State of the Art: Background and Recent Developments—Millimeter and Submillimeter Waves*

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Summary—**The aim of this survey is to discuss the basic problems encountered in the general areas of generation, transmission, and detection of millimeter waves. Representative examples of work in these three areas since 1959 are reviewed with respect to the methods and techniques employed to circumvent present limitations and extend the frontier into the submillimeter range.**

Subject classifications include classical and quantum electronics, harmonic generation optical frequency pumping and mixing, waveguide and optical transmission systems, resonators, and detectors. At the end of each section, a few critical evaluation remarks are made on the work in progress and the prospects of success in the near future.

A fairly comprehensive list of some 157 references dating from 1959 is listed by year and subject title. While substantial progress has been made, especially in technology, in the last few years, the submillimeter wave problem appears as formidable as ever and no breakthrough idea has yet been recognized.

I. Introduction

SUBMILLIMETER wave research, while appearing to be a rather specialized area, has one of the broadest technical bases that can be imagined for a problem of scientific and practical interests. Almost every phenomenon in physics has been examined for possible application to the problem of generating, transmitting, and detecting coherent ultramicrowave energy. Subject areas include: classical electronics, quantum electronics, semiconductors, solid state, ferrites, ferroelectrics, field emission, tunneling, superconductors, physical optics, electromagnetic theory, acoustics, relativistic physics, nonlinear phenomena, plasmas, and spectroscopy. This horizontal aspect of the work is both a challenge and a frustration for the ultramicrowave engineer who must be a jack-of-all-trades applied physicist.

Organized submillimeter wave conferences [1]–[5] go back at least 12 years. Since 1951, they have been held on the average of every two years, the last U. S. conference being the 1959 symposia at MRI [4] in New York. Millimeter wave survey papers [6]–[21] have recently been appearing at the rate of six a year, so frequently in fact that one often wonders if the subject might not get overexposed.

It has often been said that the task of the scientists is to ask the right questions. The interesting thing about the submillimeter wave problem is that enormous numbers of questions have been presented at the conferences and in the survey papers, but the items that are still missing are the answers and the submillimeter waves. Unfortunately, this survey will not appreciably alter this situation.

The aim of this survey is to discuss the basic problems encountered in the general areas of generation, transmission, and detection of millimeter and submillimeter waves. Representative examples of research work since 1959, indicating directions in which ultramicrowave research appears to be developing, are briefly reviewed along with the problems encountered.

No matter what the approach taken to the ultramicrowave area, the same basic problems and limitations always seem to appear. One objective of this paper will be to try to identify them and point out the forms they take as the attack is varied.

The history of a research field seems to follow the pattern of first a big flurry of ideas followed by a longer period of exploring, developing, and evaluating the suggestions. While several new ideas in the ultramicrowave area have appeared in the last four years, the major effort has been in applying new technology to previously suggested ideas. This effort has yielded substantial progress, but as yet, no breakthrough on the problem.

II. Classical Electronics

A. General Considerations

The problems of extending classical electronics devices into the submillimeter range are well-known and have been discussed in many papers. Since there is a scarcity of radiation, it is obvious that the answers to the problems are the things that are unknown.

Now the engineer in developing a device draws on two areas: 1) physical laws and principles, and 2) technology and art. Usually the state of the art limits the achievement at any given time. As new techniques are devised, old principles and ideas often again become practical to extend the frontier.

The question that can be asked is: Is classical electronics nearing the end of its theoretical frequency limit rope and will new technology not appreciably extend electronic devices further in frequency? It is not expected that the output of devices will fall off abruptly but that the power output will decrease toward zero as the frequency is increased.

All classical electronics is based on the Lorentz force law, expressing the force $\boldsymbol{F}$ acting on a charge q having a

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velocity v in an electromagnetic field E and B,

$$F = qE + qv \times B. \tag{1}$$

The number of basic ways the kinetic and/or potential energy of the unbound charge q can be converted into electromagnetic energy is rather few. They may be distinguished by considering the type of E field that is exerting a force on the charge. In Fig. 1, four basic types of interaction are illustrated.

