Milestones of Microwaves

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Invited Paper

***Abstract*—This paper presents a compilation of the important milestones in the development and applications of microwave technology from the time of Hertz until 1980. The years from 1980 to the present are not addressed since this period will be covered in depth in other papers of this TRANSACTIONS. The primary technology areas addressed are electromagnetics, guided microwave structures, free-space propagation, power generation using tubes and solid-state devices, passive devices, microwave integrated circuits, ferrites, microwave acoustics, and microwave biological effects. The primary application areas are communications, radar, heating, and medical applications. Design techniques, measurements, and instrumentation are also discussed.**

***Index Terms*—Microwave applications, microwave detection, microwave ferrites, microwave generation, microwave history, microwave integrated circuits, microwave passive devices, microwave solid-state devices, microwave tubes, waveguides.**

I. INTRODUCTION

THE field of microwave technology is based on a rich history dating back to the 19th Century and the fundamental discoveries in electromagnetics by such giants as Faraday, Maxwell, and Rayleigh and the ingenious experiments of Hertz that verified the concepts of electromagnetic-wave propagation. Subsequent workers were fortunate to have had a very strong and elegant foundation, especially that established by Maxwell with his famous equations. The primary efforts of these workers were in the generation, guidance, detection, and control of short-wavelength electromagnetic-wave propagation. The development of the field over the past 100 years may be characterized in very general terms as follows:

1) study and applications of electromagnetic-wave propagation, described by Maxwell's equations, in various media with a wide range of boundary conditions;
2) interaction of propagating electromagnetic waves with solids, gasses, fluids, and charged particles;
3) interaction of propagating electromagnetic waves with matter under various states of energy excitation and the reciprocal conversion of microwave energy to other various forms of energy in this matter.

Applications of the technology have been a key driver in the development of the field over the past 100 years. Marconi was the earliest to recognize and advance communication technology using electromagnetic propagation in free space and in doing so established the base for the development of radio, radar, television, long-distance telephony, satellite communication links, and wireless access systems. Microwaves have become a ubiquitous technology that is used not only for communications and radar, but also for the characterization and analysis of materials, cooking and industrial drying, medical diagnosis and treatment, radio astronomy, and transmission of power. Today, the technology plays a key role in fiber-optic communication and high-speed computing systems.

The thrust of the research supporting microwave technology has been in establishing the basic elements to support the growth and development of the applications and also to extend the usable spectrum to higher and higher frequencies including the millimeter and submillimeter wavelengths and eventually to the optical wavelengths.

The origin of the term *microwave* deserves mention in a discussion on microwave milestones. Nebeker of the IEEE History Center has provided the following information on the subject. Early published work in 1902 referred to short waves and "quite short waves." Erskine-Murray's 1907 *Handbook of Wireless Telegraphy* refers to "short-wave Hertzian telegraphy." The first citation of the term *micro* in the context of electromagnetic waves was in 1931 in a paper [1] published by the International Telephone and Telegraph describing an 18-cm wavelength radio link from Dover, U.K. to Calais, France. The radiation was called *micro-wave* and the radio system was called *micro-ray*. A photograph of a *micro-ray* terminal is shown in Fig. 1 [1], [2]. Subsequently, in a 1933 publication [3], the term *microwave* (one word without a hyphen) was used to refer to wavelengths of about 0.5 m. Reference [4] referred to *microwaves* as wavelengths less than 10 m and the 1940 *Amateur Radio Handbook* referred to *microwaves* as wavelengths below 1 m. In retrospect, *centimeter waves* would have been a better choice and would have been consistent with the later terms *millimeter* and *submillimeter* wavelengths. However, this latter choice would have created an awkward name for the *centimeterwave* used to pop the popcorn.

This paper lists the major milestones in microwave technology over a period of approximately 100 years, up to 1980. Progress in the last 20 years of the 20th Century is not addressed since the area is covered in detail in other papers in this TRANSACTIONS. In an effort to keep the reference list to a reasonable length, references for the milestones are usually cited as previously published microwave history papers that addressed those milestones. Where this was not possible, the original references are shown. Several

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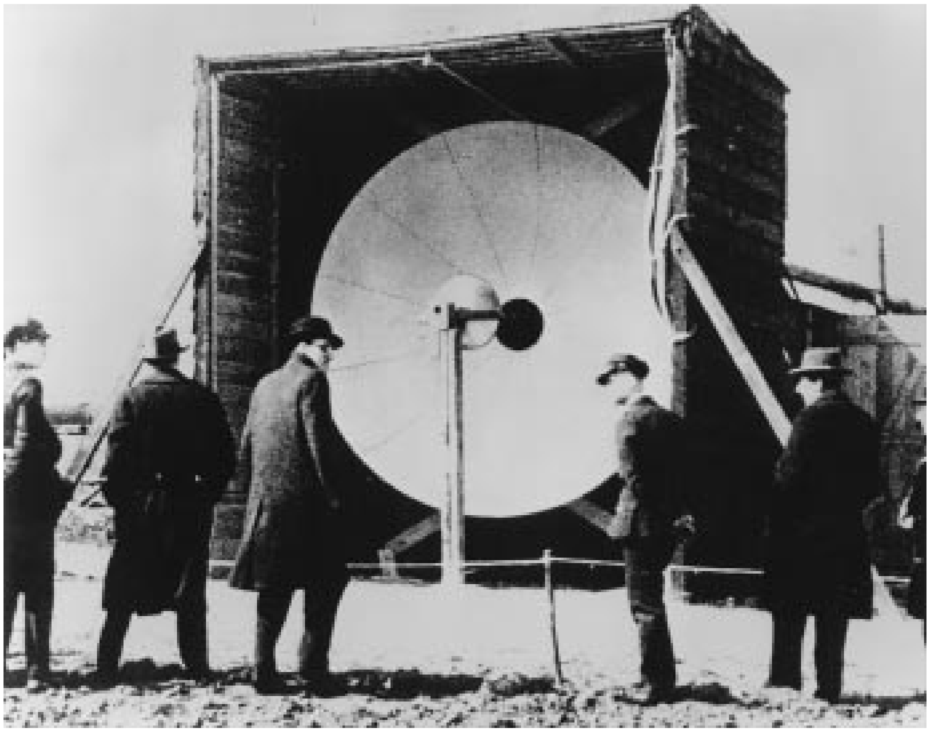

Fig. 1. Terminal of micro-ray link, Dover, U.K. to Calais, France, 1931 (courtesy of ITT) [15].

publications [5]–[12][1] that present excellent detailed histories were used for much of the source material for this paper. The milestones are, in most cases, associated with either the contributing individuals or the sponsoring entity.

II. Time Periods and Technical Areas

The milestones are presented in several time periods and for specific technical areas. Each of the time periods is briefly summarized in the milestone charts. The technical areas are categorized as follows:

- electromagnetics and waves;
- guided microwave structures;
- free-space propagation of microwaves;
- power generation and tubes;
- solid-state devices;
- microwave integrated circuits;
- receivers;
- passive devices;
- ferrites;
- microwave acoustics;
- design techniques;
- measurements and instrumentation;
- microwave applications—communications;
- microwave applications—radar;
- microwave applications—heating;
- microwave biological effects and medical applications.

The applicable categories are discussed for each of the time periods.

[1]Reference [11] was reprinted for the 1991 IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Symposium, June 10–14, 1991, Boston, MA.

III. Milestones

A. Prior to 1880: "Seeds of the Field"

This is the period of fundamental discovery of electromagnetic waves and also the invention of electrical information transmission.

1) Electromagnetics and Waves:

1831: Faraday discovers electromagnetic induction [7].
1864: Maxwell presents his theory of electromagnetics [7].
1877: Lord Rayleigh presents his theory of sound propagation [14].

2) Applications of Microwaves—Communications [15]:

1844: Morse invents telegraphy.
1876: Bell invents the telephone.

B. 1880–1900: "Proving and Applying Maxwell's Theory"

This was a very significant period in which Hertz performed many experiments that showed that Maxwell's equations indeed described the propagation of electromagnetic waves through the atmosphere and space. He developed equipment to produce, radiate, and detect microwaves and observed the reflection of microwave energy from solids, the basis of radar. During this period, Maxwell's equations were applied to describe propagation in certain waveguide structures and Hertz's spark generator was extended to produce millimeter waves. Edison observed electron emission from filaments, the basis of electron tubes that were invented many years later. Marconi extended Hertz's work in the laboratory to wireless transmission of telegraphy over paths of several miles. A photograph of Hertz's equipment setup is shown in Fig. 2.

