History of Millimeter and Submillimeter Waves

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I. Introduction

IN THIS REVIEW an attempt is made to identify many of the major events that have occurred in the development of millimeter- and submillimeter-wave technology from its beginnings in the 1890's until the present time. The review is not intended to be the definitive history of the field, but may form the basis for someone to later write a more comprehensive or encyclopedic version. The history conveniently divides into three periods: 1890 through World War II, Post War (1947 to 1965), and Modern Age (after 1965).

The techniques of millimeter and submillimeter waves have overlapped in recent years, having originated from different ends of the spectrum. Millimeter-wave advances have mainly grown from extensions of centimeter-wave technology, largely based on the availability of coherent oscillators, whereas submillimeter-wave developments were initially derived by extensions of optical and infrared techniques. The latter were originally based on the use of noncoherent sources and later on the use of harmonics of microwave- or millimeter-wave coherent sources, but often in both cases employing optical techniques. More recently the gas laser has been extended from the infrared all the way to the 2-mm wavelength (150 GHz) region, providing an optical coherent source. In this paper we will concentrate on the frequency ranges from 30 to 300 GHz (millimeter or extremely high-frequency waves) and 300 GHz to 3 THz (submillimeter or extremely far-infrared waves). These correspond, respectively, to wavelengths from 1 cm to 1 mm and from 1 mm to 100 μm, and are illustrated, along with other terminology, in Fig. 1.

II. 1890 Through World War II

The first millimeter- and submillimeter-wave activity occurred in the 1890's. By that time Hertz had performed experiments confirming Maxwell's theory predicting the possibility of radio waves. Hertz produced the radiation with a spark-gap generator, and his first recorded wavelengths were in the centimeter range [1]. In 1895 Lebedew, using methods similar to Hertz's, generated and detected wavelengths which he estimated to be as short as 6 mm. Similar detection of wavelengths of 4 mm was reported by Lampa in 1896, but more than two decades later W. Mobius, in 1918, reporting on dispersion of water and ethyl alcohol between 7 and 35 mm, was unable to get waves shorter than 7 mm and expressed doubt that Lebedew or Lampa had done so. In 1923 Nichols and Tear [2], [3] stated that very probably both Lebedew and Lampa had underestimated the wavelengths that they had produced [1].

Additional fundamental research was carried out in the 1890's by J. C. Bose (of Presidency College, Calcutta, India), who is said to have made the first quantitative measurements at millimeter waves (down to 5 mm) [4]. As a source he used a spark gap having platinum electrodes specially shaped to emphasize the radiation at millimeter waves. He developed various components of sulfur or glass and investigated many natural crystals to obtain their birefringent properties.

In the same 1890's era other research in the far-infrared and submillimeter regions began with the work of Rubens and his coworkers [5]. Basically their approach differed primarily in the type of source of radiation. Rather than the Hertzian spark-gap generator, Rubens used an infrared heat source and "reststrahlen" interference filters to produce quasi-monochromatic beams of radiation. Later, in 1911, Rubens and Baeyer began to use the quartz-envelope mercury lamp as a far-infrared source. Rubens was a prolific author, producing more than 140 papers; he collaborated with a large number of students and distinguished scientists. The period between 1892 and 1922 has been termed "the Rubens era" of far-infrared research [5].

In the 1920's the work of Nichols and Tear [2], [3], [6] and also that of the Russian scientist Glagolewa-Arkadiewa [7] closed the gap between the radio and optical regions by overlapping earlier optical measurements from the radio side. Nichols and Tear developed a special version of the spark-gap source [5], used a reflecting echelon grating to separate and measure the wavelengths, and a radiometer for detection. By patient development of these instruments they were able to extend their wavelength regime beyond the earlier 7-mm limit down to 0.22 mm. The following year, in 1924, Glagolewa-Arkadiewa reported on production and detection of waves from 50 down to 0.082 mm, corresponding to frequencies from 6 GHz to 3.7 THz.[1] She also developed a special type of source which employed

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[1] Note aside: An article in the *Encyclopedia Britannica*, 14th edition, 1973, vol. 8, p. 233, gives these frequencies incorrectly, although the wavelengths are similar.

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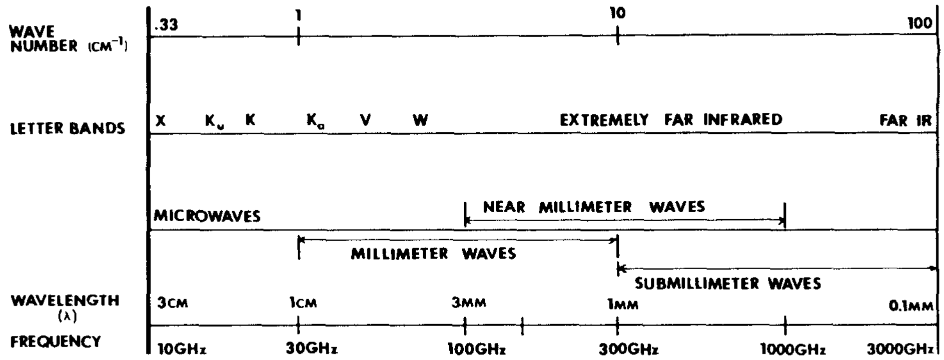


Fig. 1. Nomenclature for millimeter/submillimeter waves and other frequency ranges.

metal filings immersed in mineral oil and energized by a spark gap [5].

