity of the metal. We now know that that is not too likely. Since the width of his reflector was less than two wavelengths, it must have been refraction.

That was not Hertz's main problem, however. He got a measured wavelength that was too long, so that the product of wavelength and calculated frequency gave too great a velocity. The problem was probably due to waveguide effects, reflections from the floor, iron columns in the lecture room, or an iron stove located near the propagation path. Hertz published promptly, however, warts and all, as was his practice. He was obliged to observe that the velocity appeared to differ from that on the wires. He noted that since they were both finite, his results could still be in keeping with Maxwell's theory. In any case, the experiment was replicated by Sarasin and de la Rive in Switzerland [36]. They confirmed that the velocities were indeed the same. In later experiments, using a shorter wavelength, Hertz also got the correct result.

XI. The Fields from a Dipole Antenna

Hertz interspersed his experiments with analytical work. In his paper "The Forces of Electric Oscillations Treated According to Maxwell's Theory" [37], Hertz explained:

> The results of the experiments on rapid oscillations which I have carried out appear to me to confer upon Maxwell's theory a position of superiority to all others. Nevertheless, I based my first interpretation of these experiments upon the older views, seeking partly to explain the phenomena as resulting from the cooperation of electrostatic and electromagnetic forces. To Maxwell's theory in its pure development such a distinction is foreign. Hence I now wish to show that the phenomena can be explained without the introduction of this distinction. Should this attempt succeed, it will at the same time settle any question as to a separate propagation of electrostatic force, which indeed is meaningless in Maxwell's theory. Apart from this special aim, a closer insight into the play of forces which accompany a rectilinear oscillation is not without interest.

A brief description cannot do justice to the scope and detail of results described in the paper. Fig. 19 is Hertz's illustration of his calculations of the development of fields around an oscillating electric dipole (very short dipole antenna). This is for each quarter cycle, or, by suitable reversal of the arrows, for all subsequent times which are whole multiples of one quarter-period. A portion of each of the outer lines of force detaches itself as a self-closed line of force which advances independently into space, while the remainder of the lines of force sink back into the oscillating dipole. This loss of energy each half-cycle corresponds to radiation into space. At a large distance the fields become entirely transverse.

XII. Shorter Wavelength Apparatus

Hertz had previously tried his large transmitter of 6 m wavelength in front of a cylindrical parabolic reflector, but obtained no focusing [38]. He realized that the reflector was much too small in terms of wavelength. Rather than build a larger reflector, which would have required him to work outside the building, he scaled his signal source and detector to a shorter wavelength, around 70 cm (430 MHz frequency). The transmitter's resonant circuit is again a half-wavelength dipole (Fig. 20). The cylindrical brass body, 3 cm in diameter and 26 cm long, is interrupted in the center with spheres 4 cm in diameter to act as the switch. The receiver (Fig. 21) is a circular loop, scaled to 7.5 cm diameter so as to resonate with the oscillator.

With the shorter wavelength waves Hertz repeated previous experiments. One result was finding that "these short

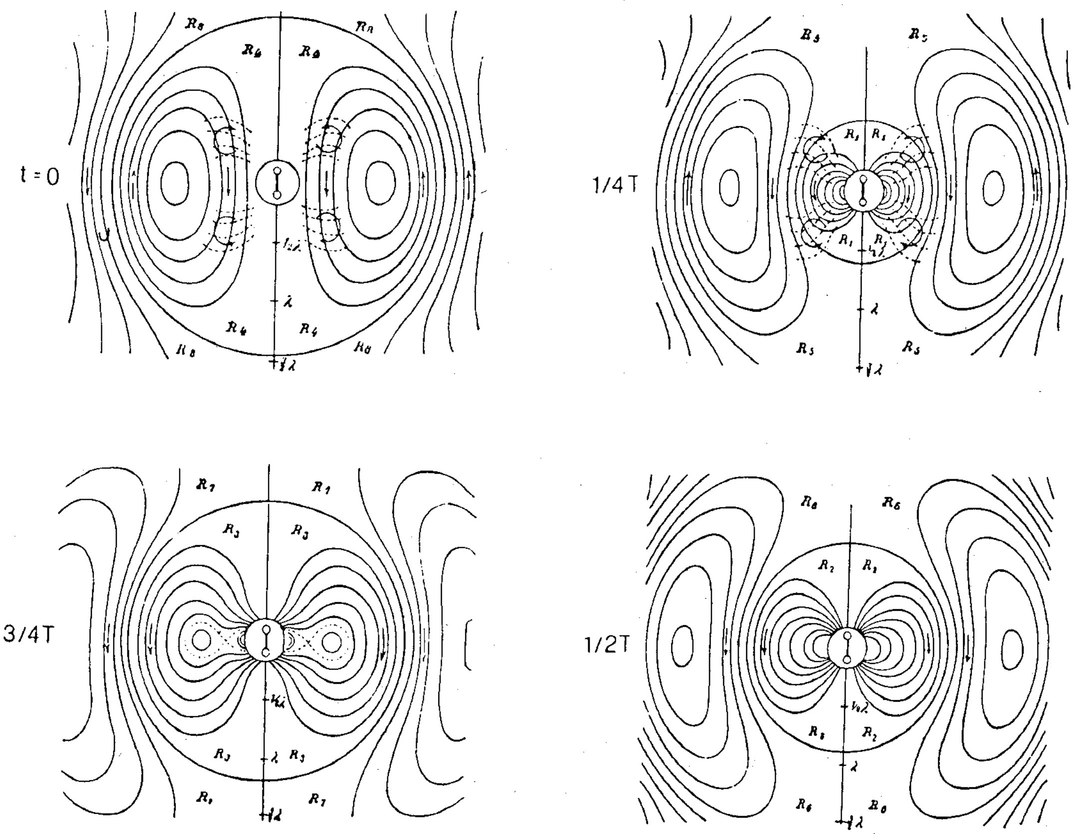

Fig. 19. Hertz's diagrams of the formation of fields from a rectilinear oscillator (very short dipole), and their propagation outward, shown for four instants of time separated by 1/4 period of the oscillation, or, by suitable reversal of arrows, for all subsequent times which are whole multiples of one quarter period. (After Hertz.)

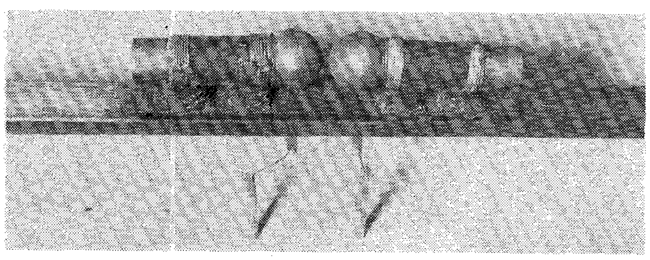

Fig. 20. Hertz's half wave dipole resonant element for 70 cm wavelength oscillator. (Courtesy of the Science Museum, London—replica.)

waves traveled along wires at very nearly the same velocity as in air" [39].

XIII. Focused-Beam Experiments, at Shorter Wavelength

With apparatus operating at shorter wavelength and after getting good results, Hertz started a new phase of investigation [40]. His purpose was to show the similarity in characteristics of electromagnetic waves at metric wavelengths to that of light at wavelengths a million times shorter. Apparatus for operation at about 70 cm wavelength is shown in Fig. 22. The story is better told in Hertz's words:

> As soon as I had succeeded in proving that the action of an electric oscillation spreads out as a wave into space, I planned experiments with the object of concentrating this action and

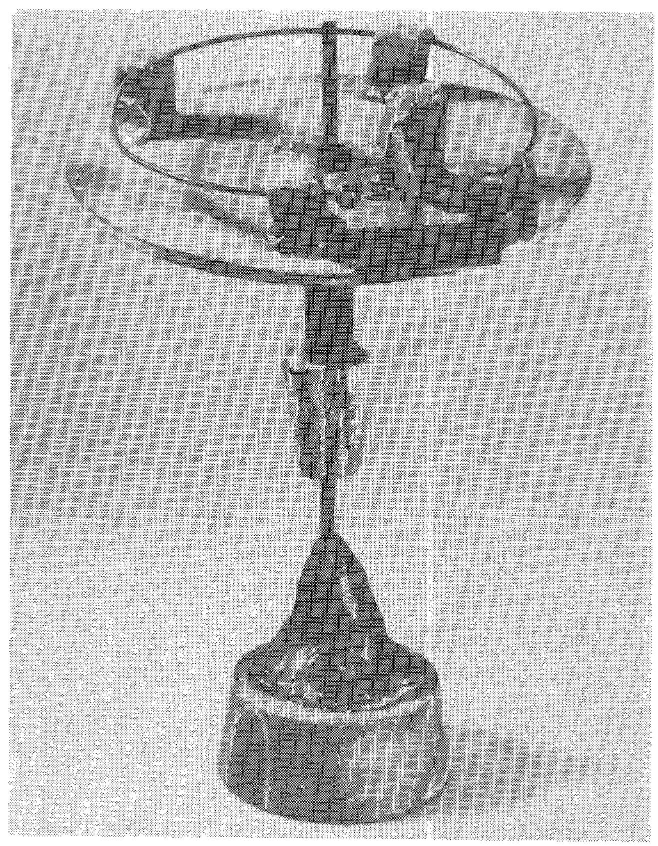

Fig. 21. Circular receiver/detector for 70 cm wavelength. (Courtesy of the Deutsches Museum—original.)