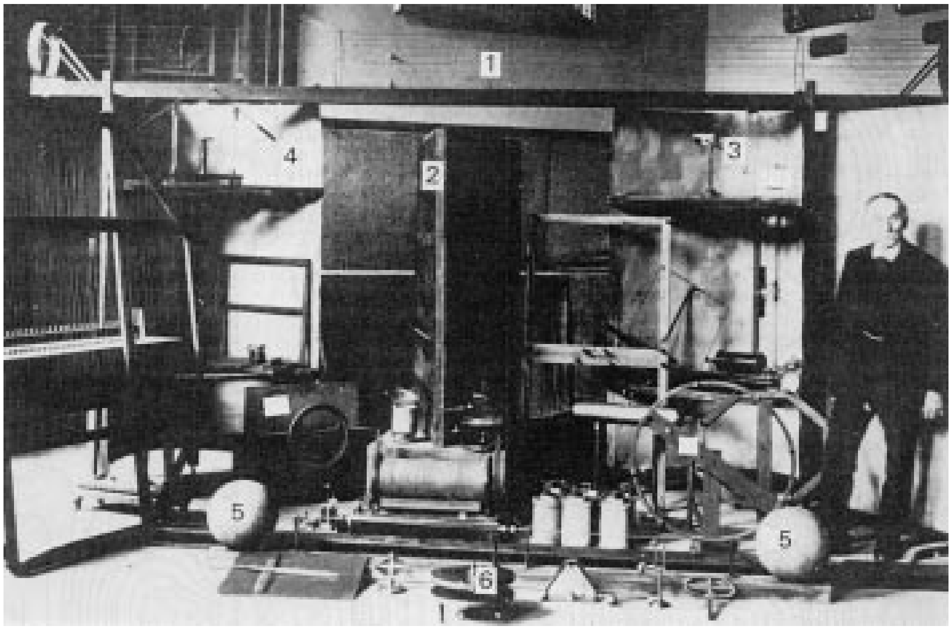

Fig. 2. Hertz's original apparatus, which he used in his epoch-making experiments at the institute of technology at Karlsruhe. Photograph taken in 1913 at the Barvarian Academy of Science in Munich, Germany, where the equipment has been transferred (courtesy of the Museum of Science and Technology, Chicago, IL) [8].

1) Electromagnetics and Waves:

1885: Hertz demonstrates electromagnetic-wave propagation in a series of experiments covering a period through 1897 [8].

1897: Lord Rayleigh applies boundary values and describes the modes that electromagnetic waves exhibit when propagating in metallic cylinders [13].

1899: Sommerfeld studies electromagnetic waves guided by lossy cylindrical wire [13].

2) Power Generation and Tubes:

1883: Edison discovers electron emission from heated filaments [15].

1893: Hertz uses a spark gap generator to produce 0.5–1-GHz signals [9].

1895: Bose and Lebedew extend Hertz's work on the spark gap generator to produce 5–6-mm-wavelength signals [17].

3) Free-Space Propagation of Microwaves:

1894: Marconi, using Hertz-type equipment, transmits telegraphy signals over a two-mile path during the period through 1896. Marconi was awarded a Nobel Prize in 1909 for his work on wireless telegraphy [15].

4) Applications of Microwaves—Communications [15]:

1898: Lodge invents tuned transmitters and receivers that use resonant circuits.

5) Applications of Microwaves—Radar [18]:

1886: Hertz observes that electromagnetic waves are reflected from solid objects.

C. 1900–1920: "Long Distance Communications and Vacuum Tubes"

During this period, wireless systems operating over very long distances (but at relatively low frequencies) were developed and placed into commercial service. Vacuum tube devices were developed for power generation and receiving functions at frequencies extending into the microwave range. Fig. 3 is a photograph of Marconi in 1901 with the receiving equipment for his first transatlantic transmission experiments.

Fig. 3. Marconi at Signal Hill, St. Johns, Newfoundland, December 1901, after the first transatlantic wireless transmission (courtesy of Marconi Corporation plc, L. Weymouth).

1) Electromagnetics and Waves [13]:

1902: Weber proposed that propagation in a hollow tube was equivalent to a plane wave following a zigzag path due to reflections from the walls of the tube. As a consequence, the group velocity of the wave is less than the velocity of light in the medium. This interpretation was revived in later years and is usually used in introductory courses on microwaves.

1909: Hondros, DeBye, Zahn, Ruter, Schriever, Zenneck, and Watson conduct studies of propagation on dielectric rods and surface waves over the period through 1920.

Fig. 4. Audion vacuum triode, 1908. Bulb diameter is 2 in (5 cm) (courtesy of the Historical Electronics Museum).

2) Power Generation and Tubes [15]:

1902: Fleming invents the vacuum tube diode detector.
1906: Fessenden builds an 80-kHz rotating alternator and applies audio modulation.
1907: DeForest invents the vacuum tube triode amplifier. Fig. 4 is a photograph of an early DeForest amplifier.
1914: AT&T builds a 170-kHz transmitter with 18 triode tubes in the final stage.
1919: Southworth uses a Lecher line circuit to operate a vacuum tube triode at a wavelength of 110 cm.
1919: The Barkhausen-Kurz tube is invented and operated at 10 GHz [16].

3) Solid-State Devices [15]:

1906: Thomas, Hunt, Whittmore, Dunwoody, and Pickard invent and develop crystal detectors over the period through 1916.

4) Receivers [19]:

1906: Einstein predicts spontaneous fluctuation of current and voltage in circuits, a basis of noise in receivers.
1918: Schottky discovers the shot effect.

5) Ferrites [20]:

1909: Hilpert invents the synthetic ferrite.

6) Applications of Microwaves—Communications [15]:

1900: Marconi develops and operates a transatlantic low-frequency radio-communication system with a 1700-mile path length using ground-wave propagation and by 1920 operates on the path at 15–20 MHz with skywave propagation.
1914: AT&T operates a 170-kHz radio-communication system with a 4900-mile path length using 500 triode tubes in the final amplifier to obtain 2.5 kW of transmitted power.

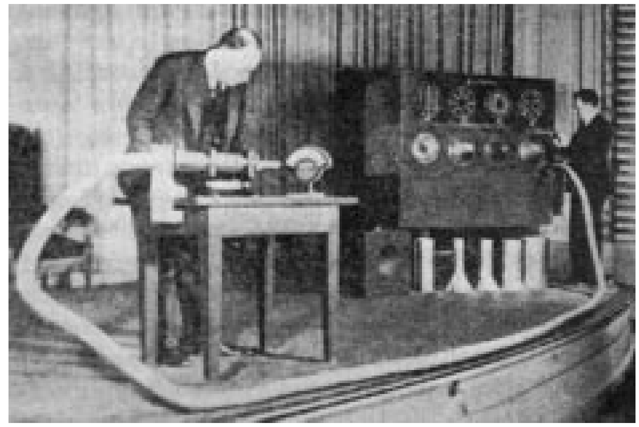

Fig. 5. Southworth demonstrating different waveguide modes and cutoff frequencies on Feb. 2, 1938. This was the first demonstration of waveguides before the IRE in New York. (courtesy of Gordon and Breach) [27].

7) Applications of Microwaves—Radar [18]:

1903: Hulsmeyer in Germany patents a system for detection of obstacles and navigation for ships using reflected radio waves.

D. 1920–1935: "The Waveguide Era Blossoms and Microwave Communications and Radar are Born"

During this period, major advances were made in the theory and development of cylindrical and rectangular waveguides. Early work was reported on the first magnetron and velocity-modulated tubes. The concept of thermal noise was presented. The first radios operating in the microwave bands were developed and significant advances were made in establishing the feasibility of radar systems. Fig. 1 shows a photograph of the *micro-ray* microwave terminal discussed in Section I. Fig. 5 shows a photograph of Southworth demonstrating his circular waveguide transmission.

1) Guided Microwave Structures [13]:

1932: During the period until 1936, Southworth of AT&T conducts experimental studies and demonstrates that the TE_{11} mode is the lowest order propagating mode in a circular waveguide. Carson, Schelkunoff, and Meade provide theoretical support. Southworth's goal was to use waveguides as a broad-band transmission media for high-capacity telecommunications.
1933: Barrow of the Massachusetts Institute of Technology (MIT) also conducts experimental and theoretical studies of circular waveguide propagation.
1934: Schelkunoff and Meade discover the TE_{01} mode in circular waveguide and find that the loss decreases as frequency increases. Schelkunoff, Espenchied, and Strieby present the principles of coax circuit design. Schelkunoff introduces the concept that discontinuities in waveguide could be theoretically represented by lumped elements.

2) Power Generation and Tubes:

1920: Hull invents the magnetron and produces a low-power signal at a frequency of 30 GHz [21].

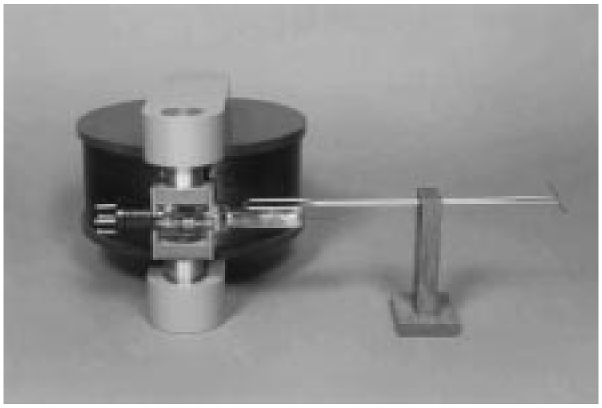

Fig. 6. Kilgore 9-cm split-anode magnetron and magnet, with external coupling loop and dipole antenna, circa 1933. The glass part of the tube is about 4-in long (10 cm) (courtesy of the Historical Electronics Museum).

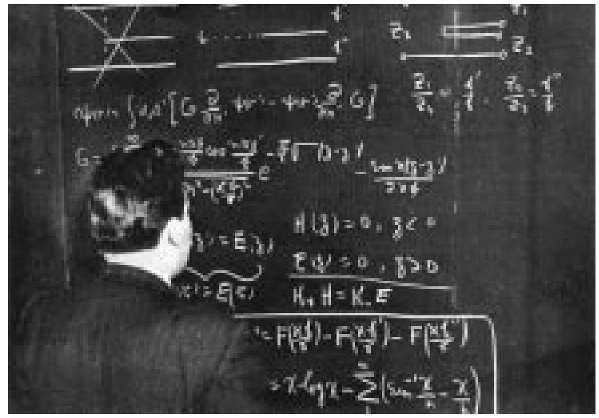

Fig. 7. Schwinger lecturing at the MIT Radiation Laboratory during World War II (courtesy of [11]), [27].