Nichols and Tear were enthusiastic about their results, and in their 1924 paper [3] they wrote: "The present methods and results throw open for intensive study practically the last unexplored region in the whole extent of the electric wave spectrum…." Unfortunately, this did not really happen for another two decades, in part because the spark-gap generator was not a stable, monochromatic signal source; in fact, its output is more nearly like that of an infrared heat source than a coherent oscillator. Very few results of spectroscopic significance were obtained with these methods. As Gordy has indicated [1]:

> In the millimeter-wave region a few qualitative physical measurements were made on nonresonant, Debye-type absorption of liquids···. In the overlapping infrared region, low-resolution measurements of a few rotational transitions of simple gaseous molecules were made with infrared optical techniques, as is illustrated by the work of Czerny [9] and Cooley and Rohrbaugh [10] on HI.

Czerny published his first observations of the pure rotation spectra of HCl in 1925, and this is regarded as the beginning of far-infrared molecular spectroscopy [11]. Others followed with the detection of the rotational spectrum of ammonia and the inversion splitting of the NH_3 rotation lines. The era of far-infrared grating spectroscopy begun by Czerny continued for several decades, and the spectral range was gradually extended to 1 mm [12].

It was not until 1934 that the first resonant spectral frequency measured in the microwave/millimeter-wave region (the ammonia inversion) [8] was observed by Cleeton and Williams using an early type of magnetron, rather than a spark-gap generator. In 1936 they operated such a tube as high as 47000 MHz (0.64 cm). The late 1930's saw the development of new coherent radio sources based on various vacuum tube configurations. These included the klystron (invented during 1937 by the Varian brothers and reported by them in the *Journal of Applied Physics*, February 1939) [13] and the cavity magnetron (invented in 1939 by Boot and Randall) [14]. They were immediately used in the radars of World War II, and of course the early applications occurred at microwave frequencies (centimeter wavelengths, not millimeter). Late in the war the microwave traveling wave tube also was developed [15].

The typical airborne radar in use by the Americans and British in the latter part of World War II operated in *X*-band (near 10 GHz). However, as the war progressed, frequencies were pushed up to *K*-band and beyond. The impetus to move to higher frequencies was prompted in part by the desire to obtain better angular resolution from apertures limited in size. Late in the war a new radar design operating near 24 GHz was produced. The naive choice of frequency, it was later found, was unfortunate because of the increased atmospheric attenuation (nearly an order of magnitude greater than at *X*-band), resulting from the fact that a broad absorption by water vapor occurs centered near 22.3 GHz. From lack of knowledge of atmospheric effects, the radars were rendered less effective than anticipated.

Until World War II only one discrete spectral transition had been measured [8]. During the war Beringer, using a crystal harmonic generator driven by a centimeter-wave klystron, obtained enough second-harmonic signal to measure the 5-mm wavelength (60 GHz) absorption of oxygen, but did not resolve its fine structure [16]. Thus the period through World War II closed out with the stage set for the extension of coherent radio frequency techniques into the millimeter/submillimeter range.

III. Post War—1947 to 1965

After the war the new sources were used to develop the discipline of microwave/millimeter-wave spectroscopy. For the first time molecular spectra could be studied with coherent radiation. The resolving power was remarkable and permitted precise determination of molecule sizes and shapes. Gordy's group at Duke was one of the first to take advantage of this capability. He obtained from Raytheon a few of the first klystrons developed for frequencies from 30 to 50 GHz, and starting in 1947 and continuing for many years he and a succession of graduate students made many high-resolution spectral measurements. It was necessary to develop various components which obviously were not available commercially. Particular emphasis was placed on making the harmonic multipliers more efficient (producing more power at higher harmonics) and broad band [1], [17].

After receiving their Ph.D. degrees, several of Gordy's students went on to other organizations where they set up or participated in millimeter-wave research groups. Examples include R. F. Trambarulo and C. A. Burrus who joined Bell Telephone Laboratories, and C. M. Johnson (and later W. C. King) who initiated a very successful program in millimeter-wave spectroscopy at the Johns Hopkins University. Bell Labs had developed an interest in millimeter waves even before World War II as an outgrowth of early waveguide work by G. C. Southworth, and the discovery by S. A. Schelkunoff that, for the circular electric mode in ideal round pipe, the attenuation decreases asymptotically toward zero as the carrier frequency increases indefinitely [18]. In addition, there was interest in millimeter-waves for conventional radio communication. For point-to-point transmission attractive advantages included high gain from small antenna apertures and the availability of bandwidths of thousands of megahertz from small-percentage-bandwidth components; atmospheric attenuation due to oxygen, water vapor, and rainfall was a serious disadvantage, but was not well understood at first. Beringer's early measurements on oxygen absorption near 5 mm (60 GHz) had been reported in 1946 [16], Van Vleck's analysis in 1947 [41], and the Gordy group's more detailed measurements in 1949 [19]. Further measurements on oxygen in the 2–3-mm region were not reported until 1950 [20]. (For transmission in enclosed waveguides atmospheric attenuation is not a problem since an inert filling gas, such as dry nitrogen, can be substituted for air.)