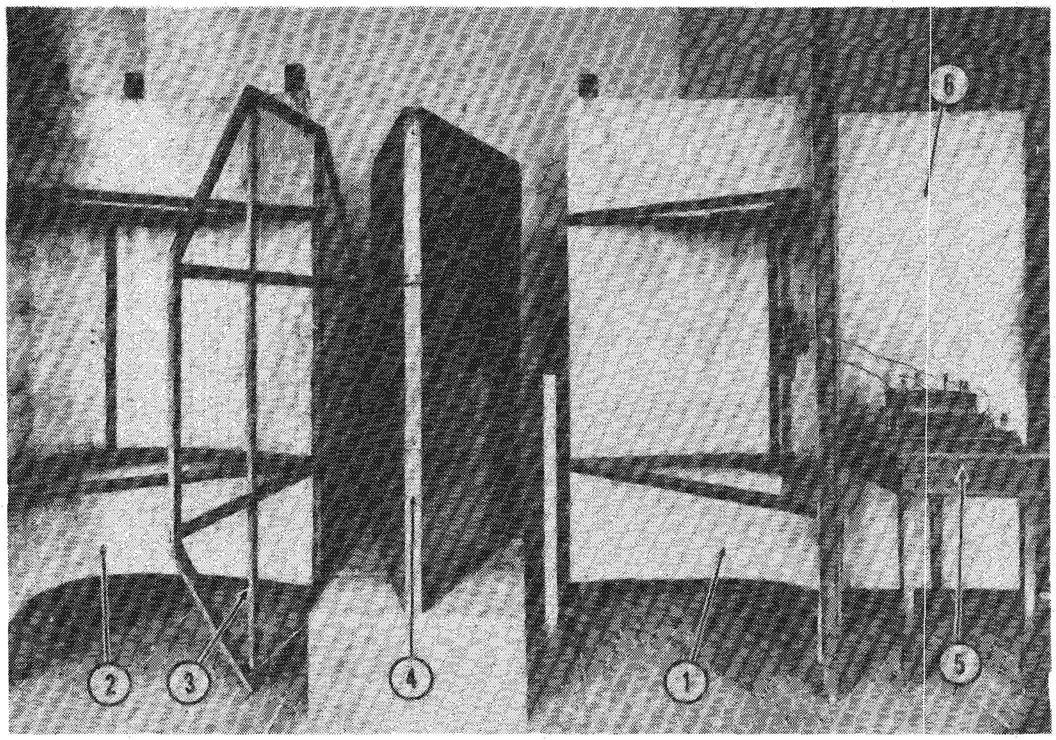

Fig. 22. Apparatus used by Hertz for focused-beam experiments to demonstrate the optics-like properties of electric waves of about 70 cm wavelength: *1* Oscillator/transmitter with cylindrical parabolic reflector. The focal length of the reflector is 12.5 cm and the aperture 1.2 m wide, giving an f/D ratio of about 1/10. *2* Receiver/detector with similar cylindrical parabolic reflector. *3* Octagonal wooden frame with parallel wires for polarization demonstration. *4* Stack of three wooden boxes (on pedestal) to hold dielectric materials for refraction experiments. *5* The power supply (on the table). The two output leads from the induction coil pass through (glass tubes in holes in) the back of the reflector, and are attached to the transmitter dipole. This induction coil appears to have an adjustable vibrator/current interrupter mounted on the end at the right. A wire from it may be seen that (presumably) goes to a battery located behind the induction coil. The table is on casters, and therefore can be moved around with the transmitter to the desired position for use. *6* the plane metal sheet used for the demonstration of reflection is standing behind the table. (From [25]—originals.)

making it perceptible at greater distances by putting the primary conductor in the focal line of a large concave parabolic mirror. These experiments did not lead to the desired result, and I felt that the want of success was a necessary consequence of the disproportion between the length...of the waves [wavelength] used and the [largest] dimensions which I was able...to give to the mirror. Recently I have observed that the experiments which I have described can be carried out quite well with oscillations of more than ten times the frequency,...less than one-tenth the [wavelength] of those which were first discovered. I have, therefore, returned to the use of concave mirrors, and have obtained better results than I had ventured to hope for. I have succeeded in producing distinct rays of electric force, and in carrying out with them the elementary experiments which are commonly performed with light and radiant heat.

Transmitter

Hertz placed the transmitter dipole in the focal line of a parabolic cylinder reflector (Fig. 23) with a focal length of 12.5 cm. The reflector was made from a sheet of zinc 2 m long and 2 m wide bent over a wooden frame of the desired curvature. The resulting reflector is 2 m high and 1.2 m wide at the aperture; its depth is 0.7 m. The high-voltage pulses from the induction coil are brought through leads from the back.

Receiver

For the first time Hertz made use of a dipole as the resonant element in his receiver (Fig. 24): "The circular conductor gives only a differential effect, and is not adapted for use in the focal line of a concave mirror. Most of the work was therefore done with another conductor arranged as follows. Two straight pieces of wire, each 50 cm long and 5 mm in diameter, were adjusted in a straight line so that their near ends were 5 cm apart." With a length of 105 cm, the receiver dipole is near to 3/2 wavelengths long. This receiving dipole is mounted in the focal line of the reflector. Behind, fed by a short length of parallel wire transmission line, is his adjustable spark gap detector.

Rectilinear Propagation

The transmitter and receiver units (Fig. 22) are on casters. If they are aimed toward each other, the maximum signal is obtained. If a sheet of metal is interposed, there is no signal. Placing them side by side and aiming them both in the same direction likewise yields no signal.

Reflection

When the units are aimed at a reflecting surface (Fig. 25) the angle of reflection is equal to the angle of incidence, as in optics.

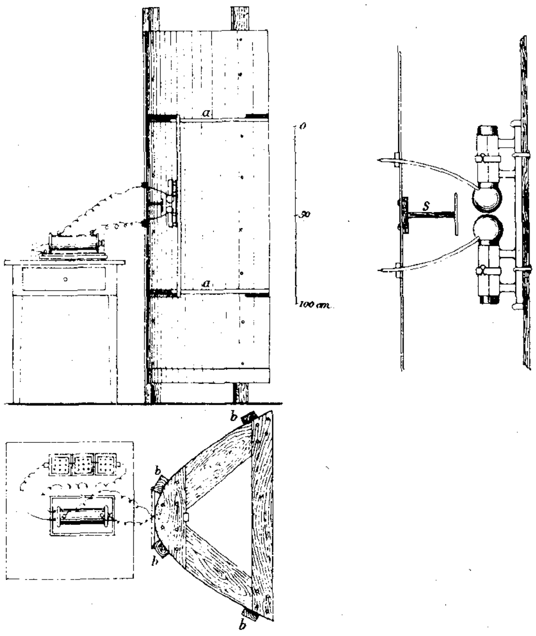

Fig. 23. Transmitter detail. (After Hertz.)

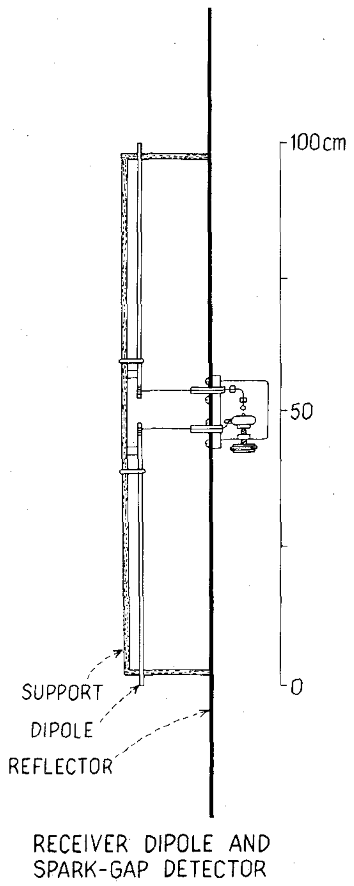

Fig. 24. Receiver detail. The dipole is connected by a short length of parallel wire transmission line to the spark gap detector mounted behind the reflector. (Adapted from Hertz.)