1923: Nichol and Tear use a spark gap to produce a 0.22-mm-wavelength signal. Glagolewa and Arkadiew produce a 0.082-mm-wavelength signal using a spark gap in 1924 [17].

1927: The split-anode magnetron is invented in Japan by Okabe. Yagi presents Okabe's results during a visit to the U.S. in 1928 [24].

1931: Kilgore develops a 9-cm-wavelength split-anode microwave magnetron. A photograph of the magnetron is shown in Fig. 6 [16].

1935: Samuel builds a close-spaced vacuum tube triode that produces a 20-cm-wavelength signal [15].

1935: Heil and Heil describe velocity modulation of an electron beam. This was to become the principle of operation of many microwave tubes in the future [16].

3) Receivers [19]:

1927: Johnson defines thermal noise and, in 1928, Johnson and Nyquist describe the thermal noise voltage of a resistor.

1931: Llewellyn defines a qualitative measure of the signal-to-noise ratio of a receiver.

4) Passive Devices [25]:

1922: Affel invents a quarter-wave two-wire line directional coupler. The patent is granted in 1927.

5) Microwave Acoustics [14]:

1922: Brillouin predicts theoretically the acoustooptic effect in which light is diffracted by an acoustic beam. This effect was to play a significant role in future years in microwave and optical surface acoustic wave devices.

6) Applications of Microwaves—Communications [15]:

1931: Marconi tests a 600-MHz radiolink over an 18-mile path in Italy. The signal source was a Barkhausen tube.

1931: Clavier of ITT builds an 18-cm-wavelength radio link from Calais, France to Dover, U.K. This system also used a Barkhausen tube as a signal source and was called the micro-ray. This term was instrumental in naming this part of the spectrum "microwaves."

1932: Marconi installs a 57-cm-wavelength radio providing telephone and teleprinter service over the 15-mile path from Vatican City to Castel Gandolfo, the summer residence of the Pope.

7) Applications of Microwaves—Radar:

1922: Marconi urges the use of short waves for radio detection of objects [18].

1924: Breit and Tuve use pulse ranging (first application) for measuring the height of the ionosphere [18].

1925: Yagi invents the Yagi antenna in Japan for high directivity at short wavelengths [16].

1933: The U.S. Naval Research Laboratory demonstrates detection of aircraft with a 3-MHz continuous wave (CW) radar at a 50-mile range. The frequency is extended to 60 MHz in 1934. A patent was issued for this effort [26].

1934: Watson-Watt sets up an experimental radar station that led to British Home Chain air defense system [18].

E. 1935–1945: "The Golden Years"

This period includes World War II and was a very difficult and catastrophic era for the peoples of the Earth. The war efforts on the development of radar in both the Allied and the Axis nations were very concentrated and led to a time of unmatched growth in microwave technology. Radar played a decisive role in World War II and the period can be classified as the *golden years* for advances in microwave technology. The major microwave developments in the U.S. occurred at the MIT Radiation Laboratory, whose peak employment was 4000 in 1945. Nine individuals who were at the Radiation Laboratory would later win Nobel Prizes for their work in other areas of physics, chemistry, and economics. Three who played very important roles in the microwave effort were Schwinger, Bethe, and Purcell. The 28-volume Radiation Laboratory Series published in 1947 contains an excellent summary of the history making progress that was achieved at the Laboratory during the war years. Fig. 7 is a photograph of Schwinger lecturing on waveguide theory at the Radiation Laboratory and Fig. 8 is a photograph of the SCR-584 radar developed there in 1943.

1) Guided Microwave Structures:

1936: Southworth of AT&T and Barrow of MIT both demonstrate microwave propagation in circular waveguide at the Institute of Radio Engineers (the predecessor of the IEEE) and the American Physical Society conventions [13].

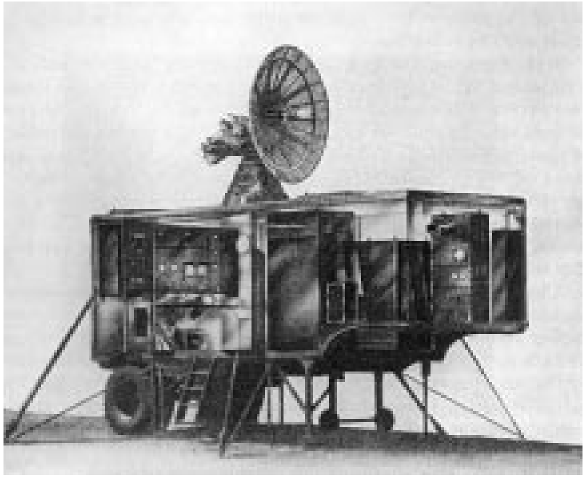

Fig. 8. SCR-584 antiaircraft gunfire control radar [34].

Fig. 9. Western Electric WE-700C magnetron, without its external magnet. Manufactured during World Ware II, it produced about 40-kW peak power at 690–700 MHz. Body diameter is 5.8 in (14.8 cm). Two of the output probes have protective covers installed (courtesy of the Historical Electronics Museum).

1936: Brillouin publishes analysis of propagation in lossless rectangular waveguide, unknowingly repeating the analysis Rayleigh did years earlier. Schelkunoff in 1937 extends the analysis by considering loss [27].

1938: Chu analyzes elliptical waveguide propagation [27].

1939: Barrow invents the magic tee [25].

1930s: During the period through the early 1940s, unanimity on classification of E, H, TM, and TE characterization of modes is not reached [27].

1940: Considerable progress is made at the MIT Radiation Lab by Schwinger and Marcuvitz in the early 1940s on field formulations of discontinuities in waveguide. Schwinger's integral equation formulation of field problems is developed in the early 1940s [27].

1942: Wheeler develops a line-stretcher with conductors on a high dielectric-constant substrate. This is one of the earliest mentions of stripline technology [28].

1943: Bethe, Lippmann, and Julian describe a variety of directional couplers in the period through 1944 [29].

1944: Bethe publishes the small aperture theory for discontinuities in rectangular waveguide [27].

1944: Mumford invents the multihole directional coupler [25].

2) *Free-Space Propagation of Microwaves:*

1936: Barrow introduces the horn antenna for an aircraft landing system [13].

1939: Barrow and Lewis invent the sectoral electromagnetic horn antenna [27].

1940: Hansen patents the slit antenna, a leaky-wave device [27].

3) *Power Generation and Tubes:*

1937: The Varian brothers invent the klystron, a velocity modulated tube [16].

1937: Alekseev and Malairov in Russia invent and build one-, two-, and four-cavity magnetrons and produce a CW power of 300 W at 9-cm wavelength. The pulsed-power cavity magnetron built in the U.K. several years later produced higher powers due to improved cathode emission in a pulsed mode. The work was published in 1940 [22].

1938: Hansen invents the high-Q reentrant cavity. This cavity played a major role in the success of various microwave tubes. The original filing of patents was in 1936 [16].

1939: Boot and Randall invent a cavity magnetron in the U.K. The tube operated at 10-cm wavelength and produced 1-kW pulsed power. The tube was brought to the U.S. by Tizard in 1940. In 1940, a 700-MHz scaled version of the cavity magnetron was made at Bell Laboratories. A photograph of the 700-MHz device is shown in Fig. 9. Microwave tubes operating to X-band and producing hundreds of kilowatts of peak power were developed shortly thereafter. This device played a major role in U.S. microwave radar during World War II [21].

1939: A split-anode magnetron produces CW power of 500 W at a frequency of 3 GHz in Japan [23].

4) *Receivers [19]:*

1937: Jansky measures and characterizes galactic noise as a component of total receiver noise. This work eventually opened the field of radio astronomy.

1939: Peterson, Llewellyn, and Hussen analyze the vacuum tube diode mixer.

1940: North introduces the temperature limited-vacuum diode as a noise generator.

1942: Herold extends the Peterson-Llewellyn's work to broad-band UHF receivers.

1942: North introduces noise factor as a measure of receiver performance and the concept of the matched filter optimum receiver.

1945: Friis presents the analysis of multistage receivers and introduces noise figure as a measure of receiver performance.

5) *Passive Devices:*

1937: Waveguide filter development is initiated by Mason and Sykes [30].

1940: Quakenbush of Amphenol develops the UHF coax connector [31].

1941: Over the period through 1945, workers at Harvard Radio Research Laboratory, MIT Radiation Laboratory,

and Bell Laboratories develop waveguide cavity filters and broad-band and low-pass tunable coaxial filters [30].
1942: Neill of Bell Laboratories develops the type N coax connector [31].

6) Design Techniques:

1939: The Smith chart, a very significant design aid that is still used today for impedance matching, is developed by Smith [33].

7) Measurements and Instrumentation:

1940s: Techniques for microwave measurements including power detection, power measurement, frequency measurement, phase measurement, voltage standing-wave ratio (VSWR), etc. are developed, improved, and documented in volume 11 of the Radiation Laboratory Series in 1947. This is one of the earliest publications devoted entirely to this field [32].
1940s: Spectrum analyzers utilizing reflex klystrons as the tunable sources are developed [29].
1944: Meyers, Charles, and Julian introduce reflectometers and impedance measurement techniques [29].