In the tube devices category, the field E is the field produced by charges other than q in the system. For Cerenkov and transition radiation devices, the charge q in cooperation with the material boundaries set up a field E to oppose its motion. In acceleration devices, the charge q produced its own self-field, as a result of its accelerated motion.

The overwhelming effort in classical electronics has been and still is on tube type devices [25], [39], [45]. Many theoretical papers have been written on the last three types of interaction, but relatively little experimental work has been done and the principles certainly have not been reduced to practice.

In the last four years, progress on tube devices has been substantial but it has been mainly technological progress in the areas of improved electron guns with higher convergence ratios and corresponding current densities, improved fabrication techniques for circuits with greater heat dissipation capabilities and, perhaps most important of all, more customers demanding tubes.

While it was recognized four years ago that, in a traveling-wave device, one could have either a smooth beam and a slow wave periodic circuit or a periodic beam and a smooth fast wave circuit, experimental work on this problem in the form of the Ubitron [26] and Cyclotron Resonance Amplifier [22], [24], [38] has been a new development.

In the last four years, more experimental work on the Cerenkov [27], [34], [36], [37], [43] problem to reduce these principles to practice has been performed than at any previous time. It has now been demonstrated that the Cerenkov interaction, which is also a traveling-wave interaction, can be as strong as that in conventional tubes.

The Tornadotron [111], conceived as an acceleration radiation device, has successfully produced signals over 100 Gc but at discrete frequencies indicating electron beam interaction with a resonator mode.

One coherent transition radiation experiment [35], the annihilation of a prebunched beam by a metal plate, has been reported. The interaction for this geometry is rather weak but other geometries, such as thin dielectric films, hold promise for greatly increased power outputs.

An alternative to a slow wave circuit obtained by a periodic loaded metal guide is a plasma waveguide. A plasma in a dc magnetic field is a very dispersive medium having two characteristic frequencies, the plasma and cyclotron frequencies (ω_p and ω_c), which can readily be varied.

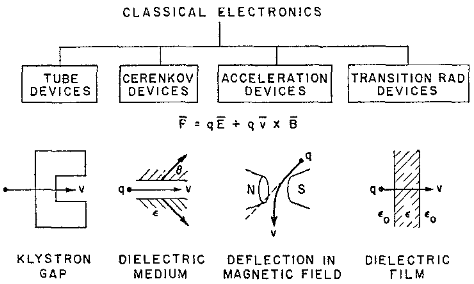

Fig. 1—Classical electronics methods of producing coherent radiation.

While this beam-plasma work goes back many years, the present research as resulted in better technology in plasma production and, consequently, much better agreement between theory and experiment. However, to extend this endeavor into the submillimeter region requires solving the familiar problems of making ω_p and/or ω_c sufficiently large.

As a general summary on classical electronics, it appears safe to state that the progress in the past few years has been mainly improved technology and the reduction to practice of ideas that were suggested previously.

B. Millimeter Wave Tubes

Approximately 20 companies [17], [21] are now producing the order of 120 electron tubes in the frequency range 30–450 Gc. Klystrons are most numerous in the lower part of this range, while in the submillimeter region only O-type BWO's are available. A partial list of commercially made millimeter wave tubes is shown in Fig. 2.

An excellent review paper in 1960 by Karp [29] on millimeter wave tubes is still applicable since, without exception, all of the present-day tubes are scaled versions of lower frequency tubes. It is not evident that any new principles of electron beam-RF interaction have been found which are more suited to ultramicrowave generation. Practical tubes all operate on the principles of microwave types.

In Fig 3 are shown the four basic types of slow wave circuits used in millimeter wave tubes. All the tubes require an electron beam of a diameter small compared to the wavelength, usually magnetic focusing of the beam, and precise alignment of gun and interaction structure.