Refraction

A stack of three wedge-shaped forms (Fig. 22, *4*) was built which could be filled with dielectric material such as tar (pitch). From the angle of refraction (Fig. 25) and the angle of the wedge one may calculate the index of refraction, the square of which is the relative dielectric constant (or permittivity) for a homogeneous, isotropic material. This was the first dielectric-constant measurement at microwave wavelengths.

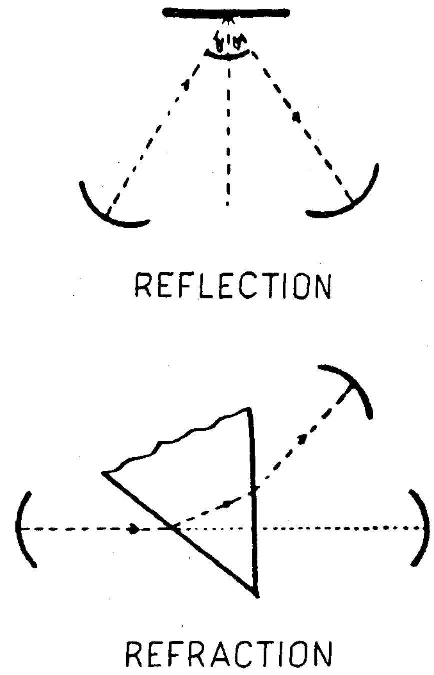

Fig. 25. Illustration of reflection and refraction of electromagnetic waves.

Polarization

Fig. 22, *3*, shows a wooden frame with parallel wires. When the wires are placed in the plane of polarization between the transmitter and receiver, the signal is cut off, but when the wires are at right angles the signal is transmitted. Hertz made the frame octagonal. He showed that when the wires are set at 45° to the plane of polarization, the wave is resolved into two components, one horizontal and one vertical. Thus even if the receiver were turned at right angles to the transmitter, half the signal power would be transmitted.

XIV. The Mechanical Action of Electric Waves: Attempts to Measure the Strength and Distribution of Electromagnetic Fields

In his September 1889 lecture on electricity and light (Fig. 1) Hertz revealed that he endorsed Maxwell's theory as he interpreted it. In his paper "On the Mechanical Action of Electric Waves in Wires" [41] Hertz revealed that he would still like to *experimentally* dispose of the action-at-a-distance concept. In this he was not successful, but he did succeed in experimentally giving further elucidation to the nature of electromagnetic waves. He stated:

> The investigation of the mechanical [pondermotive] forces to which a conductor is subjected under the action of a series of electric waves appeared to me to be desirable for several reasons. (1) In the first place, these forces might supply means of investigating such waves quantitatively.... (2) In the second

place, by examining the nature and distribution of the mechanical forces, I hoped to find a means of demonstrating the existence of the magnetic force in addition to the electric force. Only the latter has manifested itself in the observations hitherto made.... (3) In the third and last place—and this was more especially the object of the investigation—I hoped to be able to devise some way of making observations on waves in free air,—that is to say, in such a manner that any disturbances which might be observed could in no wise be referred to any action-at-a-distance. This last hope was frustrated by the feebleness of the effects produced under the circumstances. I had to content myself with examining the effects produced by waves traveling along wires, although in so doing the most important object of the experiments was missed....waves in wires [with associated conduction currents] cannot be made use of to decide between the older and the newer views [of electromagnetics].

Thus the lack of sensitivity of his instruments prevented Hertz from achieving his third objective. Apparently he did not attempt to calibrate his apparatus for quantitative measurements (first objective) which would have been of interest to him only if he could have measured the fields in free space.

Hertz did achieve his second objective, and thus further clarified the nature of electromagnetic waves.

His instrument for measuring the mechanical action of the electric force made use of a small tube 5.5 cm long and 0.7 cm in diameter made of rolled-up gilt paper, suspended by a silk thread with its axis horizontal (Fig. 2, *6*). A very small magnet gave the tube a definite position of rest, and a deviation from this position was measured by means of a small mirror. The whole system was mounted in a glass case. This has been called a rolled-paper galvanometer. By this time, starting in 1889, he was able to make some use of contributions by other investigators who were already working in the new field of electromagnetics which he had opened up. He found that a two-wire transmission line of the type which was being used by Ernst Lecher (hence the term Lecher line) at the University of Vienna produced strong enough fields to be measured. The signal source was a 6 m wavelength oscillator. Hertz found minimum deflection at nodal positions, and maximum deflection in between.

To investigate the magnetic force, use was made of a circular loop of aluminum wire 6.5 cm in diameter suspended by a silk thread, with a magnet to give a definite position of rest, and a mirror to indicate a deviation from that position. This assembly was enclosed in a glass case. Hertz noted deflection of the same magnitude as for the electric force detector. He noted maxima at the nodal positions of the electric force, and found the direction of the magnetic force to be perpendicular to the direction of the electric force, as he had expected. These, his last experiments in electromagnetics, were started in Karlsruhe in February 1889 and completed in Bonn in January 1891.

XV. Equations of Electromagnetics for Bodies at Rest and for Bodies in Motion

The last two chapters of *Electric Waves* have no technical significance today but are of scientific interest. In chapter 13, "On the Fundamental Equations of Electromagnetics for Bodies of Rest" (1890), Hertz formulated Maxwell's equations in the compact form that has been standard ever since and that rapidly achieved widespread influence. Heaviside had also formulated the equations, but it was Hertz's work that spread the equations through the physics community.

In chapter 14 of *Electric Waves*, "On the Fundamental Equations of Electromagnetics for Bodies in Motion" (1890), Hertz was on the track of one of the most fundamental concepts in the history of science [the special theory of relativity]. In a letter to Heaviside of 3 September 1889, Hertz states: "The motion of the ether relatively to matter—this is indeed a great mystery. I thought about it often but did not get an inch of advance" [42]. Hertz, like most physicists of the day, assumed that electric and magnetic fields moved along unchanged with the matter that carried them. This assumption has a fundamental flaw, as Einstein was to discover 15 years later, including the fact that the concept of an ether is not necessary. Knowledge of the fields is enough so long as account is taken of the fact that the velocity of light is constant in all coordinate systems, moving or not—the special theory of relativity. But this knowledge was not available in 1890.

Part II: The Hertzians and Their Work

I. Introduction

The analytical and experimental work of Hertz opened up a vast new field for research and experimentation. Scientific investigations quickly went to shorter wavelengths, where it was more convenient to conduct experiments. Fig. 26 reviews Hertzian oscillators and detectors. The first three oscillators are attributed to Hertz himself.

Looking at oscillator #4, one may see what happens when the dipole is scaled down so that there is no more pole—just the two spheres. A sphere in isolation is almost critically damped; that is, at the end of one half-cycle, about 98 percent of the energy has been radiated [43], [44]. By placing two spheres in close proximity, however, they oscillate as a dipole. The purpose of the outside gaps is merely to implant the charge. If the charge is applied fast

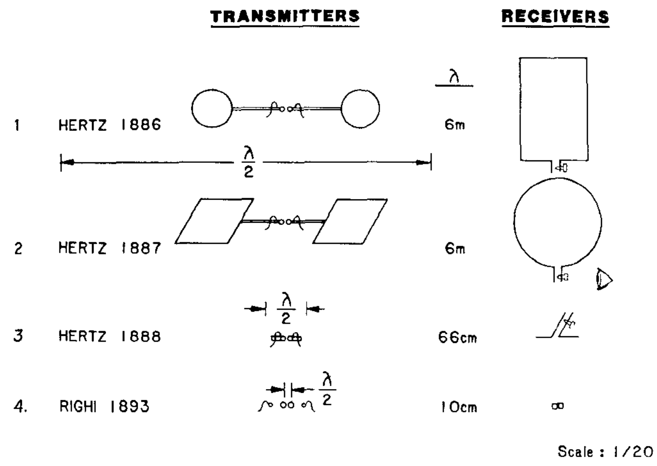

Fig. 26. A review of Hertzian transmitters and receivers.

enough, oscillation takes place, damped by radiation. The resonant wavelength of an *isolated* spherical conductor is related to the circumference. Stratton [45] gives the wavelength as 7.3 times the radius or 1.16 times the circumference.