The Bell Labs effort grew steadily from the mid-1940's and continued as a significant effort in several areas for many years. The circular-electric mode transmission using the "helix-guide," plus the development of associated sources, detectors, and components (such as filters) continued for decades, culminating in the installation in the mid-1970's of a complete 14-km-long system which was buried in the ground in New Jersey and made a part of the Bell System's network [20]. Similar systems have also been installed in Japan and England [21].

While the members of the Duke group were developing their spectroscopy methods, a Columbia University group was experimenting with the filtered harmonic energy obtained directly from high-powered magnetrons. As early as 1949 they announced detection of harmonic energy in the 1.5–3-mm wavelength range utilizing a Golay cell [22], [23]. Later, however, they discontinued the magnetron measurements and instead used the klystron/harmonic-multiplier approach. (Speaking of the Golay pneumatic detector, its availability after 1947 was an important factor in the measurement instrumentation field [24]. It was used from the far-infrared to millimeter wavelengths, providing relatively good sensitivity and ease of operation as well as broad-band response.) By 1953 spectroscopic measurements in the 1–2-mm region were reported by the groups from Duke [1], Columbia [25], and Johns Hopkins [26] (which had now been joined by J. J. Gallagher).

While these important advances were being made from the radio side of the spectrum, progress was also occurring from the far-infrared side. A very good description of events of this "grating era" has been given by Ginsburg [12]. Although much of his discussion involves wavelengths in the 30–100-μm range (i.e., shorter than our range of interest), there is considerable description (somewhat anecdotal) of the development of instrumentation and measurements on materials at wavelengths longer than 100 μm. One of the better FIR spectrometers of the late 1930's was employed by Randall and his associates, who measured the ammonia and the water vapor spectra with improved resolution [12], [27]. Several other FIR spectrometers were built in the 1930's and early 1940's. The grating instruments built by Marr and by Hopf covered the region from 150 to 400 μm (750 GHz). The typical detector used at this time was the thermopile, and Ginsburg gives an interesting commentary on the art of making a good thermopile [12]. The greater ease of working in the submillimeter range occurred after World War II with the advent of the Golay cell, which gave an order of magnitude improvement in voltage and speed of measurement compared to the thermopile. Sensitive pen recorders also became available at that time.

By 1950 an expanded development of FIR spectrometers occurred in many laboratories, starting first with McCubbin and Sinton at Johns Hopkins University, Baltimore, MD, whose instrument worked out to 700 μm (430 GHz). Further expansion during the early 1950's occurred at Massachusetts Institute of Technology, University of California at Berkeley, and Ohio State. Overseas, Yoshinaga at Osaka University in Japan, Hadni at the University of Nancy in France, and Genzel and Eckhardt at Freiburg in Germany, built spectrometers. Several years later Yaroslavski (1958) in Leningrad, U.S.S.R., and Bloor *et al.* (1961) in London, England, entered the field. By the late 1950's commercial instruments became available, the first being offered by Perkin Elmer.

During the 1950's there were very important developments in Fourier transform spectroscopy (FTS) and Fabry–Perot interferometry. These were coupled with the introduction of new detectors with greatly improved sensitivities and much better time constants than the Golay cell. The earlier ones included bolometer types such as carbon, gallium-doped germanium, and superconducting tin. Other (intrinsic) detectors, such as broad-band InSb, epitaxial GaAs, and pyroelectric, gave detectivities 10 to 100 times that of the Golay cell. A disadvantage was the need for operation at liquid-helium temperatures. A historical review of the development of FTS up to 1965 has been given by Lowenstein, and an excellent review of interferometry from 1950 to 1977 has been presented by Genzel and Sakai [28]. The FTS, based on two-beam (Michelson or lamellar grating) interferometry, provided a dramatic breakthrough and is clearly one of the most important spectroscopic methods for the whole IR and submillimeter range. Fabry–Perot interferometry became possible in the FIR after the introduction of metal mesh as nearly lossless reflectors [28].

The first published spectrum of atmospheric transmission at submillimeter wavelengths was reported in 1957 by Gebbie [29] (then at Johns Hopkins), who measured the