An example of a low millimeter wave helix tube [23] is the one described by McDowell and Danielson [30]. By glazing the helix to a single wedge dielectric rod (sapphire, beryllium oxide) the helix temperature could be reduced by a factor of 10 or more for a heating of 3 watts/inch over that by direct radiation. Even so, heating caused the power output to fade from 1 watt to 0.5 watts as the RF dissipation increased, pointing out again

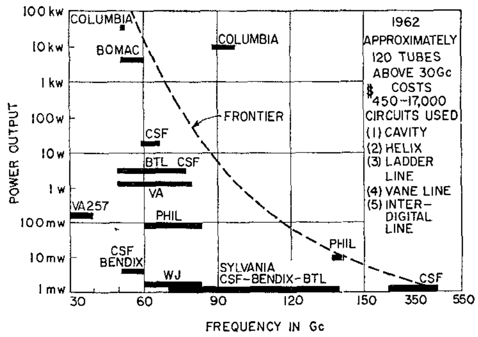

Fig. 2—Partial list of commercially available millimeter wave tubes.

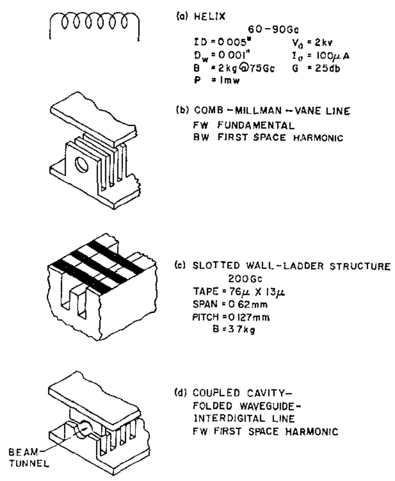

Fig. 3—Basic types of circuits used in millimeter wave tubes.

A. FABRICATION TECHNIQUES

1. PRECISION MILLING
2. HUBBING
3. LAMINATIONS
4. PHOTO-ETCHING
5. PHOTO-DEPOSITION
6. SONIC CUTTING
7. SPARK EROSION
8. ELECTRON BEAM CUTTING
9. MASER BEAM CUTTING

B. ELECTRON GUN DESIGN

MAX. CURRENT DENSITY-CONVERGENT MAGNETICALLY FOCUSED BEAM (ASH)

$$i_m = i_0\left\{R-(R-1)\exp\left[\frac{-eV}{kT(R-1)}\right]\right\}$$

WHERE $R = B/B_c$ $\quad i_0$ = CATHODE CURRENT DENSITY

FOR $R \gg 1$

$$i_m \rightarrow i_0 \frac{eV}{kT} > 10^3\ A/cm^2$$

Fig. 4—Millimeter wave technology.

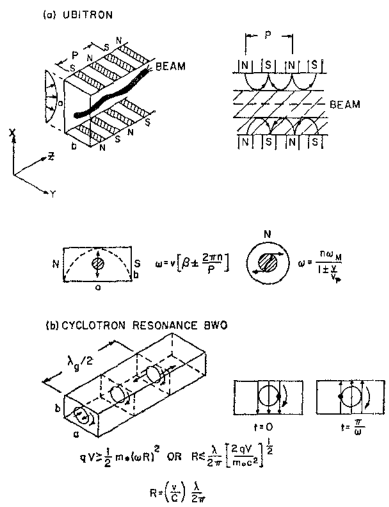

Fig. 5—Periodic beam—smooth fast wave structure.

the problems of attenuation as the frequency limits of tubes are raised.

An example of the vane line structure in low millimeter and submillimeter tubes is the CSF type O-Carcinotron which has produced the shortest wavelength (~0.7 millimeter) yet achieved. These vane-type slow wave structures are capable of withstanding hundreds of watts of power without undue damage.