Augusto Righi

Professor Augusto Righi at the University of Bologna was especially prolific in his work. Righi worked at wavelengths of 20, 10, and 2 cm. The extensiveness of his work is illustrated by a long article [46] and a lengthy review [47], but space does not permit an accounting of the experiments and contributions of Righi and numerous other investigators [48]–[51] using Hertzian waves, as they were called.

First Scientific Uses of the Electromagnetic Spectrum

Fig. 27 traces progress in the generation and use of Hertzian waves for scientific purposes, starting with the work of Hertz in the VHF range in 1886, UHF in 1887, continuing into the millimeter range by 1895, and the submillimeter range after 1900. Scientific work using the Hertzian-type oscillator continued to about 1925. At that time, wavelengths around 1/10 of a millimeter (100 μm), frequency 3 terahertz (THz), had been reached. The investigations were looking at the dielectric properties of solid and liquid materials [52]. Scientific results of work at millimeter and submillimeter wavelengths were limited at best [53], and spectroscopic work awaited the availability of continuous wave (CW) sources.

Simultaneously, experimentation, especially at the University of Berlin by Heinrich Reubens and his associates, brought the use of infrared sources to long wavelengths that overlapped those of the Hertzian oscillator.

Wireless Telegraphy

One of the first practical uses of the Hertzian oscillator and receiver was wireless telegraphy [54]. The family Marconi lived in the vicinity of Bologna. The parents of Guglielmo Marconi prevailed on Professor Righi to allow the young man to visit his university classes and laboratory. Righi's laboratory and shops were undoubtedly academic state of the art in Hertzian wave techniques and technology.

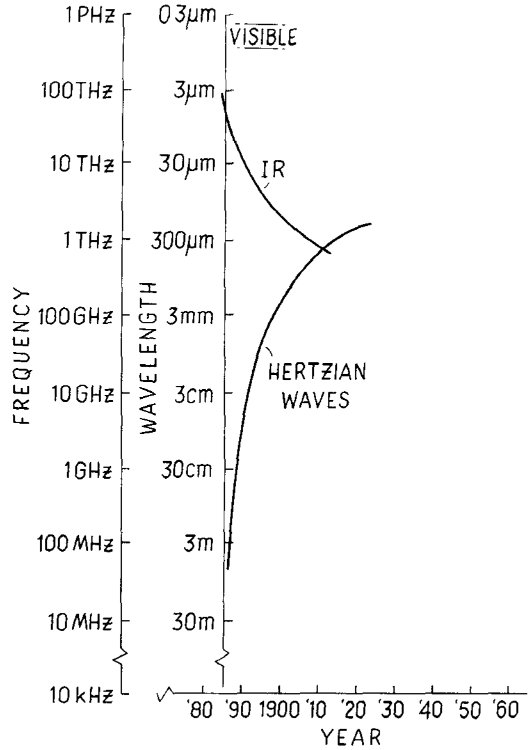

Fig. 27. "First use" of the RF spectrum.

In his wireless telegraphy system Marconi replaced the wire used in telegraph systems with a Hertzian transmitter and receiver. The high-power pulses of RF energy from the Hertzian oscillator could quite readily be formed into dots and dashes of Morse code for the transmitted signal in Marconi's wireless telegraph system. Since the eye was no longer suitable as a detector in the receiver, a device was needed that would detect an incoming electromagnetic wave and actuate the telegraph relay at the receiving end. Marconi found such a device in the *coherer* detector, described by Edouard Branly in 1890 and further developed by Lodge and others. The coherer consists of a glass tube containing loose zinc and silver filings, and metal plugs to make contact at each end. By placing the coherer detector in the center of the receiver dipole (in place of the detector spark gap), the filings cohere (stick together) with a sudden drop in resistance (e.g., from 2500 down to 1500 ohms) on receipt of even a faint signal of Morse code pulse. A telegraph relay in series with a battery and the coherer can thus be made to close each time a pulse signal is received. A means for separating the filings (decohering) for the next signal was also available from prior work by others: an extension arm on the relay strikes the coherer almost the instant the filings cohere, readying them for the next pulse signal. So far as the telegraph operator was concerned, he still had a telegraph key and he had a sounder.

The system that Marconi took to England and demonstrated to the British Post Office in 1896 operated at a wavelength of about 25 cm, frequency 1.2 GHz—in the microwave range. Operation was demonstrated between rooftops in London, and over distances of two miles on Salisbury Plain. Soon thereafter, for longer distances, recourse was made to much longer wavelengths by connecting one side of the spark gap switch to ground and the other side to a high and/or long antenna. This basic system was used extensively for at least 30 years.

High-Frequency Continuous Wave (CW) Sources

The start of systems applications, which centered on communications and early radar experiments, was stimulated by the advent of CW microwave signal sources in the 1920's.

The Barkhausen–Kurz (B–K) Tube

At the University of Dresden in 1919, Heinrich Barkhausen and K. Kurz discovered that a triode electron tube, when operated with the grid positive, could give high-frequency oscillations [55]. The highest frequency of operation obtained was around 1.5 GHz (wavelength 20 cm). The grid is operated positive, while the plate potential is made slightly lower than the cathode potential to reflect electrons back through the grid. The electrons oscillate back and forth in the potential well of the grid at a frequency determined by geometry (the radial dimensions of the tube elements) and voltage. By attaching an RF circuit that is resonant at the oscillation frequency, useful amounts of power may be extracted. A short section of Lecher line was commonly employed for the circuit. Unfortunately, Lecher line has low Q with some radiation due to its open construction, and therefore is unsuitable for systems use. Enclosed circuits in the form of coaxial line and waveguide (or a hollow cavity) came into use around 1932 and 1935, respectively.

The efficiency of converting dc to RF power is rather low and drops rapidly at shorter wavelengths [56]. The power output is limited, since the grid must collect all of the electrons, and grids are not designed to dissipate large amounts of energy. Nevertheless, the B–K tube was widely used for almost two decades from 1920, both as an oscillator and as a detector. Its CW output, in contrast to the Hertzian oscillator, made it suitable for use in experimental systems, as well as in tests and measurements.

Directed-Wave Radio, and First Use of the Term "Micro Waves"

Professors Hidetsuga Yagi and Shintaro Uda at Sendai University in Japan [57] made propagation studies in the mid-1920's and developed a directional antenna design developed by Uda that became known as the Yagi or Yagi–Uda antenna. Use was made of B–K tubes for both signal source and detector. Marconi got back to experimentation with radio at centimeter wavelengths in the late 1920's [58], also using B–K tubes for both signal source and detector. Some elaborate, well-known early experiments in microwave radio transmission across the English Channel were carried out in 1931 by IT&T engineers led by Adnre G. Clavier [59]. It was in connection with reporting on this project that the expression *micro waves* (as two words) was first used [60].

The Split-Anode Magnetron

The split-anode (segmented cylindrical anode) magnetron, useful down to wavelengths of 1 cm or less, was developed in at least three places: Czechoslovakia, Germany, and Japan. The work in Japan by Professor K. Okabe at Sendai University was aided by the high-frequency work in progress there due to Yagi. A path of technology transfer can be traced from there through several locations in the United States. The Japanese results were reported in the United States by Yagi on a lecture trip in 1928 [61]. His lecture in Schenectady stimulated interest and the start of work at a frequency around 400 MHz at the General Electric Co. Laboratories. In 1929 a General Electric magnetron found its way to Pittsburgh, where extensive early work was carried out at the Westinghouse Research Laboratories [62]. Fig. 28 shows a 40 cm wavelength magnetron under test in 1931. The resonant circuit is variable-length Lecher line, which is coupled to another line that is terminated with an incandescent light bulb for power output indication and measurement.

Fig. 29 shows a 9 cm split-anode magnetron developed at the Westinghouse Research Laboratories by G. Ross Kilgore. A 3/4 wavelength Lecher line across the two halves of the anode is contained inside the envelope. Designated MS-30, this magnetron design made history on several fronts. It was used in numerous tests of experimental point-to-point radio communication as well as bistatic CW radar in the 1930's. A 9 cm radio link (Fig. 30) was shown in Chicago during the 1933 World's Fair. Two such links were sold to the U.S. Army Signal Corps for $2500 each. A number of the 9 cm tubes were sold to the Naval Research Laboratory and other places [63].

Molecular Microwave Spectroscopy

One of the MS-30 tubes made history by finding its way to the University of Michigan physics department in December 1932. The design was scaled to shorter wavelength, and about 50 tubes (some of them operable at wavelengths down to 7 mm) were fabricated in the physics department shops. The tubes were designed and assembled by graduate student Claud Cleeton for a thesis project under Professor Neil Williams—the first microwave spectroscopy experiments [64]–[67]. John D. Kraus, a colleague of Cleeton's as a graduate student, has given a brief personal account [68].