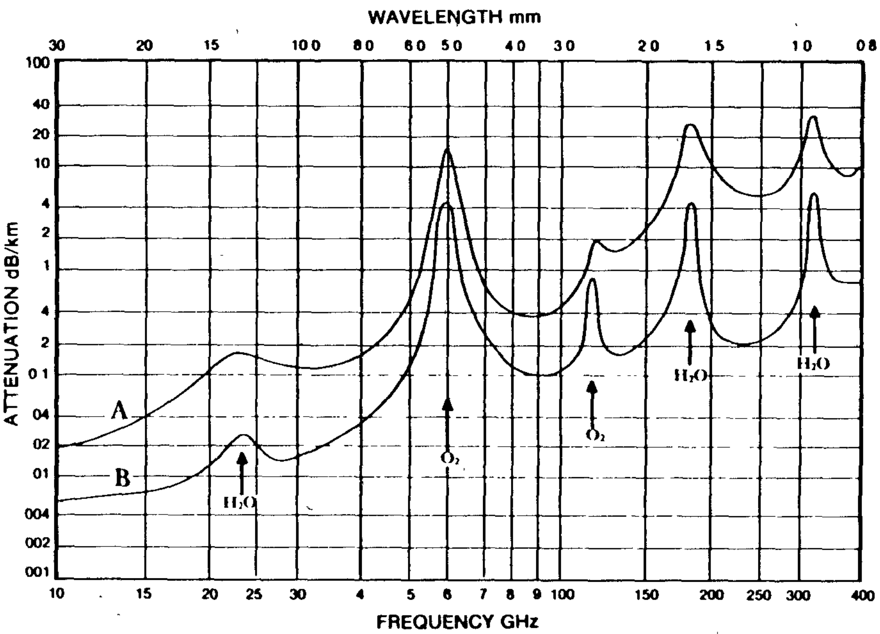


Fig. 2. Average atmospheric absorption of millimeter waves (from [40]).

A: Sea level	B: 4 km
$T = 20°C$	$T = 0°C$
$P = 760$ mm	$\rho_{H_2O} = 1$ g/m^3
$\rho_{H_2O} = 7.5$ g/m^3	

solar absorption spectrum between 1 mm and 313 μm (300 and 960 GHz) with good resolution using a large aperture lamellar grating interferometer. His work was carried out at the Jungfraujoch observatory in the Swiss Alps because he had concluded that the strong absorption of water vapor would obscure the solar spectrum at lower levels. The intense pure rotation band of H_2O is now known to be the major characteristic of the submillimeter atmospheric spectrum. Historically these first mountain observations were followed by studies from aircraft from the mid-1960's onward, and these were later followed by balloon flights [30].

It is perhaps somewhat ironic that while one group at Johns Hopkins (J. Strong, H. A. Gebbie, G. Vanasse, T. K. McCubbin, W. M. Sinton, and others) was busily moving from the far-infrared to the submillimeter, another group at the Hopkins Radiation Laboratory was working in the coherent millimeter-wave to submillimeter-wave direction. In the latter case, physics research (spectroscopy) began to spawn research on components [31], surface waveguides [32], harmonic mixing in superheterodyne receivers, radar sea clutter measurements [33], and electromagnetic scattering theory. This same effect was taking place at other laboratories. One "new" group (the Ultramicrowave Laboratory) had been formed at the University of Illinois by P. D. Coleman after his arrival in 1951. From the mid-1950's on, he and a succession of graduate students produced extensive research on components, techniques, dielectric waveguides, high-power sources ("megavolt electronics"), as well as physical measurements on materials [34]. This group was very prolific over nearly three decades. At M.I.T. Lincoln Laboratories G. S. Heller and his associates began a millimeter-wave solid-state research program, with measurements of ferrite and semiconductor material properties, as well as component and techniques development [35]. At Princeton University, NJ, a group began to use millimeter waves for making diagnostic measurements of high-temperature plasmas [36]. This work has continued for 25 years and was recently reviewed and summarized by Ernst [37].

At the University of Texas, Straiton and Tolbert were leading a very active group which became well known for its research and measurements on atmospheric propagation, and developed radars and radiometers [38], [39]. Straiton's group produced a set of curves of atmospheric attenuation per kilometer (for horizontal propagation) which have become "classics." Fig. 2 shows the curves as printed in Rosenblum's article [40]; they have doubtlessly been copied in scores of articles, reports, and books during the past two decades. The curves, derived from the theoretical analyses of absorption by O_2 and by H_2O as originally performed by Van Vleck [41], are supplemented with experimental data points measured at various frequencies by several groups, including Texas and Bell Laboratories (Crawford and Hogg) [42].

During the 1950's and early 1960's many other institutions were involved in or became involved in millimeter-wave research. For instance, at Georgia Tech, Atlanta, there was considerable emphasis on antennas (particularly the geodesic lens) and on radar designs, and a 70-GHz radar was developed to the point of being given a military nomenclature (AN/MPS-29) in 1959 by the U.S. Army (see [21, pp. 80–82]). Research on high-power sources continued at Columbia University Radiation Laboratory; the magnetron was extended upward to 115 GHz (3.3 kW) by 1954, but its lifetime and duty cycle (and average power) were low [43]. Also, Cerenkov radiation, named for the Soviet physicist who first observed the effect in 1934, was being investigated at millimeter waves [44]. At the Philips Research Laboratories, Eindhoven, The Netherlands, klystrons were extended up in frequency to 120 GHz (40 mW output CW) by 1959 [45]. Broad-brand helix traveling-wave amplifiers were being investigated at Bell Labs for frequencies up to 58 GHz [44]. Backward-wave oscillators ("O-Carcinotrons") were developed up to 150 GHz by C. S. F. of France [46] (and ultimately would be extended to beyond 1 THz by the Soviets). Other organizations conducting millimeter-wave research included Stanford, Palo Alto, CA, the Naval Research Laboratory, and the Polytechnic Institute of Brooklyn, Airborne Instruments Laboratory, and TRG.