8) Applications of Microwaves—Communications [15]:

1943: AT&T develops the AN/TRC-6, a 4.5-GHz multichannel PPM digitally modulated microwave radio for the U.S. and U.K. armies.

9) Applications of Microwaves—Radar:

1938: The British Chain Home Air-Defense System, with 25-MHz radars is installed in the U.K. This system played a major role in winning the Battle of Britain during World War II [34].
1938: The 205-MHz SCR 268 antiaircraft fire control radar is developed for the U.S. Army. The patent for the system awarded to Col. Blair. The radar used until 1944, was replaced by the SCR-584, a 10-cm microwave radar [35].
1939: The 105-MHz SCR 270 radar is developed for the U.S. Army as a long-range early-warning system. The SCR 270 later detected the Japanese aircraft in Pearl Harbor raid, but the information was not utilized. A modified version of the radar was used to detect echoes from the moon in 1946 [35].
1940: The MIT Radiation Laboratory is established October 1940 [11].
1941: In mid–1942, the Radiation Laboratory initiated an effort to develop a K-band 24-GHz radar. This work continued until the end of the war. Van Vleck of Harvard and Weisskof of MIT predicted that water vapor in the atmosphere would strongly absorb the radiation and the 24-GHz radar would have very limited range. The predictions were confirmed during testing of the radar. However, Dicke invented a radiometer that used synchronous detection similar to techniques used in infrared spectroscopy and improved the sensitivity 20 dB. This was the origin of microwave radiometry and the device is still known today as the Dicke radiometer. Fig. 10 shows a photograph of the K-band equipment developed and Fig. 11 is a photograph of Dicke and other staff members setting up a radiometer [11].

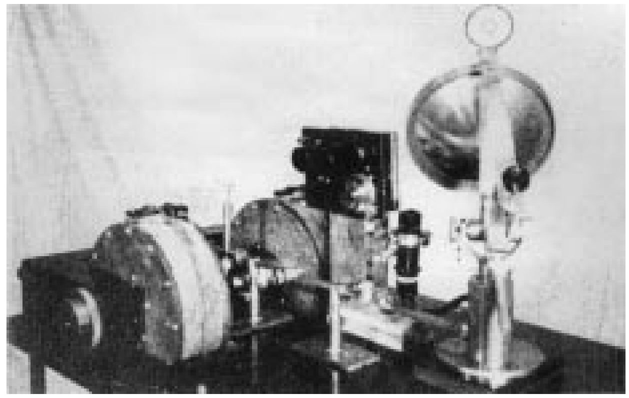

Fig. 10. First K- band experimental radar equipment developed at the MIT Radiation Laboratory during World War II (courtesy of MIT and [11]).

Fig. 11. Dicke (right-hand side) setting up a Microwave Radiometer to measure atmospheric thermal radiation at K-band (courtesy of MIT and [11]).

1943: Microwave radars using cavity magnetrons are developed at the Radiation Laboratory. The 3-GHz SCR-584 antiaircraft position finder and fire control radar went into production in mid–1943. An X-band version of the radar was also developed. The radars were widely deployed in the European and the Pacific theaters of operation. The SCR-584 is credited with directing the antiaircraft weapons that destroyed 85% of the V-1 buzz bombs engaged in raids on London [11].
1944: Rapid electromechanical scanning using an array antenna is applied to the precision tracking ground controlled of approach radar for aircraft tracking. The 3-cm-wavelength radar AN/MPN –1 was developed at the Radiation Laboratory [34].
1945: The Doppler effect is used to develop moving-target indicator radars [34].

10) Microwave Biological Effects and Medical Applications [36]:

1938: Hollman in Germany and Hemingway and Stenstrom in the U.S. propose using microwaves for therapeutic applications since the energy can be more easily focused than HF diathermy and will produce heating of deep tissues without excessive heating of the skin.
1941: Mittleman, Osborne, and Coulter propose a measure to quantify the rate of absorption of RF energy by a biological body during treatment, as the volume-normalized rate

Fig. 12. First Radarange, Raytheon Model 1132, (right-hand side) and modern microwave oven (courtesy of J. M. Osepchuk) [5].

of energy absorption in watts per liter. This value is closely related to the specific absorption rate (SAR) used today in units of watts per kilogram.

1943: Studies are conducted by Daily for the U.S. Armed Forces of the effects of microwaves on living mammalian tissue to alleviate concerns of radar operators. Further studies were conducted in 1945 by Follis, Lidman, and Cohn. No ill effects were found for the pulsed microwave exposure of laboratory animals.

F. 1945–1960: "New Waveguides, Devices, and Systems"

During the postwar years, the technology developed in the preceding decade spread rapidly. Corporations selling microwave components, test equipment, and systems were established. Government programs in many nations funded research programs in universities, large corporations, and research institutes. The Microwave Research Institute (MRI), Brooklyn Polytechnic Institute, was an example of a very significant university contributor to the advancing technology. The major efforts were in support of new weapons systems developed during the Cold War years. The research and development activities resulted in major advances in microwave technology. New waveguides structures to replace the bulky rectangular and circular guides were introduced. Many new families of microwave tubes became available. Reciprocal and nonreciprocal ferrite device and new solid-state devices were invented. New systems for telecommunications, electronic warfare, advanced radars, industrial heating and drying, and cooking were introduced. Fig. 12 shows a photograph of a Raytheon "Radarange" microwave oven of the early 1950s.

1) Electromagnetics and Waves:

1946: Brillouin publishes the theory of wave propagation in periodic structures. This work is applicable to propagation in a wide range of media, including crystals and microwave transmission lines. The use of Floquet's theorem in the analyses was introduced. The work that was first published in a book in 1946 was republished in 1953. The analyses were used in later years in studies of periodic slow-wave structures for traveling wave tubes (TWTs) and other microwave applications [37].

1953: Barlow, Cullen, and Brown in the U.K. revive and greatly expand the earlier work from 1910 on surface waves that are guided by dielectric structures or interfaces between an imperfect conductor and an air interface [27].

1956: Marcuvitz of MRI publishes the theory of leaky-wave modes [27].

2) Guided Microwave Structures:

1945: Oliner, Marcuvitz, Kahn, Lewin, and Whinnery make many very significant contributions on discontinuities in rectangular waveguide over a period through 1951 [27].

1947: Cohn develops the theory of the ridge waveguide, a structure to improve the bandwidth of waveguide [27].

1950: Goubau publishes the theory of a waveguide consisting of dielectric coating on a metal wire. The guide supports a surface wave and is called the Goubau line [27].

1951: Coleman develops techniques and components for dielectric waveguide use at millimeter and submillimeter waves [17].

1952: Barrett of the U.S. Air Force Rome Air Development Center invents stripline. Fubini and Fromm of the AIL Corporation are key contributors in the development of the new waveguide [27].

1952: Assadourian, Rimai, Kostriza, Greig, and Englemann of ITT Federal Telephone Laboratories develop and publish the properties of microstrip transmission line [27].

1952: Sanders Associates develops triplate transmission line and makes kits available [27].

1952: King and Schlesinger study dielectric image line at 10 and 24 GHz over the period through 1955 [17].

1954: The first symposium on the new waveguides, triplate, microstrip, and stripline is held at Tufts College and a Special Issue of this TRANSACTIONS is devoted to symposium papers is published in 1955 [27].

1955: Oliner and Altschuler derive equivalent circuits for discontinuities in stripline [27].

1956: Klopfenstein develops a tapered transmission line for use as a broad-band impedance transformer [38].

1958: Wiltse investigates the dielectric image line at millimeter-wave frequencies over the 35–140-GHz band [17].

3) Free-Space Propagation of Microwaves [17]:

1957: Gebbi publishes measurements of atmospheric absorption in the microwave spectrum.

1958: Straiton, Tolbert, and Britt measure atmospheric attenuation at microwave and millimeter-wave bands in the period through 1963.

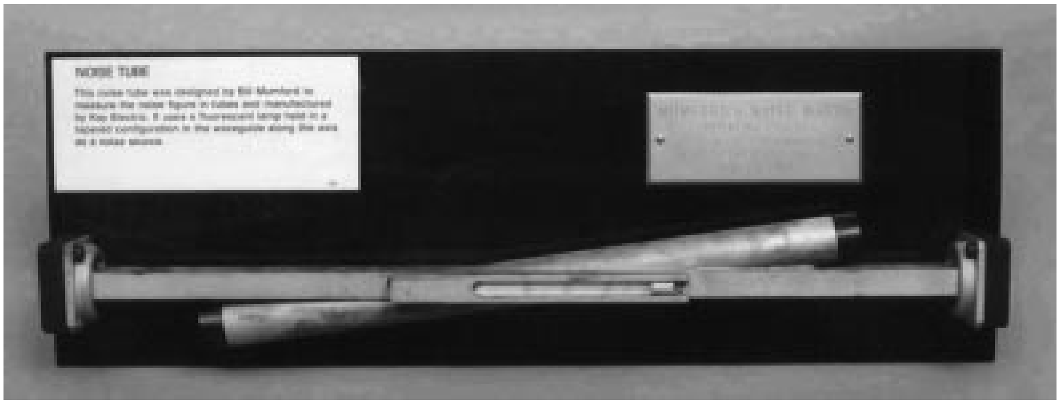

Fig. 13. Mumford 3-cm noise tube, as manufactured by Kay Electric. Overall length is approximately 15-1/2 in (39 cm) (courtesy of the Historical Electronics Museum).