One of the Cleeton 1 cm tubes has been on display at the Smithsonian Museum of American History in the first stage of the exhibit on the electronic measurement of time (in recognition of the first use of man-made electromagnetic energy to interact with an atom or molecule). More recently, a similar tube was placed in an exhibit by the same museum commemorating the first 25 years of the laser.

An interesting comparison of methods of measuring wavelength may be seen in comparing the work of Cleeton,

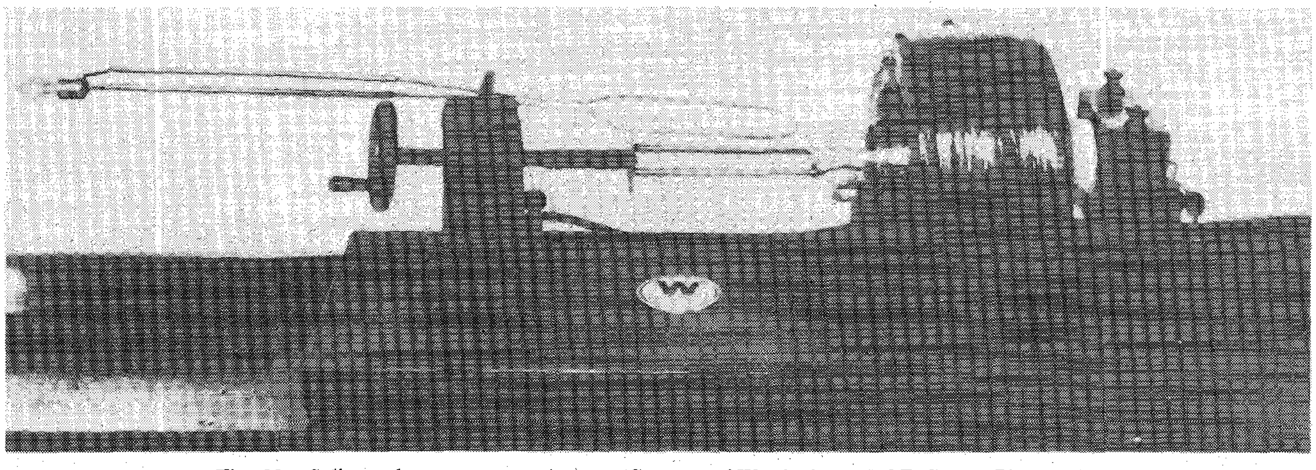

Fig. 28. Split-anode magnetron under test. (Courtesy of Westinghouse R&D Center, Pittsburgh.)

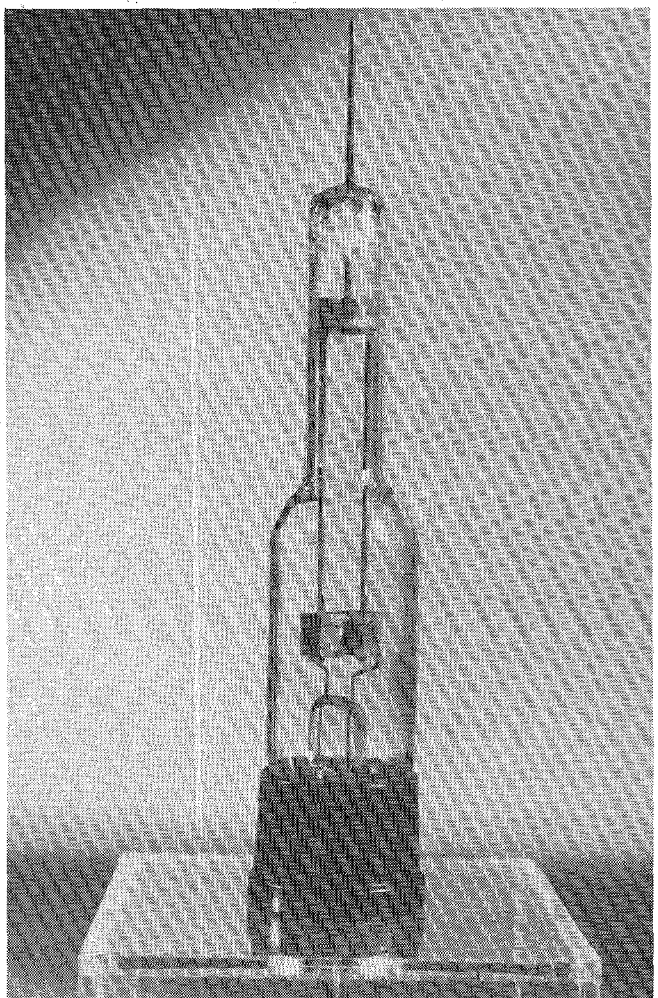

Fig. 29. MS-30, 9 cm wavelength split-anode magnetron. (Courtesy of Westinghouse.)

who used a reflecting type of echlette grating in 1934 (an idea borrowed from optical measurements) [69], and that of Harold Shaw Howe, who six years later used new technology—a waveguide resonant cavity wavemeter which he built [70]. Both Cleeton and Shaw used an iron-pyrite crystal detector and a sensitive galvanometer for their receiver, with about 25 dB dynamic range.

Still another MS-30 tube found its way to RCA in Camden, New Jersey, via Vladimer Zworykin, of electronic television fame, who spent ten years at Westinghouse before moving to RCA. At Westinghouse, Zworykin had been influential in getting the company involved in microwave electron tube work aimed at devising new means for communicating from point to point. In the latter part of 1933 Kilgore was working on 1.7 cm tubes, but the microwave work at Westinghouse was canceled in a depression move and his job was eliminated. Subsequently, at RCA in Harrison, New Jersey, Kilgore was the victim of roles and missions policy in a large corporation. The organization in Harrison was authorized to work only at wavelengths longer than 50 cm, but for Camden, New Jersey, work at any shorter wavelength was authorized. Improved 8 cm tubes by Ernest G. Linder under Irving Wolff at RCA Camden were used in early communications and radar tests, including company-sponsored field tests in cooperation with the U.S. Army [71]. The United States armed forces abandoned all interest in microwave radar around 1935 in favor of work at longer wavelengths.

Over 200 papers on split-anode magnetrons were published worldwide prior to 1940, optimizing the design or describing how to use them. This was largely a case of optimizing the wrong design, as shown by the development of the cavity magnetron in early 1940. The reporting on rapid advances in microwave components, devices, and their uses in the 1940's has, however, tended to overshadow much significant work [72] (almost all of it company-sponsored in the United States) preceding that time. In magnetrons, Linder [73] reported obtaining 20 watts of power at 8 cm wavelength with 22 percent efficiency. Kilgore reported getting over 100 watts at 50 cm [74] with 25 percent efficiency, and he projected 50 percent. Budgets were meager, however, and Kilgore has noted that the United States armed services never asked for tubes designed for pulsed operation [75]. A promising 16 cm design at SFR in France making use of an eight-segment interdigital anode was a direct influence on the early use of a