The first issue of the IRE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES was published in March 1953. However, the first paper on millimeter waves apparently did not appear until July 1954 [47]. The succeeding issue was then almost totally devoted to millimeter-wave subjects [44]. Later issues frequently carried millimeter-wave articles, but there was a dearth of submillimeter papers. In addition to describing sources, there was much emphasis on new transmission lines and on mixer diodes. Since conventional dominant-mode rectangular waveguide is fairly lossy (on the order of 1 dB/ft near 100 GHz), other media were sought. Circular waveguide propagating the TE_{01} mode was known to provide low loss, but mode conversion was a problem. The helix guide was developed at Bell Laboratories, but it was not a simple structure to fabricate [48]. Dielectric waveguides propagating the HE_{11} surface mode were also investigated at Bell (and other laboratories), and the first millimeter-wave measurements (at 48 GHz) were reported by Weiss and Gyorgy in 1954 [49].

An alternate transmission line, the dielectric image line, was reported by D. D. King (the late President-Elect of the IEEE), who developed a number of components and measured their characteristics at *K*-band [50], [50a], [32]. The image line solves the support problem which exists for dielectric waveguide, although the presence of the conducting image plane contributes to the attenuation (which nonetheless can be much less than for rectangular waveguide). The characterization of image line and associated components was carried to millimeter wavelengths by Wiltse, who performed analyses and made measurements at frequencies between 35 and 140 GHz [51], [52]. He also investigated elliptical cross sections and the "tape" line (a very thin ellipse), which reduces attenuation. Shields were also evaluated.

In addition, Wiltse and his associates investigated surface-wave propagation on dielectric-coated (Goubau line) or uncoated (Sommerfeld wave) metal wires, and applied the phase-correcting Fresnel zone plate (adapted from optics by F. Sobel) as an alternate for conventional lenses at frequencies from 35 to 280 GHz. In the same time period, Taub and his co-workers were developing oversize quasi-optical waveguide components [77]. Another low-loss

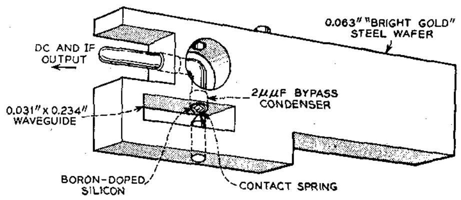


Fig. 3. Millimeter-wave wafer unit (from [54]).

transmission line which received considerable attention was the H-guide, proposed in the mid-1950's by F. J. Tischer, who also investigated its properties. Later, in 1959, M. Cohn carried out a more detailed analysis and reached some conclusions which differed from those of Tischer. The differences were discussed in the I.R.E. Transactions, but agreement does not appear to have been reached. Still later E. M. Guttsayt of the U.S.S.R. Moscow Power Institute, Department of Electronic Devices, also published some papers about H-guide. In one (1962), he compared his results for losses with those of both Tischer and Cohn, and argued that both of them are correct.

Several papers on detectors appeared in this time frame, and one made a big impression. It was a report by W. M. Sharpless, who had invented a wafer-mounted detector for use in waveguides [54]. Most of the previously available packaged diodes had been coaxial cartridges, which were typically narrowband and hard to tune. The Sharpless unit, shown in Fig. 3, provided good impedance matching in a configuration that was standardized and could be manufactured in quantity with repeatability. Sharpless mounts are still used in some applications.

In the 1950's the maser evolved as an extremely low-noise microwave amplifier, and in the early 1960's several millimeter masers were built. Other new developments took place, such as low-noise parametric, TWT, or tunnel diode amplifiers, and although they did not, in general, operate at millimeter wave-lengths, they did offer low-noise IF amplification with wide bandwidths. This meant that better receivers and radiometers could be built, stepping stones to improved radar, communications, or passive sensing systems. Since millimeter-wave local oscillators were (and often still are) noisy, it was convenient to use a very high (i.e., microwave) intermediate frequency to avoid local oscillator (LO) noise sidebands. This was more practical than using LO filtering or balanced mixers (requiring balance over extremely wide bandwidths) to improve the noise figure. Then for passive radiometer receivers, sensitivity (related to bandwidth for continuum radiation) could be improved by an order of magnitude through the use of IF bandwidths of about 1 to 2 GHz. Employing this technique, several extremely sensitive radiometers were built at frequencies between 90 and 230 GHz [55]. The method of using a single-ended mixer and a wide microwave IF now sees common usage.

The early 1960's saw the initial development of lasers. Unfortunately none operated in the millimeter-wave region, although two gas lasers did operate in the submillimeter range. (Today optically pumped gas lasers can operate at thousands of possible transitions from 150 GHz to the far infrared.) One of the most important early lasers for the submillimeter region was hydrogen cyanide gas, which operates at 890 GHz (0.337 mm) with a peak power of 10 W. This was used extensively by spectroscopists, especially by H. A. Gebbie, then at the National Physical Laboratory, Teddington, England. Scientists using an HCN laser, knowing its lethality, often kept a canary in a cage in their laboratory. If the canary suddenly expired, this gave a danger warning of possible HCN leakage. Another submillimeter laser was the water vapor laser, operating at 2.54 THz (0.118 mm). A disadvantage for both of these lasers was (and still is) the lack of appreciable tunability.