4) Power Generation and Tubes:

1945: Kompfner publishes the description of the TWT he invented earlier [39].

1947: Pierce publishes the theory of operation of the TWT [40].

1950: Warnecke, Kleen, Lerbs, Doehler, and Huber publish the theory of the crossed field amplifier [41].

1953: Kompfner and Williams disclose the backward wave oscillator [42].

1953: Chodorow, Ginzton, Neilson, and Sonkin build a multimegawatt pulsed klystron amplifier for accelerators [43].

1953: Priest, Murdock, and Woerner build a high-power (multikilowatt) CW klystron for television transmitters [44].

1954: A 115-GHz 3-kW magnetron is built at Columbia University [17].

1955: Warnecke, Guenard, Doehler, and Epsztein disclose the M-type carcinotron [45].

1955: Chodorow and Nalos build a high peak-power TWT [46].

1958: Twiss in Australia proposes the gyrotron mechanism in which amplification may result from Cerenkov and cyclotron radiation. Independently, during 1959, Gaponov, in the then Soviet Union and Schneider, in the U.S., propose the same mechanism for a device, the gyrotron or electron cyclotron maser, as a tube for high-efficiency generation of extremely high power at millimeter and submillimeter wavelengths [47], [48].

1959: A 120-GHz klystron is built at Philip's Research Laboratory [17].

1959: CSF builds a 150-GHz O-type carcinotron [17].

5) Solid-State Devices:

1956: The Manley Rowe equations and their application in microwave devices are published [49].

1956: Esaki invents the tunnel diode and Chang develops the tunnel diode amplifier (TDA). Esaki shares a Nobel Prize in 1973 for his work on tunneling [19].

1957: Kroemer proposes the heterojunction bipolar transistor as a superior device compared to the homojunction transistor because of high emitter injection efficiency and low parasitic impedance. Kroemer shares a Nobel Prize in physics in 2000 for his work on semiconductor heterostructures [50].

1957: Bakanowski, Leenov, and Uhlir develop the varactor diode[49].

1957: Hines, Uhlir, Elder, and Uenohara develop the microwave parametric amplifier (paramp) for very low-noise receivers. In many applications for satellite receivers, the paramp was able to replace a more expensive maser [49].

1958: The application of the avalanche effect in a semiconductor junction diode is proposed by Read for a microwave source or amplifier. The device is called the Read diode [51].

1959: Leenov and Uhlir develop the varactor frequency-multiplier [49].

6) Microwave Integrated Circuits [52]:

1957: The U.S. Air Force funds a program on molecular electronics for microminiaturization at Westinghouse. The application is for all electronics including the microwave system elements.

7) Receivers:

1949: Mumford invents the gas-discharge noise tube, a device for use in noise measurements of receivers. Fig. 13 is a photograph of Mumford's noise tube [19].

1953: Townes, Gordon, and Zeiger build the ammonia maser. Townes is awarded a Nobel Prize in 1964 for his maser-laser work [49].

1958: Bloembergen develops the theory for the solid-state maser and Scovil, Feher, and Seidel build the first device [19].

1959: A practical solid-state maser amplifier is developed by DeGrasse, Schulz-DuBois, and Scovil [49].

8) Passive Devices:

1947: Riblet develops the theory of waveguide couplers with n equal coupling holes with $\lambda/4$ spacing [25].

1947: Fano and Lawson describe the design of waveguide cavity bandstop filters in volume 9 of the Radiation Laboratory Series [12].

1948: Richards develops commensurate line-circuit theory [30].

1950: Riblet develops the waveguide short-slot hybrid junction [25].
1951: Dishal patents a waveguide cavity realization of elliptical function bandpass filters using generalized coupling [30].
1952: Barnett and Hunton apply Dolph–Chebyshev theory to spacing in waveguide multihole couplers [25].
1954: Oliver develops the theory of TEM couplers [25].
1954: Barnett, Cohn, Lacy, Jones, Oliver, and Young publish several papers describing the development of a wide range of TEM stripline directional couplers [25].
1955: Saad develops a practical balanced mixer by reversing the outputs of a parallel-line 3-dB coupler, which results in the mixer diodes being located on the same side of the structure and greatly simplifies the combining of the mixer diodes outputs. Although widely used in octave bandwidth mixers, the concept was never patented [53].
1958: Cohn publishes a comprehensive theory of direct coupled waveguide cavity filter design [25].
1960: Wilkinson develops an N-way power divider/combiner with isolated ports [54].

9) Microwave Ferrite Devices [20]:

1952: Hogan uses Faraday rotation in ferrites to develop a microwave gyrator and shows how to use the gyrator for circulators, isolators, switches, attenuators, and modulators.
1952: Suhl and Walker investigate Faraday rotation in bounded ferrite media in a cylindrical waveguide.
1953: Lax develops a perturbation theory for propagation in ferrite loaded waveguides.
1953: Sakiotis and Chait observe nonreciprocal propagation in a ferrite loaded rectangular waveguide. This device did not utilize Faraday rotation.
1954: Lax, Button, and Roth develop a ferrite phase shifter in rectangular waveguide.
1954: Carlin proposes and Schaug, Peterson, and Fowler analyze a three-port circulator.
1956: Chait, Thaxter, Heller, Davis, Milano, Saunders, and Bosma develop the Y-junction circulator.
1957: Duncan, Swern, Tomiyasu, and Hannwacker develop the coax isolator.
1958: Reggia, Spencer, Clavin, and Brow develop reciprocal phase shifters.

10) Microwave Acoustics [14]:

1957: Baranskii couples a 2-GHz signal to a quartz crystal to excite an acoustic wave that is detected using diffracted light.
1958: Bommel and Dransfield demonstrate the generation of longitudinal and shear waves by the surface piezoelectricity of a quartz rod inserted in a reentrant cavity. In 1959, they demonstrate excitation of 1-GHz phonons using an evaporated nickel-film ferromagnetic resonance transducer on a quartz rod. Delays of several microseconds per centimeter were observed.
1959: Jacobsen excites 10-GHz longitudinal waves in quartz bars at low temperature.

11) Measurements and Instrumentation:

1944: Beringer, Van Vleck, and Gordy measure oxygen absorption lines at microwave frequencies over the period through 1949 [17].
1945: Gordy begins high-resolution spectral measurements in microwave and millimeter-wave bands [17].
1947: Samuel develops an oscillographic display method for automatically plotting measurements on a Smith chart. The technique is useful for relatively low frequencies due to discriminator performance limitations [55].
1948: Lyons introduces molecular resonance as a frequency standard [29].
1951: Fourier transform spectroscopy is developed by Fellgett [56].
1957: Watts and Alford develop a hybrid-based vector network analyzer that enables automatic impedance plotting [57].

12) Microwave Applications—Communications [15]:

1946: Clarke forecasts the use of geosynchronous orbiting satellite relays for long-haul communications.
1946: Microwave radar signals are bounced off the moon and detected on earth by the U.S. Army Signal Corps [35].
1947: AT&T builds a 3.7–4.2-GHz microwave line-of-sight radio system with repeaters and with a capacity of 500 voice circuits or one black-and-white TV channel from New York to Boston.
1951: AT&T builds the 4-GHz TD-2 4000-mile coast-to-coast microwave system for voice and TV service. An overbuild 6-GHz system, the TH, was added in 1953. The systems were continually up graded as technology progressed and were used for many years, until the primary routes were changed to optical fiber systems.
1952: IT&T uses a TWT in a microwave radio link.
1954: Pierce presents the concepts for active and passive repeaters, synchronous, and nonsynchronous satellites to the Princeton IRE Section.
1957: The Soviet Union launches the world's first manmade satellite "Sputnik."
1958: The Eisenhower Christmas message is broadcast using the SCORE satellite.
1959: Pierce and Kompfner publish a study on various satellite systems for telecommunication applications.

13) Microwave Applications—Radar:

1955: Page invents the monopulse radar [34].
1958: RCA delivers the AN/FPS-16 precision monopulse tracking radar, a commercial instrumentation radar [34].
1959: The Georgia Institute of Technology develops the AN/MPS-29, a 70-GHz radar for the U.S. Army [17].

14) Microwave Applications—Heating [58]:

1940s: During the late 1940s, many patents are issued on heating applications using microwaves. Westinghouse and GE concentrate on industrial applications such as drying of textiles, tires, wood, etc. Raytheon concentrates on cooking and treating of food.
1946: The FCC in the U.S. allocates the 915- and 2450-MHz bands for microwave ovens.

1947: Raytheon develops the QK65 magnetron for oven applications. The 1-kW CW S-band device has an efficiency greater than 60%.

1949: Spencer of Raytheon is issued basic patents on microwave ovens and cooking including the use of a cooking cavity and methods of preparing the foodstuffs. Spencer leads the Raytheon activity on the heating development. Hall of Raytheon is awarded patents on a choke seal for an oven door and on the mode stirrer to insure uniform cooking of foods in 1950–1952.

1950s: Raytheon introduces the Radarange family of freestanding microwave ovens, primarily for the restaurant market.

1956: Tomiyasu and Bolus invent a longitudinal choke structure. After the patent expired, this type of choke was successfully manufactured for use in electrically sealing the doors of commercial and household microwave ovens [59].

1960: Several U.S. companies including Hotpoint, Westinghouse, Kelvinator, Whirlpool, and Tappan enter the consumer microwave oven market producing product under license to Raytheon. Raytheon does not enter the consumer business, but addresses the commercial and industrial market.