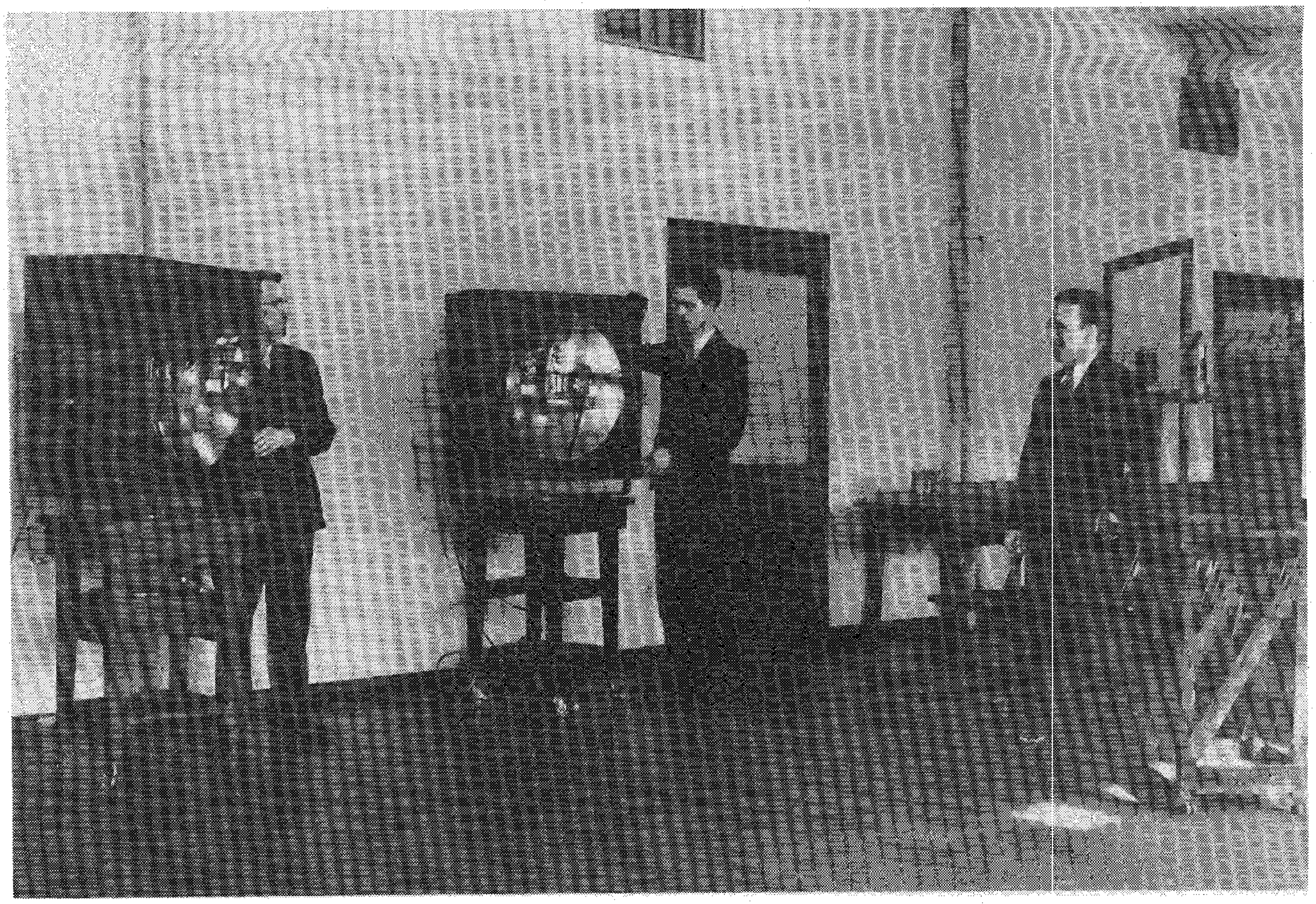

Fig. 30. 9 cm wavelength microwave link. Pictured, left to right, I. E. Mouromtseff, G. Ross Kilgore, and Henry N. Kozanowski. (Courtesy of Westinghouse.)

large-diameter oxide cathode in the cavity magnetron. This same design was scaled to 6 cm wavelength and used as a transmitter in the first microwave radio relay system, the British Wireless Set No. 10.

RF Transmission Lines

To obtain a uniform transmission line that would be free from reflecting objects in the vicinity, such as concerned him in his wire-over-ground-plane experiments, Hertz (1887) made use of a section of coaxial line. He demonstrated the shielding of waves inside the line and showed that the wavelength in the line was the same as in free space, for the same dielectric. Coaxial line was then forgotten until the first practical use began in the early 1930's [76].

The parallel two-wire type of transmission line was first used by Ernst Lecher at the University of Vienna [77], [78] in 1890 in instrumentation for the measurement of the dielectric constant of various materials, hence the term *Lecher line*. Lecher made use of the fact that, for practical purposes, the wavelength on the two-wire line is the same as in free space. The property that the wavelength on the line is practically the same as in free space makes both coaxial line and balanced two-wire line convenient for the measurement of wavelength. The distance between nodes of a standing wave is physically one half-wavelength. Wavemeters of the two-wire line configuration were often the easier of the two to build and use, while coaxial line had the advantage of being shielded as well as having higher Q.

Practical use of hollow waveguide was begun independently by Wilmer L. Barrow of MIT and George C. Southworth of Bell Laboratories in the mid-1930's [79]. In the same time period William W. Hansen began to focus on the high-Q properties of resonant cavity circuits and contributed in large measure to a turning point in the design of microwave components and devices.

Early Radar

Although the need for more and better communications produced a steady and continuous pressure on the development of microwave technology, no single application has had a more dramatic effect on microwave development than radar. Radar was not a single invention. It is a principle, the essential feature of which is the sending of high-power pulses of radio frequency (RF) energy and the reception of echoes of that energy (much reduced in strength) reflected from remote objects—mountains, ships, and airplanes. Although the long-range military bomber aircraft created a specific need for radar for defense in the mid-1930's, it seems likely that radar would have been developed without World War II. There was awareness of the need for improved anticollision and navigation systems.

Radar was developed in several countries independently and simultaneously in the 1930's [80]: Great Britain, Germany, Canada, the U.S., Italy, Russia, Japan, and the Netherlands. The desire for secrecy ensured independence of work in each country. The year 1935 was the start of the formative period. The recognized vulnerability of Britain did place urgent pressure on defense measures there, and development effort was intense in all branches of the services. In 1939 a commitment was made to develop centimeter-wave radar. This was a crucial step militarily and also for the history of microwaves.

In the United States, the National Defense Research Committee (NDRC) was initiated in June 1940. A committee on detection, which quickly became known as the Microwave Committee, held its first meeting the following month at the private laboratories of Alfred L. Loomis in Tuxedo Park, New York. Attention had quickly focused on microwave radar and navigation. The principal centers of microwave work at the time were the Massachusetts Institute of Technology (MIT), Stanford University, and the Bell, General Electric, RCA, and Westinghouse laboratories. Intense study and effort, and the visit by the British Scientific Mission headed by Sir Henry Tizard in the fall of 1940, brought into focus the need to organize a laboratory under some contractor, to carry out the vast amount of work to be done. MIT was selected as the site and the contractor for the Radiation Laboratory, and activity was initiated there in November 1940.

II. Improved Devices, Key to Modern Microwave Systems

The development of microwave systems awaited signal sources that would have better stability, greater efficiency, and freedom from stray radiation. The first modern devices with useful efficiency and stability *and* that were suitable for systems use resulted in large measure from two advances: (1) making use of transit time in electron flow, instead of having it be a major handicap to high-frequency performance, as it is in gridded electron tubes, and (2) creation of the high-Q resonant cavity. The history of microwave electron tubes [81] is rich in theoretical analysis and practical accomplishment in a wide range of devices and applications.

Heil and Heil: Velocity Modulation

In 1935 Oscar Heil and his wife, A. Arsenjewa-Heil, of C. Lorenz, AG, in Berlin, published a paper on a proposed velocity modulation device. They predicted 35 percent efficiency in converting the dc potential energy of an electron beam into useful radio frequency (RF) power [82]. No experimental results were given, and the circuits to be used were not defined. Later, tubes referred to as Heil tubes were built and used at a number of places, especially in Europe. Any results, however, tended to be overshadowed by the klystron, invented in 1937 and available from several manufacturers three years later. The high-Q resonant cavity circuit was a key factor in the success of the klystron.

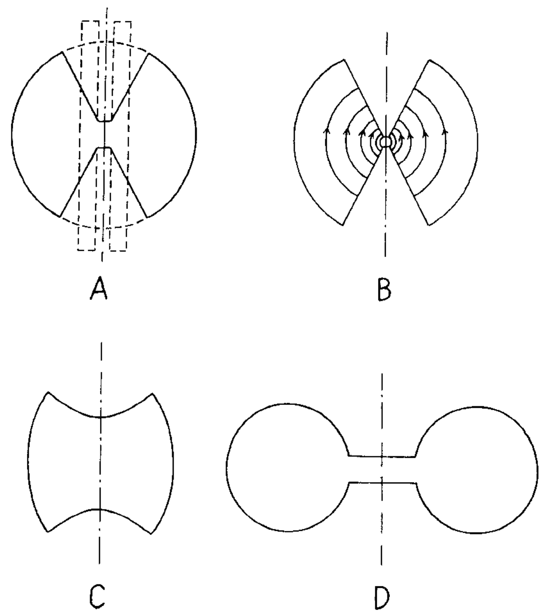

Fig. 31. Resonant cavity geometries studied analytically by William W. Hansen. (After Hansen.)

Hansen's Resonant Cavity

The klystron was developed at Stanford University as a result of work on the very high Q resonant cavity, plus intense interest on the part of Russel and Sigurd Varian in obtaining a microwave signal source.

In the mid-1930's at Stanford there was a major interest in X rays in the physics department. The high-voltage limits of ordinary power supplies had about been reached due to high-voltage breakdown in insulators. A young professor, William W. Hansen, reasoned that if he could produce high enough Q in an RF cavity he should be able to accelerate electrons using modest amounts of RF power [83], [84]. That idea was the forerunner of the linear accelerator. It took several steps, however, before a workable linear accelerator was built in the late 1940's. In the meantime, Hansen's work was applied directly to the design of high-Q resonators for use in electron tubes, a major turning point in microwave history.