One of the earliest examples of the ladder [31], [32] slow wave structure was the 100–200 Gc BWO made by Karp [29] in 1957. More recently, by incorporating a ladder structure in a cavity, narrow-band Laddertron power oscillators have become commercially available. Modified Easitron circuit amplifiers yielding 20 watts output power in the 5–6 millimeter range have been reported by Forster [44].

C. Millimeter Wave Technology

Two factors which are contributing the most to the extension of conventional electron tubes to higher frequencies are: 1) circuit fabrication techniques, and 2) advances in electron gun design and beam focusing. Fig. 4 lists the techniques used, along with an expression derived by Ash [47], for the maximum current density j_m that can be obtained by a convergent, magnetically focused beam.

Increased application of the last three techniques (spark, electron, and maser beam) are anticipated in future work. Beam current densities presently used in millimeter wave tubes may exceed 100 a/cm^2, although the WJ 100-Gc experimental tube [46] has a gun capable of 1000 a/cm^2. The theoretical limit, as seen from Ash's formula for practical numbers, can even exceed 1000 a/cm^2. As improved guns are developed, the frequency limits of present tubes should be extended correspondingly.

D. Fast Wave Interaction Tubes

The idea of undulating a beam by a periodic magnetic field goes back at least to 1949. Also the concept of the equivalence of waveguide and electron periodicity is on the order of 4–5 years old. Interaction is possible between either: 1) a smooth beam and a periodic waveguide wherein the phase velocity is less than the velocity of light C, or 2) in a smooth waveguide having a phase velocity greater than C and a periodic beam.

Theoretical analysis of schemes applying this "fast wave" idea [24], [26], [38] started around 1959, but successful experimental verification came several years later in the form of the Ubitron and Cyclotron Resonance BWO shown schematically in Fig. 5.

The Ubitron [26] achieves its undulating beam by the use of a periodic magnetic field structure, while the Cyclotron Resonance device [24] relies on rotating the beam at the cyclotron frequency in a longitudinal magnetic field.

The advantages of the Ubitron are: 1) its large beam tunnel, and 2) its low loss TE_{01} mode circular waveguide interaction structure. On the other hand, a periodic circuit fabrication problem exists in the form of the periodic magnetic field configuration required to undulate the beam. Some compromise can be made by operating the tube at high voltage, but then the beam gets stiffer or more difficult to bunch and gain falls off. At the moment it appears that the Ubitron is capable of the highest pulse power at the highest frequency of any electron tube.

The advantage of the Cyclotron Resonance BWO is the simplicity of its structural form. Its high magnetic field requirements represent a practical problem which would be acceptable if the tube could be extended beyond 300 Gc.

Unfortunately, at high power levels, as pointed out by Dickson *et al.* [38], helical bunching can fail to occur because the transverse electric field can complete the energy exchange before the transverse magnetic fields can accomplish any bunching. Other problems with this type of device are: 1) securing sufficient ratio of transverse to longitudinal energy in the beam, and 2) possible bunching difficulties because the beam does not rotate as a whole but as individual electrons spiraling around a magnetic line of force with a radius R much smaller than the wavelength λ.

It has been known for a long time that fast wave interaction with a swept electron beam can occur, although this old idea has yet to be reduced to practice. While an individual charge cannot move with velocity greater than C, a swept beam, such as that in an oscilloscope, can have sweep speeds or virtual velocities far greater than C. One of the first experiments of this type was the Rotatron shown in Fig. 6(a).

A circularly swept, unbunched, electron beam is passed through a slot in a fast wave structure made in a circular geometry. Coherent interaction is achieved by making the sweep speed of the beam coincide with the phase velocity of the wave in the structure.

It will be observed that the beam in this device is not bunched in the usual sense, although the number of electrons passing through a given point in the structure is varying periodically.