15) Microwave Biological Effects and Medical Applications [36]:

1946: Tests on therapeutic applications are started at the Mayo Clinic using 3-GHz 65-W exposure of laboratory animals. The experiments showed that skin temperature was somewhat higher than that of deep muscular tissue, but deep heating did occur. These experiments launched the use of microwave diathermy.

1946: The FCC assigns the frequency 2450 MHz (same as the microwave oven frequency) for physical medicine applications. This remains the only frequency used for microwave diathermy for the next 35 years. Unfortunately, the decision did not consider many of the important parameters in coupling to biological bodies.

1948: Richardson *et al.* induce cataracts and other eye tissue damage, as well as testicular damage in laboratory animals exposed to high-power 2450-MHz generators located 5 cm away. The damage is thermal in origin.

1950: Gessler, McCarty, and Parkinson are the first physicians to use microwave energy in experimental treatment of cancer and eradicated mammary carcinoma in mice with 2450-MHz radiation.

1953: Schwan of the University of Pennsylvania recommends a safe exposure level of 10 mW/cm^2. This is based on the fact that exposure greater than 100 mW/cm^2 is required to produce biologically significant effects. The American Standards Institute (later ANSI) adopts this recommendation over the frequency range of 10 MHz–100 GHz for a period of five years. Since no alternate standard was agreed on, the recommendation stayed in effect until 1982, when a new standard, based on the specific absorption rate (SAR) of a human of 0.4 w/cm^2 over the frequency range of 300 kHz–100 GHz was enacted.

1955: Allen eradicates Crocker sarcoma in rats by applying a combination of microwave and X-ray exposure. Considerable experimentation followed for a number of years on combination treatments using microwave, RF, and X-ray radiation. In the 1970s, interest increased considerably due to favorable reports on combined therapies.

1958: Nonthermal effects on the central nervous system at microwave exposure levels below 10 mW/cm^2 are reported by the Soviets. As a result, the limit on human exposure level in the U.S.S.R. was set at 10 μW/cm^2. The study was heavily criticized in the U.S. since it involved limited statistics and inadequate controls.

1960: Anne *et al.* in the U.S. and Franke in Russia analyze the absorption of microwaves by the human body by modeling using various geometric shapes and dielectrics and considering exposure frequency, size, and shape. Franke was the first to characterize resonance in the models. Experimental models were constructed and tested by Gandhi of the U.S. in 1965.

G. 1960–1970: "Solid-State Devices and Integrated Circuits"

This decade witnessed significant advances in the technology for microwave solid-state devices and the invention of many new two- and three-terminal devices for power generation and amplification. These advances were critical to meet the needs of the sophisticated microwave systems that were being planned. Major emphasis during this decade was to reduce the size of microwave subsystems such as transmitters and receivers to reduce the cost of microwave systems and to improve the manufacturability and the reliability. This required the use of new structures to replace rectangular waveguides and the use of batch fabrication photolithographic manufacturing techniques in place of machine tool manufacturing. As a result, the technology of microwave integrated circuits was developed and both hybrid and monolithic technologies made significant progress. Fig. 14 is a photograph of one of the microwave-integrated-circuit transmit/receive modules used at each antenna element of the Texas Instrument (TI) Incorporated-developed MERA solid-state phased-array radar. In this decade, the cosmic microwave background radiation was detected and used as evidence in favor of the big-bang theory of creation of the universe.

1) Electromagnetics and Waves:

1962: Tamir and Oliner study surface waves guided by plasma layers to understand the problems of communications during reentry phase of a spacecraft mission [27].

1966: Yee introduces what is currently known as the finite-difference time-domain (FDTD) method for solving field problems. The approach utilizes a unique discretization scheme of space that is currently known as the Yee Lattice. FDTD did not become popular until high-speed digital computers became available and today it is widely used for both microwave and antenna problems [60].

2) Guided Microwave Structures [61]–[63]:

1960s: Interest was rekindled in microstrip as a media for microwave integrated circuits and significant advances

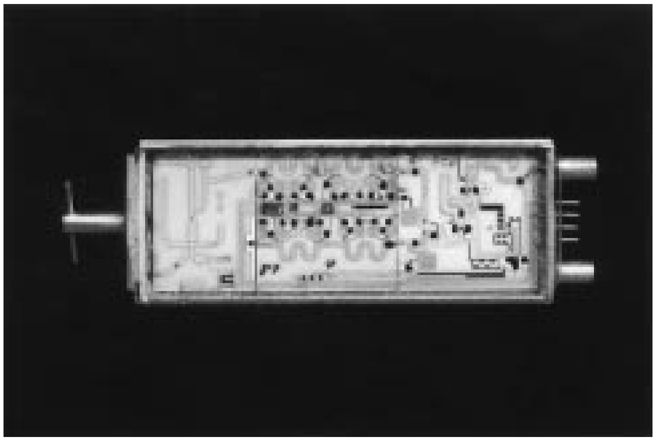

Fig. 14. TI Incorporated MERA module, developed 1964–1968. Rectangular housing is 2 1/2 $\times$1 in (6.35 $\times$2.54 cm) (courtesy of the Historical Electronics Museum).

were made in many laboratories. A wide variety of dielectric substrates was employed. It was apparent that former studies of the properties of microstrip were not sufficiently accurate for design of microwave integrated circuits.

1965: Wheeler applies conformal mapping to derive accurate representation of quasi-TEM propagation between parallel strips.

1965: During the period through 1968, Sobol and Caulton at RCA, Hyltin at TI, and Schneider at AT&T apply Wheeler's analysis to determine accurate characteristics of microstrip lines for microwave integrated circuits at frequencies up to 10 GHz and measure the properties of lines on a wide range of dielectric and high-resistivity semiconductor substrates.

1968: Cohn invents the slot line, an alternate to microstrip for application in microwave integrated circuits. This line allows mounting of devices in a single plane.

1969: Wen invents the coplanar waveguide for application in microwave integrated circuits. This line also allows planar mounting of devices. The coplanar waveguide was widely applied in future years.

1970: Silvester introduces the finite-element method (FEM) for analysis of waveguide problems. The FEM has been widely used and several commercial software packages are available [64].

1971: Itoh and Mittra develop the wave analysis for frequency-dependent solution of propagation in microstrip. This analysis of microstrip was the first useful at frequencies well above 10 GHz.

3) Free-Space Propagation of Microwaves [65]:

1964: Penzias and Wilson, while tracing the source of radio noise at the receiving antenna input that was interfering with satellite communications, detected a relatively high level of isotropic radiation at a wavelength of 7.3 cm. After discussing the results with Dicke, inventor of the Dicke radiometer and author of a theory that this type of radiation would be present as the residue of the intense heat associated with the birth of the universe following the big bang, it was concluded that the measurements did indeed verify the big-bang theory. Penzias and Wilson were awarded a Nobel Prize in 1978 for their work.

4) Power Generation and Tubes:

1960: Brown describes the Amplitron, a high-power cross-field amplifier tube. In 1964, a 400-kW 3-GHz CW amplitron with an efficiency of 80% was developed [66], [67].

1964: Hirshfield and Wachtel in the U.S. experimentally demonstrate the feasibility of the gyrotron. The U.S. effort subsided during the mid-1960s, but the effort in Russia continued and produced outstanding results. The U.S. activity started again in the 1970s [47].

1967: Gapanov, Petlin, and Yulpatov report a gyrotron that produced 1-kW CW at millimeter wavelengths [48].

5) Solid-State Devices:

1963: Silicon bipolar transistors capable of 5 W of power at 500 MHz are developed by Carley. These transistors were extended to the 2-GHz range by harmonic operation by Lee, Caulton, Sobol, and Ernst in 1965. Fundamental frequency operation at 2 GHz with 5 W was achieved in 1967 [68], [69].

1963: Gunn discovers a negative resistance in bulk GaAs, which leads to the Gunn diode, an extremely useful device as a microwave and millimeter-wave source [70].

1964: White builds a 100-kW peak power switching phase shifter using p-i-n diodes [71].

1964: Kroemer points out that the Gunn diode operation was suggested in the earlier theoretical work of Ridley and Watkins in 1961 and is the result of the transferred electron effect between high- and low-mobility states in the conduction band of certain semiconductors [72]–[74].

1965: Gunn diode oscillators and amplifiers are developed by Hakki and Irvin [75].

1965: The first successful demonstration of a silicon avalanche diode microwave device, the IMPATT diode, as a microwave source was by Johnston, DeLoach, and Cohen in 1965 [76].

1965: Meade fabricates the first GaAs Schottky barrier FET [77].

1965: Yamashita and Baird introduce an electromagnetic characterization of a diode mount in a waveguide [78].

1966: During the period through 1968, high peak power modes are discovered for the Gunn and IMPATT diodes. These devices, LSA, and TRAPATT diodes, respectively, were able to produce nearly 100 W of peak power, but did not gain much acceptance in systems because of high noise levels [79], [80].

1967: Hooper and Lehrer report the first microwave GaAs MESFET with an $f_{\max}$ of 3 GHz [77].

1967: Draingeid and Wolf demonstrate an Si MESFET with $f_{\max}$ of 12 GHz and a GaAs MESFET with $f_{\max}$ of 30 GHz in 1970 [77].

6) Microwave Integrated Circuits:

1964: TI is awarded the MERA program to build a 9-GHz feasibility demonstration solid-state phased-array airborne radar using microwave-integrated-circuit transmit/receive modules at each antenna element. The program initiates a very large activity at TI on the development of monolithic and hybrid microwave integrated circuits [52].