Fig. 31 [85] shows the cross sections of four geometries that Hansen could analyze mathematically. Here he is emphasizing the optimization of volume-to-surface ratio, with the knowledge that the Q_0 of a cavity is defined as 2π times the ratio of the time-averaged energy stored in the cavity to the energy loss per cycle. Note the outline of a reentrant coaxial cavity on the resonator at (a). The contrast in the (smaller) surface area compared to the coaxial line resonator is dramatic. The doughnut shape at (d) became the resonant circuit for the first klystron.

The Klystron

When the flat surfaces are made into grids, an electron beam sent through the first set of grids is velocity modulated by any RF voltage present. In the field-free drift region, going to the second cavity, the electrons become bunched. These bunches, passing through the second cavity, give up significantly more energy than that required to do the bunching in the first cavity. The device is an amplifier. By feeding some of the RF energy back to the input cavity in the correct phase, one has an oscillator.

A one-cavity, reflex klystron oscillator [86], in which the bunched electrons are directed back through the cavity by means of a variable-voltage electrode in correct phase to sustain oscillation, was discovered by several investigators. In addition to being mechanically tunable by changing the size of the cavity, the device is voltage tunable by as much as 1 percent with the potential on the reflector. This electronic tunability afforded automatic frequency control (AFC) for the local oscillator to drive the mixer in microwave radar receivers.

The klystron was the workhorse signal source in experimentation, systems development, tests, and measurements in the ensuing years of intense microwave systems development and use. Independent early investigations of velocity modulation electron tubes at both General Electric [87], [88] and Stanford produced operable devices. The General Electric work did not follow through to systems applications, although William C. Hahn and his associates extended their work to include a number of interesting devices.

The invention of the klystron at Stanford [89] was the result of teamwork, combining diversified talents: Russel Varian, an engineer with industrial experience including vacuum tubes; his brother Sigurd, a pilot with knowledge of the shortcomings of available electronics equipment; Hansen, skilled in analytical and experimental work; and David L. Webster, head of the physics department. Webster was the source for the meager budget, provider of the facilities, level-headed mentor, and spokesman. Webster did an analysis of the devices' operation, predicting theoretically that 57 percent of the energy in the electron beam could be converted to RF [90].

By 19 August 1937 the first laboratory model was built on a shoestring budget [91], operating on a vacuum pump, with a barely discernible but identifiable output. To move from this pioneering device to an extensive series of devices available in the 1940's from multiple manufacturing sources required the application of diverse talents, know-how, facilities, and support, both academic and industrial.

A great deal of insight into the formative years of the klystron's development, from 1937 through 1940, can be obtained from the book *The Inventor and the Pilot*, a biography of the Varian brothers [92], [93]. Taking it as an account of personal records and assuming its accuracy in detail as far as it goes, due regard must be taken of the evident conflicts and often strained relations with the company which sponsored them from an early date. The book presents an absorbing story. Reading it, one can appreciate the heroic struggle and sacrifice of the Varians and their colleagues to bring the klystron into being on a severely limited budget. The story of the Sperry Gyroscope Company's essential role starting at that point is not contained in the book and has not been fully reported to date.

Briefly, the Sperry Gyroscope Company took an early and active interest in the new invention, and came to a business agreement with the inventors and with Stanford University. William T. Cooke, a Sperry employee, moved with his family from Long Island to California in mid-1938 to become the manager of the Sperry klystron project. He and a new employee engineer, Joseph J. Caldwell, became research associates without pay in the physics department at Stanford, as did Charles V. Litton, a well-known local manufacturer of mechanical and high-vacuum pumps and glassworking equipment. Support for equipment and salaries for the Varians and for Hansen was started in 1938.

A Sperry plant was set up in San Carlos in 1939. Corporate attorneys worked with Russel Varian and Hansen on patent coverage, as well as licensing other companies to manufacture klystrons. Production designs were made and two types were manufactured, both of the two-cavity oscillator design. High-power 750 MHz continuous pumped tubes were used in tests of aircraft blind-landing equipment in Boston and Dayton. *S*-Band (3 GHz) klystron tubes manufactured at the plant were shipped to the Bell Laboratories, Federal Telephone and Radio, General Electric, Westinghouse, CSF in France, a laboratory in England, the Alfred Loomis Laboratory, and the MIT Radiation Laboratory [94].

The Sperry San Carlos facility was moved and ten Sperry employees relocated to Garden City, Long Island, New York, in December 1940. They were joined by eight people from Stanford including the Varian brothers (all of whom became employees). This combined group of people became the nucleus of management and staff in an organization which performed an important function in wartime product development and production. The well-known company Varian Associates, Inc., was formed in California in 1948.

The High-Power Cavity Magnetron

Many separate inventions contributed to the development of varied forms of radar equipment. One of the most important and timely inventions was the high-power cavity magnetron, created by Henry A. H. Boot and John T. Randall under wartime pressure at a research center headed by Mark L. Oliphant at Birmingham University in England in early 1940 [95]. This magnetron, in contrast with the split-anode magnetron used since 1927 in scientific and experimental systems work, allowed the efficient generation of very high power pulses of RF energy at wavelengths of 10 cm, and at 3 cm soon thereafter. Microwave radar thus became feasible: high-definition radar that was small enough to use in aircraft, and long-range radar for ships and ground-based installations.

Randall credits Heinrich Hertz's resonant loop, which he remembered reading about, for the idea which led to the specific design of the resonant cavity [96], [97] (Fig.

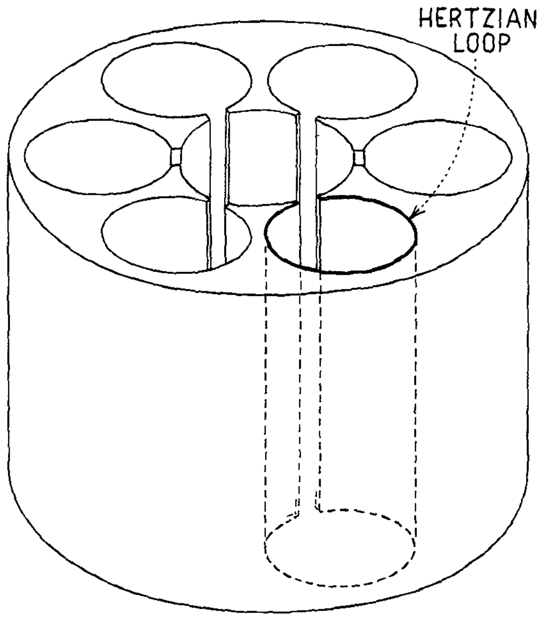

Fig. 32. Illustration of the concept of making a resonant cavity by drawing the Hertzian resonant loop down to a cylinder with a side slot, and the placement of several (an even number) of these around a central cathode space to form the anode block of a multicavity magnetron.