It is clear that by the early 1960's there was widespread activity in both the millimeter and submillimeter fields. In addition to spectroscopy, there were many system applications being tested. The U.S. Navy had conducted early development on a secure short-range ship-to-ship communication system, and this program had in turn supported development of high-power TWT's in the 50–60-GHz range. Several high-resolution 70 GHz radars had been developed by the U.S. Army Signal Engineering Laboratories, Bell Laboratories, and Georgia Tech, and others. Phenomenology data had been measured on atmospheric propagation, rain attenuation, and radar clutter (from sea or land). Radio astronomers had begun to work in this wavelength region.

As a focal point, a major symposium, the I.R.E. 1963 Millimeter and Submillimeter Conference, was held in Orlando, FL, and attracted many attendees from overseas. In fact, a follow-up conference was also held in 1965 in Estes Park, and papers from this meeting were collected for a special issue OF THE IEEE, PROCEEDINGS April 1966, edited by D. D. King. Thus the entire field had grown tremendously in the post-World War II era. Although the author has not given a complete coverage of all the activities of that period, the conclusions are clear: the field had matured greatly, activity (in people, institutions, and funds) had grown significantly, and technical growth and evolution had been enormous. For the interested reader, an overall summary article, written at that time, is available [56]. My coverage of developments outside the U.S. has been limited, but unfortunately complete coverage is impractical. A view of U.S.S.R. activity in the millimeter/submillimeter region, as well as a Soviet view of such activities in other countries, is given by Katsenelenbaum in "Quasi-optical Methods of Generation and Transmission of Millimeter Waves," *Soviet Physics Uspekhi*, May 1964. There was much work in Japan, and a good summary is described in English in "*Report of the Research Committee on Millimeter Waves in Japan*," Corona Publishing Company, Tokyo 1963.

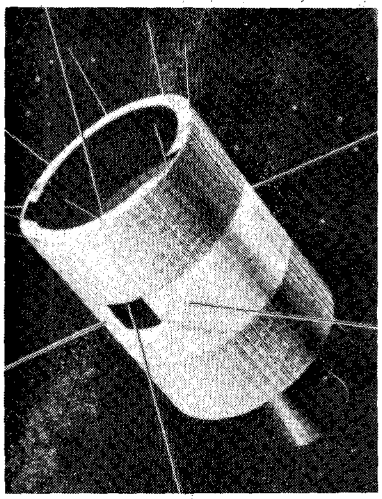
IV. Modern Age—After 1965

The advent of lasers in the mid-60's produced a negative effect on research and development in the millimeter/submillimeter field. Laser research was new and fascinating, and laser technology promised quick solutions for many practical applications, including military requirements. Consequently, laser funding increased enormously and funding for millimeter-wave projects declined noticeably (except in a few specific areas). The decline lasted until the early to mid-1970's and probably affected submillimeter-wave research most. A slow transition was taking place because of technology developments, some of which occurred before 1965. For example, the Gunn effect was discovered in GaAs by Gunn in 1962; he has described the discovery in an interesting article [57]. Also, in 1964 the silicon IMPATT oscillator was developed at Bell Laboratories (and at approximately the same time in the Soviet Union); this story is told in a recent historical article by De Loach [58]. By the early 1970's both Gunn and IMPATT oscillators operating at 35 GHz were commercially available.

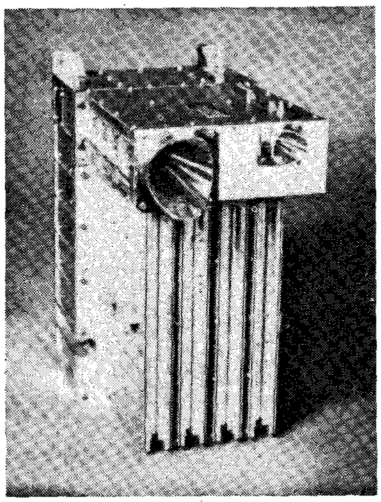
Comments from De Loach's article [58] are interesting. He points out that work at Bell Labs had been concentrating on a "circular-electric mode guided wave millimeter communications system," the helix guide system that we have already mentioned. The ultimate capacity of such a system was in excess of a million one-way voice channels in one 2-in diameter tube. In 1962, however, it was decided that the system was more expensive than alternate systems due in part to the short life of available tube sources, and as a result the potentially super capacity system was relegated to mothballs. A quest for long-lived solid-state sources was then begun. This story is probably symptomatic, even today, of several possible millimeter-wave systems, in that although they are technologically feasible and fulfill a need, they are not economically advantageous.

Throughout the 1960's there was some major funding for certain programs. A notable example was the activity supported by the U.S. Army Ballistic Research Laboratory, Aberdeen, MD, which initiated a program in the early 1960's to develop millimeter-wave components, particularly at 35, 94, 140, and 220 GHz, for application to radiometers, radars, and missile guidance [59]. The program has continued to the present and has produced some very valuable results. The Royal Radar Establishment, Malvern, England, also had some similar projects during the 1960's and 1970's.