1964: Cronin and Hasty grow semiinsulating Cr doped GaAs crystals with very high room-temperature resistivity. This material is useful as the first substrate for GaAs monolithic microwave integrated circuits [52].

1965: Many companies follow TI's lead and start programs on microwave integrated circuits. RCA concentrates on hybrid integrated circuits and uses both distributed, as well as lumped circuit elements. Sperry investigates the use of ferrite substrates. AT&T uses suspended substrate technology where a hybrid integrated circuit is placed in a waveguide. Additional approaches are also used [61]–[63].

1966: During the rest of the decade, many reports, papers, presentations, and panel discussions describe the successes that the industry is having in developing nearly all microwave functions as hybrid integrated circuits and in integrating these function into subsystems and systems. During this period, the technology to fabricate monolithic microwave circuits at reasonable yield was not yet developed [61]–[63].

1968: TI completes the build of the feasibility phased array MERA radar using 604 hybrid integrated microwave modules. The successful completion of this program was followed by the start of many phased-array radar programs for specific applications. The technology was also applied to communication and electronic warfare systems [52].

7) Passive Devices:

1960: Precision coax connectors are standardized for use in high-accuracy microwave measurements. General Radio produces a 14-mm connector usable to 8.5 GHz and Amphenol produces a 7-mm connector usable to 14 GHz. These connectors will be the standard on the automatic network analyzers that are introduced in the mid-1960s [31].

1962: Matthaei introduces interdigital and combline filters to shorten the length of direct coupled cavity filters [30].

1962: Omni Spectra introduces the precision miniaturized coax OSM connector that was usable to 26 GHz and also played a major role in the future microwave integrated circuits [31].

1962: Getsinger investigates coupled rectangular bars between parallel planes for application in couplers [81].

1963: Young investigates the stepped-impedance coupled-line directional coupler [82].

1963: Cohn develops the re-entrant cross-section wide-bandwidth 3-dB hybrid coupler [83].

1963: Levy presents the synthesis of asymmetric multielement coupled transmission-line directional couplers [84].

1964: DuHamel and Armstrong develop the asymmetric TEM hybrid tee [25].

1964: Matthaei, Young, and Jones publish *Microwave Filters, Impedance Matching Networks and Coupling Structures* (The Big Black Book). This book serves as the major reference for filter designers [85].

1964: Cristal investigates coupled circular cylindrical rods between parallel ground planes for use in coupled line structures [86].

1965: Wenzel presents an exact analysis of the interdigital filter [30].

1965: Cristal and Young develop the theory of optimum symmetrical TEM-mode coupled-line directional couplers [87].

1967: Horton and Wenzel develop wide-band elliptical filters [30].

1968: Levy and Rozzi present a precise design of the coax low-pass filter [30].

1968: Cohn introduces bandpass filters utilizing high-Q dielectric resonators [30].

1969: Lange develops the interdigitated microstrip quadrature hybrid, which produced good coupling and isolation over an octave of bandwidth [28].

8) Ferrites [63]:

1966: Hershenov introduces the microstrip circulator.

1969: Roome, Harrison, Savage, and Taft develop microwave integrated circuits on ferrite substrates.

9) Microwave Acoustics [14]:

1961: Damon and Eshbach publish the theory of magnetostatic mode propagation in uniformly magnetized YIG; Olsen and Yaeger experimentally confirm the theory and build a delay line in 1965.

1965: Foster, de Kleck, Malbon, Winslow, and Shaw develop thin-film piezoelectric transducers for bulk acoustic-wave delay lines on quartz and sapphire. Devices are made commercially available and are applied in systems in 1970.

1965: White and Voltmer excite surface acoustic waves using thin-film interdigital transducers deposited on crystalline quartz and CdS.

1968: Collins, Gerard, Lakin, and Shaw develop the surface acoustic wave (SAW) filter.

10) Design Techniques:

1967: Policky and Cooke introduce the concept of computer-aided design (CAD) and optimization of UHF and microwave circuits [88].

1968: Gelnovatch describes the use of CAD for wide-band integrated microwave transistor amplifiers [89].

1969: Bandler develops an approach the use of optimization techniques for microwave CAD [90].

11) Measurements and Instrumentation:

1960: Cutler and Bagley introduce the atomic clock as a frequency standard [29].

1961: Cohn and Oltman develop a precision microwave phase measurement system with a swept frequency presentation [91].

1964: Anderson and Dennison of Hewlett-Packard (HP) introduce a microwave network analyzer that operates from 100 MHz to 12.4 GHz. Many of the concepts for the network analyzer were introduced by Lacy in 1961. The analyzer was first presented in a paper at Wescon in 1966 and the first archival publication was in the *Hewlett-Packard Journal* in 1967 [92].

1964: Halverson of HP introduces a "user-friendly" spectrum analyzer that eliminates ambiguity due to harmonics and spurious signals. Many other companies followed and advanced spectrum analyzers that were microprocessor controlled were introduced in later years [93].

1966: Weinert develops the RF vector volt meter [94].

1968: Hackborn develops the computer-controlled automatic network analyzer and Adam describes the use of the system for precision measurement. In subsequent years, many features are added including computational capability, digital functions, time-domain features using convolution techniques, and inverse Fourier transformations [95].

12) Microwave Applications—Communications [15]:

1960s: A millimeter-waveguide system prototype, the long-term vision of Southworth, is built during the 1960s at Bell Laboratories for very high-capacity digital transmission system using IMPATT diodes and cylindrical waveguide operating in the low-loss TE_{01} mode. The activity was later abandoned as fiber-optic systems were developed.

1962: AT&T develops the TELSTAR (4/6 GHz) satellite to operate in a nonsynchronous orbit for television transmission.

1964: Hughes develops Syncom 111, the first synchronous orbit active satellite (4/6 GHz) and Early Bird, the first commercial communication satellite in synchronous orbit in 1965.

1968: NASA launches the Advanced Technology Satellite, ATS-E, and conducts propagation experiments at 31.65 and 15.3 GHz.

13) Microwave Applications—Radar [34]:

1965: Beginning in 1965, all major radar development is for phased-array systems. First practical systems (AN/SPS-48, 3-D radar) were frequency scanned and combined mechanical rotation with electronic elevation scan.

1968: The AN/FPS-85 full phased-array radar is built for the Safeguard missile defense system.

14) Microwave Applications—Heating [58]:

1964: Twisleton of the U.K. develops a 900-MHz magnetron that produces 20–30-kW CW with 90% efficiency. This device meets the requirements of the industrial heating area.

1964: Brown *et al.* of Raytheon develop a 400-kW CW S-band amplitron that has an efficiency greater than 80%. This device, developed for defense applications, can also be used in industrial heating applications.

1965: In the early 1960s, many companies in the U.S. developed industrial drying and heating equipment for a wide variety of applications including drying tires, potato chips, nylon fibers, paper, highway paint, urethane foam heating, and sand core drying. Unfortunately the business of these ventures did not experience the expected growth and most of the ventures failed. However, substantial work did continue in Sweden and other nations.

1967: The consumer market for microwave ovens was also below expectation, primarily because of the relatively high cost of the magnetrons. A dramatic turn occurred when Amana (a Raytheon company) introduced a countertop oven with a significantly reduced cost magnetron made by the New Japan Radio Company. The tube, a metal ceramic magnetron, utilized an integral ferrite magnet. As a result, the price of the oven was less than one-half the price of earlier ovens and the market quickly developed. Soon other U.S. companies also participated in the market.

15) Microwave Biological Effects and Medical Applications [36]:

1967: Congressional hearings are held in the U.S. on radiation controls for the 1967 Health and Safety Act.

H. 1970–1980 "GaAs and Digital Systems"

GaAs was called the material of the future for many years prior to this decade. During this decade, substantial gains were made on processing, yield, and cost problems. Significant progress was achieved in the development of GaAs three-terminal microwave devices, LEDs and laser diodes, early monolithic analog microwave integrated circuits, and high-speed monolithic digital integrated circuits. GaAs discrete devices reached commercial status and were used in communication systems, EW, and radar systems. At the close of the decade, the yield and cost of GaAs integrated circuits did not yet satisfy the requirements for wide application in systems. The large U.S. Department of Defense program MIMIC (microwave and millimeter-wave integrated circuits), involving many corporations, was established during the 1980–1990 decade and was successful in achieving many of the necessary cost and yield objectives. During the 1980s and 1990s, GaAs integrated circuits were applied in both defense and commercial systems. One of the major applications of analog monolithic integrated circuits was in mobile cellular telephone systems and one of the major applications of digital integrated circuits was in high-speed fiber-optic systems.

1) Guided Microwave Structures:

1970: Knox and Toulios develop a dielectric strip waveguide on a dielectric substrate as a media for integrated millimeter-wave circuits. A similar waveguide was developed by Marcatili in 1969 for optical integrated circuits. In 1981, Yoneyama and Nishida develop a form of a dielectric strip waveguide with the strip between two vertical metal plates. This waveguide originally introduced by Tischer in 1959 is called the H-guide. The new structure of 1981 is less than 0.5-wavelength wide and is renamed the nonradiating dielectric guide (NRD) and is suitable for millimeter-wave integrated circuits. [27]

1972: Meier and Konishi independently invent the fin-line microwave structure that places planar microwave integrated circuits in a waveguide. This type of circuit configuration is particularly useful for millimeter waves [96], [97].