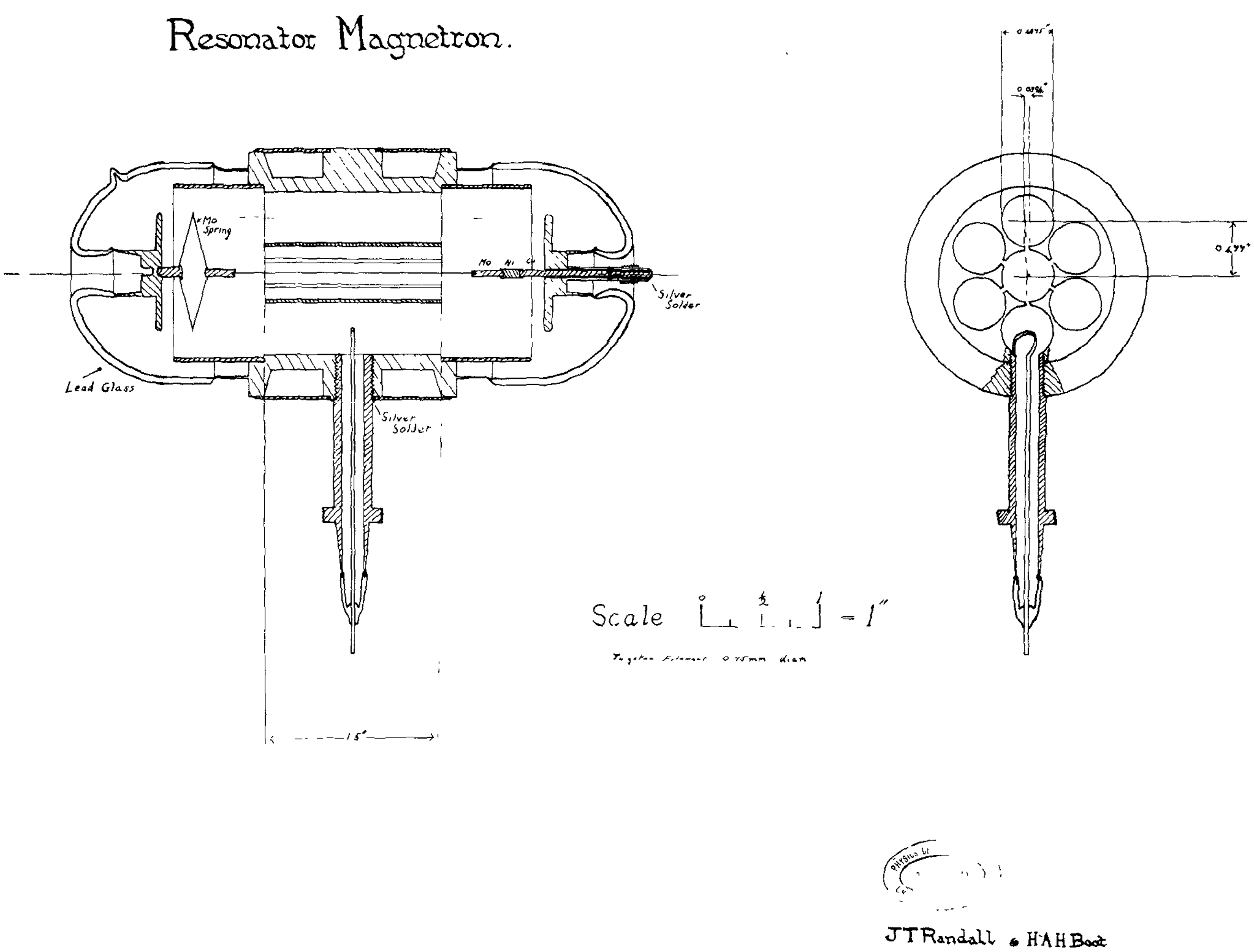

Fig. 33. Drawing of the first multicavity magnetron. The stamp at lower right reads: "Physics Dept. A. Research Univ. of Birmingham. 21 Feb., 1940." (Courtesy the Institution of Electrical Engineers, Savoy Place, London.)

32). Randall reasoned that if the loop were drawn down into a cylinder with a slot on the side, one could store a great deal of energy with resulting high Q. Placing a number of these resonators (an even number) around a cathode, such as had been done with multisegment split-anode magnetrons, yielded the design for the anode block of the multicavity magnetron. Starting with the first machined anode block in October or November 1939, they operated the first model on the pumps on 21 February 1940.

Test equipment was in short supply in the Birmingham laboratory. The investigators had built their own power supply. For the needed magnetic field they adapted an electromagnet that had been used for another purpose. It was evident from the corona discharge around the output probe that the tube was producing a great deal of power. Although the investigators had designed the tube for operation at 10 cm wavelength, they thought that for some reason it must be operating at a longer wavelength. After hours of work they succeeded in loading the tube with enough light bulbs to indicate that the tube was producing several hundred watts of CW power. Using a Lecher line, they determined that the wavelength was 9.8 cm [98].

Fig. 33 [99] is a drawing of the cross-section detail of the magnetron. The anode block has six cavities, placed around the central filamentary cathode. The cavities are closely enough coupled that power can be taken from just one of them. The output coupling loop located in one of the cavities is connected by a short piece of coaxial line to a probe for coupling to waveguide. The design is remarkably well suited for use as a high-power, pulsed transmitter. The anode is a block of copper, suitable for rugged mechanical design and large power dissipation. In April 1940 the Research Laboratories of the General Electric Co., Ltd., at Wembley was asked to help with the design of a sealed-off, manufacturable version of the tube. Eric C. S. Megaw of GEC Laboratories in particular made substantial contributions to improvements in the design. The anode block was shortened, allowing use of a permanent magnet. Megaw was in communication with engineers at SFR (Societie Francais Radioelectrique) in France, and had discussed possible use of oxide-coated cathodes in magnetrons in place of filamentary cathodes of tungsten wire. An SFR 16 cm wavelength eight-segment anode (M-16) magnetron with a filamentary cathode is in the IEEE MTT-S Historical Collection (Inventory #A82) [100]. A later, oxide-cathode version was delivered to the GEC Laboratories in Wembly on 9 May 1940 by Dr. Maurice Ponte of SFR. This directly contributed to a very significant advance in the design of the cavity magnetron, the adaptation of a large-diameter, oxide-coated cathode. One of the M-16 oxide-cathode tubes, if not the identical one, is also in the IEEE MTT-S Historical Collection (Inventory #A125).

The filamentary cathode (Fig. 33) was replaced with a large-diameter, oxide-coated cathode. Such a cathode affords high peak currents under pulsed conditions.

This type of free-running oscillator was extremely important at the time as the answer to the urgent need for high-peak-power transmitters in the first microwave radars. Within 20 years it was made obsolescent by amplifiers for use in radar transmitters and other transmitting equipment.

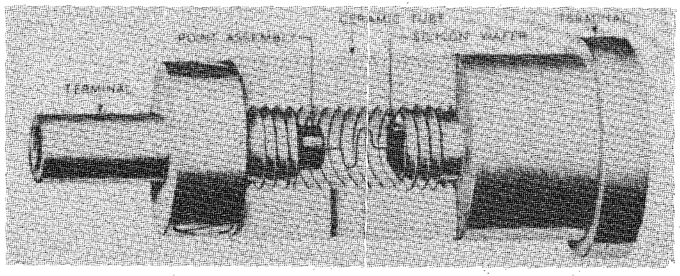

Fig. 34. Silicon point contact diode. (Courtesy of D. van Nostrand–Wadsworth Publishing Company.)

Crystal Detector

A typical semiconductor diode (used either as a detector or a mixer) of 45 years ago—a silicon point contact diode—is shown in Fig. 34. It was used extensively in mixers (superhet converters) in early microwave radar receivers, and was improved and widely used into the 1960's. Seeing it today, however, and contrasting it with what is now available, we can realize just how fast progress has been in solid-state devices in the past 45 years.

III. Microwave Radio Relay System

The first microwave relay system was the British Wireless Set No. 10. Sidney Metzger describes its influence on similar United States designs [101]:

> During the summer of 1942, the United States Army Signal corps received word that the United Kingdom's Signals Research and Development Establishment (SRDE) at Horsham, Sussex, had developed an 8-telephone-channel time division multiplex (pulse width modulation) and 5 GHz (6 cm wavelength) RF system (transmitter and receiver) designed to operate in tandem as a radio relay. On September 24, 1942, Harold S. Black of Bell Telephone Laboratories, Bertram A. Trevor of RCA (Riverhead and Stony Point, New York) and myself representing the Signal Corps Labs., flew to England to examine this equipment, so that American versions could be built in the United States. We visited the SRDE Lab at Horsham, where a prototype had been built. In addition, we visited the companies who were starting production of what was termed Wireless Set No. 10. The Pye company in Cambridge was building the RF section, and the TMC Company was building the multiplex portion.
>
> Upon our return to the States, November 14, 1942, Bell embarked on the design of an 8-channel pulse position modulation radio relay set, the AN/TRC-6, of which 90 sets were built and used in both the European and Pacific Theaters. RCA's version was designated AN/TRC-5, which performed the same overall mission, but differed from the AN/TRC-6 in a number of design parameters.

Published descriptions of these microwave radio sets appear in [102]–[105]. The statement on page 337 of [106]: "AN/TRC-6 radio set—first microwave multichannel communication equipment" seems incorrect. That distinction must go to the British Wireless Set No. 10. The

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John H. Bryant (M'50–SM'52–F'67) is an Adjunct Research Scientist in the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor. He holds the B.S.E.E. degree from Texas A&M University and the M.S. and Ph.D. degrees from the University of Illinois.

He spent six years each at IT&T Laboratories, concerned with microwave electron tubes, and the Bendix Research Laboratories, with interests in passive microwave components and radar systems. In 1962 he was a founder of Omni Spectra, Inc., and served as its President and Chief Executive Officer. In 1980 Omni Spectra became a part of M/A-Com, Inc.

Dr. Bryant is a Past President of the IEEE Microwave Theory and Techniques Society (MTT-S), and served as Chairman of the IEEE MTT-S Hertz Centennial Committee.