Another example of a major U. S. Program was the National Aeronautics and Space Administration Advanced Technology Satellite (ATS) project. The fifth satellite in this series, the ATS-E, contained a wideband 31.65-GHz uplink and a 15.3-GHz (all-solid state) downlink to measure satellite-earth propagation effects (particularly as a function of weather) [60], [61]. Fig. 4 shows a photograph of the ATS-E equipment. A later satellite, the ATS-F, similarly was used to measure propagation effects across 1-GHz widebands near 20 and 30 GHz. Numerous other satellite experiments were also investigated [62], [63]. Much later, in the mid-1970's, NASA's Nimbus-F satellite carried five downward-looking superheterodyne radiometers with center frequencies between 22 and 60 GHz. Temperature profiles were successfully measured for a variety of geo-



(a)



(b)

Fig. 4. (a) ATS-E spacecraft and (b) millimeter-wave package.

graphical locations and atmospheric and climatic conditions.

The Aerospace Corporation in Los Angeles has had a significant on-going millimeter-wave program since about 1963. They were one of the first groups to obtain a large (15-ft diameter) precision paraboloid antenna. Their projects have included radar, communications, and radio astronomy investigations [64], [65], as well as work on component development. They are presently involved in the EHF (Extremely High Frequency) Satellite Communication System, a major effort to install military communications equipment at frequencies of 20, 30, and 44 GHz operating between earth and satellites.

In the late 1960's a number of technology firsts were reported. Phase-locking of the 890-GHz HCN laser to a multiplied radio frequency standard was reported by Corcoran and Gallagher [66]. An exciting development was the discovery of water-molecule emission sources in the galaxy, radiating at frequencies near 22.2 GHz [67]. The extended interaction klystron oscillator was developed, and in the past few years this has become a very important medium-to high-power source. The metal–oxide–metal diode was first reported in 1966; in excess of 60 articles have been published on this subject since then [68]. F. A. Benson's book on millimeter waves was published by Iliffe in 1969, and in July 1970, a special issue of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION dealt with millimeter-wave antennas and propagation.

On the submillimeter-wave side of the spectrum there has been extensive growth of activity level in the modern era, in spite of limited funding. In 1970 a major symposium was held at the Polytechnic Institute of Brooklyn, NY, dealing primarily with submillimeter waves [66]. Some 57 papers (including a few millimeter papers) were bound in the PROCEEDINGS OF THE IEEE. By this time, the optically pumped submillimeter laser had been developed and was reported on, along with presentations on other sources, detectors, components, spectroscopy, materials measurements, and special applications. Numerous other major submillimeter wave symposia have been held since then. A series of IEEE-sponsored conferences on Millimeter Waves and Infrared started in Atlanta, GA, in June 1974, followed by meetings in 1976 and 1978, and since then they have been held annually, alternating between North America and Europe. The most recent Eighth Conference was held in Miami Beach in December 1983 [68]. The content has been mainly submillimeter-wave topics, although a significant portion of the last one dealt with millimeter waves. The conferences were initiated by K. J. Button and J. J. Gallagher. The papers from the conferences are now usually published in the International Journal of Infrared and Millimeter Waves, published by Plenum Press, NY, and edited by K. Button. A series of texts on Infrared and Millimeter Waves has also been edited by Button and published by Academic Press [21]. The content of these volumes is heavily oriented toward submillimeter-wave technology. Other symposia on submillimeter waves have also been sponsored by the S.P.I.E. (Society of Photo-Optical Engineers) [69].

Throughout the decade of the 1970's both the millimeter and submillimeter fields continued to expand in level of effort, diversity, and technical progress. The advent of solid state sources has been a major boost to millimeter waves, but so, also, has recent progress in new vacuum tube sources such as extended interaction oscillators (EIO) and amplifiers (EIA) and gyrotrons. Millimeter-wave IMPATTS first became available in the 1970's, but by 1976 37-GHz IMPATT *amplifier* transmitters were operating in space in the Lincoln Laboratory Experimental Satellites (LES-8 and LES-9). And by 1978 the U.S. Army's STARTLE radars (developmental) were using all-solid state transmitters consisting of a 94-GHz phase-locked Gunn oscillator chain whose frequency controllable output was used to injection lock the IMPATT transmitter, which provided 4 W peak power in a pulse mode. Various modulation formats were employed: short-pulse/spread spectrum or coherent MTI (moving target indication) or pulse compression with frequency agility. Two charts borrowed from J. Kuno further illustrate this type of progress (see Fig. 5).