A second example of a coherent effect from a seemingly unbunched beam is the example of a beam in the form of a "sine wave" as illustrated in Fig. 6(b). The harmonic current collected by the metal plate will be a function of the angle θ. For $\theta=90°$, there is no harmonic current, while for $\theta=\alpha$, the shortest harmonic current wavelength will be λ min$\simeq(D/\beta)$ sin α, where β is the velocity ratio v/C and D is the beam diameter. Thus, in principle, the shortest wavelength of RF that

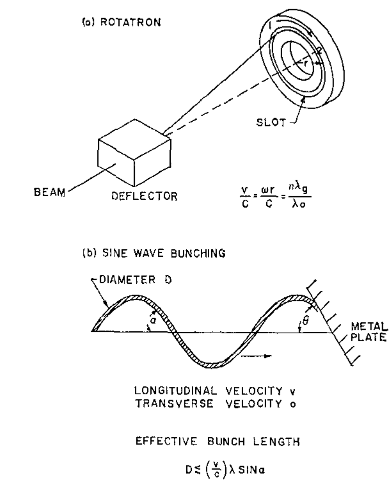

Fig. 6—Bunched "dc beam" schemes.

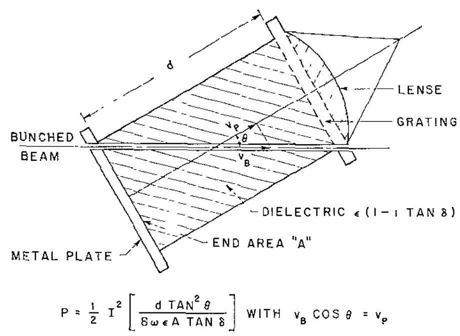

Fig. 7—Beam excitation of a Fabry-Perot resonator.

could be generated is determined by how small the diameter of the beam can be made.

E. Quasi-Optical Electronics

Most microwave tubes operate in the dominant or lowest order mode of the guide system or resonator. This restriction obviously imposes problems of small physical dimensions in fabricating the structure as the wavelength of interest decreases.

As the modes of a resonator are increased, the waves become more like plane waves with phase velocity approaching C. One problem then in attempting to excite an optical resonator, for example a Fabry-Perot system, with a prebunched beam, is to arrange to have coherent interaction with essentially a plane wave.

This coherent interaction can be achieved if the beam of velocity v_p interacts with a plane wave of phase velocity v_B in an appropriate dielectric medium so that the synchronism condition

$$v_B \cos\theta = v_p$$

can be realized. Here θ is the angle between the beam and the wave normal.

An application of this idea [33] is shown in Fig. 7, where a prebunched beam passes diagonally through a dielectric-filled Fabry-Perot resonator. A grating and dielectric lens are used to couple the radiation out one end of the system.

The power output of this device varies inversely as the loss tangent of the dielectric. While problems of resonator size are solved very neatly by this device, there is the eternal problem of a small beam tunnel through the material.

F. Cerenkov Radiation

A characteristic feature of past work on the Cerenkov effect is that it is almost all theoretical [36] with a restricted amount of numerical analysis and very little experimental effort. This situation has undoubtedly contributed to the belief that the Cerenkov interaction is weak, and hence, an efficient, practical realization of a Cerenkov device would not be found.

At the MRI Millimeter Wave symposia in 1959, Coleman predicted that an effective Cerenkov scheme would be found in the near future. In Sept., 1960, the first experimental results [27] in a 35-Gc Cerenkov radiator driven by a 0.042-ampere beam gave output powers approaching the watt level, some 70 db more than had been achieved previously. These experiments were done with an isotropic, nondispersive, dielectric radiator.

Further gains [37], [43] in output power and efficiency could be made by using highly dispersive, anistropic media and depressed electron collector schemes. Media with characteristic frequencies could be expected to interact more strongly with an electron beam when a harmonic current frequency of the beam coincided with that of the medium.

Fig. 8 illustrates the efficiency considerations of a depressed collector, Cerenkov radiator. Since it is important to minimize the velocity spread in the bunched beam driving the Cerenkov radiator, it makes the use of a depressed collector very attractive.