1976: Itoh develops the inverted dielectric waveguide for millimeter-wave integrated circuits [27].

1979: Itoh and Hsu use a periodic structure in a dielectric waveguide to form a Gunn oscillator. This waveguide is a one-dimensional version of a photonic-bandgap structure (PBG) [98].

2) Power Generation and Tubes:

1970: Nation reports huge peak power is observed when intense relativistic electron beams are used in the electron cyclotron maser. Freidman and Herndon report 2-MW peak power at 2-mm wavelength in 1973. In 1974, Granatstein *et al.* report 900 MW of peak power at 4-cm wavelength and 200 MW at 2 cm [47].

1974: Zaytsev *et al.* report a gyrotron operating CW at 2.78-mm wavelength and producing 12 kW of power [47].

1980: Shively *et al.* report a 28-GHz gyrotron operating CW and producing 200 kW of power. In 1982, Arfin *et al.* report a 35-GHz gyrotron operating CW with 320-kW of power. Applications of these very high-power devices are for accelerators and for fusion research [99].

3) Solid-State Devices:

1972: Baechtold, Walter, and Wolf develop a GaAs MESFET with an $f_{\max}$ of 60 GHz. This was increased to 100 GHz in 1973 [77].

1973: Liechti develops a low-noise GaAs MESFET with a noise figure of 3.5 dB at 10 GHz [77].

1973: Napoli of RCA and Fukata *et al.* of Fujitsu independently introduce the microwave power GaAs FET with 0.25 W at 4 GHz and 1.6 W at 2 GHz, respectively. By the end of the decade, over 5 W were achieved at X-band [52].

1978: Yuan of TI develops the first ion-implanted heterojunction bipolar GaAs transistor (HBT) and, in 1980, fabricates an inverted HBT using molecular-beam-epitaxy technology. Asbeck *et al.* at Rockwell introduce the HBT for GaAs logic circuits in 1981 [52], [77].

1980: Mimura *et al.* of Fujitsu develop the high electron-mobility transistor (HEMT), a GaAs-based heterojunction device with very high-frequency capabilities [77].

4) Microwave Integrated Circuits:

1972: Van Tuyl and Liechti of HP develop the first buffered FET logic gate (BFL) and flip-flop using GaAs MESFETs. This was followed by a 4-GHz master–slave flip-flop in 1976 and an MSI 5-GB/s word generator in 1981 [77].

1976: Pengelly and Turner of Plessey develop the first monolithic GaAs X-band amplifier [52].

1978: Eden *et al.* at Rockwell develop the Schottky diode FET logic (SDFL), which dissipates considerably less power than the BFL approach. SDFL is used to fabricate a 1008-gate 8 $times$ 8 multiplier in 1980. At this time, many companies including Hughes, McDonnell Douglas, TI, TRW, Tektronix, and Honeywell in the U.S., CSF and LEP in France, and Fujitsu, NEC, and NTT in Japan all mount large efforts to develop a wide variety of GaAs digital ICs [77].

1979: Sokolov *et al.* of TI and Pucel *et al.* of Raytheon develop the first GaAs monolithic power amplifiers, a 1.26-W 9.5-GHz push–pull amplifier and a 0.4-W 10-GHz single-ended amplifier, respectively. Significant development of multistage amplifiers followed the initial work [52].

5) Passive Devices:

1970: Atia and Williams develop elliptical function, linear-phase waveguide filters with dual-mode cavities for satellite communications in the period 1970–1974 [30].

1970: Podell develops a high-directivity microstrip coupler by equalizing even- and odd-mode velocities through the application of a serrated coupling region [100].

1972: Crystal and Frankel develop the hairpin filter for stripline applications with dielectric resonators [30].

1974: Levy presents a solution to dispersion of the combline filter to achieve linear phase performance. Wenzel in 1976 expands and improves the earlier results [30].

1979: Bell Laboratories and Murata develop barium titanate ceramics with high-Q and stable-temperature characteristics that result in practical dielectric-resonator filters [30].

6) Microwave Acoustics [14]:

1970: de Vries of Zenith and Mitchell of Philips develop lithium–niobate SAW filters for channel selectivity in color TV sets. These filter are now standard units in TV receivers.

1972: Claiborne and Hartmann of TI introduce the impulse model for SAW filters, a major advance in filter design.

1973: Paige and Maines at RSRE, U.K. and Bristol at Hughes use lithium–niobate SAW devices in matched filtering for radar pulse compression.

1974: Lewis of RSRE, U.K. develops the SAW oscillator, using a SAW delay line in the feedback path.

7) Design Techniques:

1970: Gelnovatch and Chase develop DEMON, an optimal seeking program for the design of microwave circuits [101].

1971: Schindler develops COSMIC-A, a general-purpose microwave CAD program and Perlman in 1972 develops COSMIC-S, a segmented real-time version with enhancements [102].

1974: Cusack, Perlow, and Perlman apply automatic load–pull to characterize and design microwave power amplifiers [103].

1970s: Besser develops COMPACT and SUPER COMPACT, the first commercially available microwave CAD software [104]–[106].

8) Measurements and Instrumentation:

1975: Hoer and Roe of NBS introduce the six-port technique of impedance measurement, which is closely related to the method Samuel used in 1974, but is improved by the use of the computer correction introduced by HP for discriminator quadrature errors [107].

9) Microwave Applications—Communications:

1976: Rockwell develops an 11-GHz 90-MB/s digital radio for line-of-sight applications. The system utilizes 8-PSK direct modulation of the carrier. In 1983, a family of 90/135-MB/s 64-QAM radios for the 4-, 6-, and 11-GHz common carrier bands were introduced [15].

1977: AT&T develops the single-sideband 6 –GHz analog microwave radio system. Each radio channel has a capacity of 6000 voice circuits or three times the capacity of earlier FM radios [15].

1970s: AT&T completes development of the first U.S. 800-MHz analog advanced mobile phone service (AMPS) cellular system. After a long delay in FCC proceedings, the first field trials of the system are held in Chicago by Ameritech in 1983. The market for cellular service expands exponentially in later years [108].

1980: GaAs power FETs are used by several manufacturers of 6-GHz microwave radio in place of TWTs [15].

10) Microwave Applications—Radar [34]:

1974: RCA starts production of the AEGIS multifunction C-band ship borne phased-array radar to support a missile air defense system for fleet operations. The AN/SPY-1 radar uses four array faces fed by a corporate feed with monopulse sum and difference receivers.

1974: Raytheon starts production of the Patriot multifunction ground-based mobile C-band phased-array radar for the Patriot missile air defense system. This system achieves lower cost by the use of an optically fed array.

1976: The Cobra Dane AN/FPS-108 very large phased-array L-band radar is installed in the Aleutian Islands to observe missile reentry during the Cold War period.

1976: The Pave Paws is the first large phased-array radar to be produced in large numbers. This UHF system is installed on the ocean and gulf coasts of the U.S. to detect submarine-launched missile attacks. Each such radar utilizes thousands of solid- state transmit/receive modules and radiating elements.

1980: The L-band AN/TPS-59 3-D solid-state phased-array radar is placed into production.

11) Microwave Applications—Heating [58]:

1975: The market for consumer countertop microwave ovens grows from 10 000 per year in the 1960s to more than 1 000 000 per year in 1975. Models have many computer-controlled features. Japanese companies, Toshiba, Sharp, Hitachi, and Matsushita entered the U.S. and other markets and became dominant suppliers. By 1977, Sharp was selling over 2 000 000 units per year.

1979: The worldwide market for industrial microwave heating and drying remains sluggish. The technology is used for a limited number of applications, but there are still hope for future opportunities.

IV. Conclusion

This paper has been an attempt to list the major milestones in the development of microwave technology over a 100-year period. The microwave field has grown considerably in this period, from some abstract scientific concepts to the realization of systems that have profoundly impacted society. The development of the field has been application driven and the major contributions have been those that enabled the evolution of the applications. The technology is still rapidly growing, as will be described in other papers in this TRANSACTIONS. The future contributions in the development of wireless access systems will insure that microwave technology will play an even bigger role in the advancement of society than it did in the past.

Acknowledgment

It would be presumptuous of the authors to think that they captured all of the major work over this period and, unfortunately, there are probably some significant contributions that were not included here. The authors' major sources of historical information have been from the U.S. literature and, as a result, while the milestones shown do include some global input, there are probably contributions from outside the U.S. that we have not included. The authors wish to apologize for such omissions. Hopefully, at some point in the future, authors with access to the literature of other nations will summarize contributions to the microwave field in their lands and complete the overall history of this exciting field. The authors also regret not being able to list all the references, but that was not possible due to space limitations. However, the authors do refer the readers to the excellent summary history papers listed below. The authors drew heavily on these publications in assembling their list of milestones. There are particular authors within the historical publications whose papers were very helpful in writing this paper. The authors are particularly grateful and want to acknowledge the papers of [5], which were written by A. A. Oliner, D. N. McQuiddy *et al.*, S. B. Cohn, R. Levy, S. Okwit, K. Button, J. C. Wiltse, J. H. Collins, P. Greiling, S. F. Adam, D. K. Barton, A. W. Guy, and J. M. Osepchuck. The authors also wish to acknowledge the liberal use of papers by J. H. Bryant from [9] and also helpful inputs from S. Adam, L. Besser, T. Itoh, J. Osepchuck, B. Perlman, T. Saad, K. Stephan, S. Stitzer, R. Sparks, R. Sudbury, L. Weymouth, and L. Young.

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