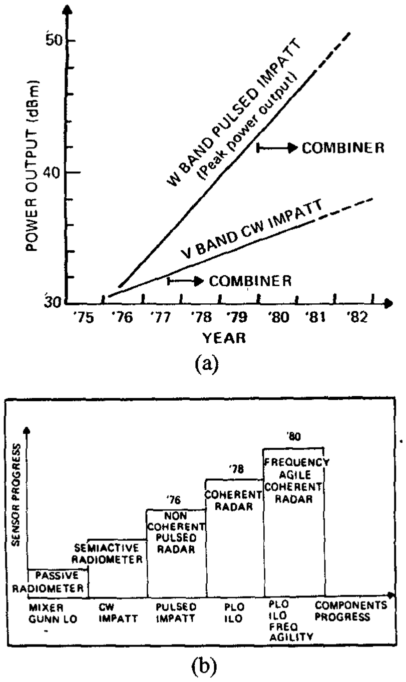


Fig. 5. (a) Solid-state millimeter-wave sources progress. (b) Millimeter-wave sensor technology development reflects solid state components progress.

If higher power (1.5 kW peak at 94 GHz) is needed one might choose an EIO. Pulsed EIO's for example, are comparable in power and cost to magnetrons at 95 GHz. However, the EIO has nearly an order of magnitude greater lifetime. Furthermore, magnetrons are not available above 100 GHz, whereas EIO's are available up to 260 GHz. Gyrotrons produce enormous powers at good efficiencies (30–40 percent), and they are now becoming commercially available. Varian has produced a state-of-art tube at 60 GHz which produces 210-kW CW output, designed for use in fusion plasma diagnostics.

The recent millimeter-wave state of the art has been summarized in several overview papers [70], [21] and in a special issue [71]. In addition, two millimeter-wave conferences have been held under the sponsorship of the S.P.I.E. [72], [73]. Taken together, the two conferences show the progress in sources, mixers, components, and devices; the improved understanding of atmospheric phenomenology and materials properties; and the development of applications in radar, communications, missile guidance, and remote sensing. A recent paper by Akabane describes the current status of very large high-resolution reflector antennas for millimeter-wave radio astronomy [74]. Two publications by Johnston summarize, respectively, millimeter-wave radar and radar-related phenomenology (up to 1980) [75], and a summary of submillimeter wave propagation measurement techniques [76].

V. Concluding Comments

From spark gap transmitters to IMPATTS and gyrotrons is a large step, but the millimeter/submillimeter fields are still far from mature. The frequency range from 30 to 100 GHz is in a state of advanced development, while the range above 100 GHz is more exploratory in character. Radar, communications, and guidance are mainly operative below 100 GHz (some work to 220 GHz), remote sensing is being conducted throughout the range from 30 to 220 GHz, astronomy is largely concentrated above 90 GHz (to the IR), and spectroscopy and materials investigations cover almost the entire range from 30 to 3000 GHz.

The total amount of funding has greatly increased, but the strong emphasis is on only a few areas, such as missile guidance and EHF communications (both satellite and terrestrial, using bands near 44 and from 54 to 60 GHz). The funding in the U.S. for guidance has exceeded $100 million, and the funding for communications will be much greater than that. World-wide expenditures for radio astronomy are also very large.

This article has attempted to trace the growth of two parallel fields as they developed and began to overlap each other. The overlap is not complete and to some degree the paths are still proceeding in parallel, although there are many common techniques. It has been interesting to note the invention of new items (such as klystrons, magnetrons, and gas lasers) and see that over the years they have been extended in frequency and power almost to their limits. The latest state of the art in detectors is approaching the theoretical sensitivity limit. Perhaps what is most needed is the invention of new sources that would provide reasonable coherent power with simplicity and good efficiency at frequencies from 100 GHz into the submillimeter.

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A Short History of Microwave Acoustics

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***Abstract*—Microwave acoustics may be defined as the subject embodying the propagation of acoustic waves in solid-state materials at micron-order wavelengths where analysis, design, and componentry realizations are similar to those used by the microwave engineer exploiting electromagnetic waves. Microwave acoustics has a short history, being about 25 years old, but is underpinned by the theory of sound propagation due to Lord Rayleigh of 100 years ago. Microwave acoustic components inherently have several distinct physical origins including volume acoustic waves in solids excited by piezoelectric thin-film transducers and magnetic propagating modes in yttrium iron garnet, both at conventional microwave frequencies; the later surface acoustic-wave (SAW) technology for operation at VHF/UHF; and the realm of acoustooptics, which can embody any of the earlier three. Over its 25-year history, microwave acoustics has matured to become a necessary building-block in many radar and communication systems for efficiently carrying out real-time analog signal processing. Contributions to microwave acoustics have been truly international and have spanned many diverse disciplines. The growth of this subject has led to the formation of several companies dedicated to its application.**

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I. INTRODUCTION

IN WRITING a guest editorial on microwave acoustics for the TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES in November 1969, Al Bahr [1] posed the question, "What has acoustics to do with G-MTT?" and answered it through a quote from the G-MTT constitution of the time, namely that "Microwave theory and techniques are related to electromagnetic waves usually in the frequency region between 1–100 GHz; other spectral regions and wave types are included within the scope of the Group whenever basic microwave theory and techniques can yield useful results. Generally, this occurs in the theory of wave propagation in structures with dimensions comparable to a wavelength, and in the related techniques for analysis and design."

Indeed, microwave acoustics has over the years demonstrated all these attributes. However, in "microwave acoustics," the "micro" part of "microwave" is normally

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