The efficiency η, giving the ratio of harmonic power P_n to dc power P_0, depends on the square of the bunching constant a_n $(0 \leq a_n \leq 2)$, the interaction resistance R_λ per wavelength, the number of wavelengths (L/λ_n) in the interaction length L, and inversely on the effective beam impedance R_c. By depressed collector techniques, R_c may be made the order of 50 K ohms or less, so that if R_λ could be made the order of 1 K ohm/wavelength, then in a distance of 10 wavelengths the efficiency of the device exceeds 10 to 20 per cent.

In Fig. 9 are shown some typical values of R_λ that might be expected from a Cerenkov device employing various types of media. These values are for the case where the beam radius is small compared to the wavelength, the typical (Ka) problem in a conventional microwave tube.

Thus, the present state of the Cerenkov art is that, under the appropriate conditions, this interaction can be relatively strong and the efficiency of the devices be made comparable to microwave tubes. With depressed collector techniques, it is conceivable that a CW Cerenkov device operating at 200 kv is practical. With an appropriate feedback system, it may even be made into a self-excited source.

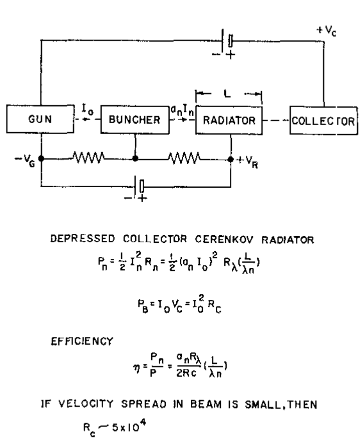

Fig. 8—Cerenkov radiator efficiency.

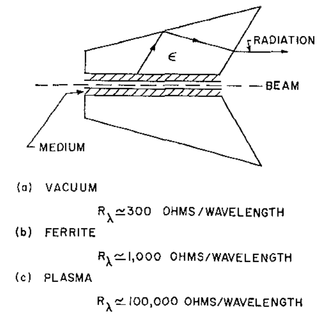

Fig. 9—Cerenkov radiation.

G. Transition Radiation

While many theoretical papers have been written on transition radiation [40], the first coherent transition radiation experiment that this author is aware of was reported by Hakki [35] in 1961. A schematic of Hakki's experimental arrangement is shown in Fig. 10(a).

In principle, the experiment involves allowing a prebunched beam to strike a metal plate and be annihilated. In this process, some deceleration radiation must undoubtedly also be produced, but it is assumed that it is small compared to the transition radiation. Values of the radiation resistance R which are frequency independent typically are the order of 100–150 ohms for a 900-kv beam. While this value is not very large, it is achieved with the simplest conceivable system with absolutely no fabrication problems.

A second possible transition radiation experiment might involve a thin, dielectric film as shown in Fig. 10(b). For a nondispersive, isotropic dielectric and nonrelativistic beam, the interaction resistance R may only be the order of 20 ohms. However, this value could be substantially increased by using a relativistic beam and a dispersive dielectric having some characteristic resonant frequencies.

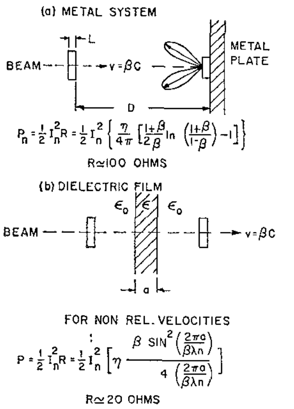

Fig. 10—Transition radiation.

The interesting aspect of a transition radiation device is that the frequency limitation appears to be the bunched beam and not the coupling structure. If a 35-Gc base frequency Rebatron beam were available, then low-level submillimeter wave frequencies could be immediately produced by transition radiation.

III. Harmonic Generation and Parametric Amplification

A. General Considerations

With 10 kilowatts of pulsed power available up to 70 Gc from magnetrons, practically every engineer interested in the submillimeter problem has at one time or another spent some time on a nonlinear scheme to produce RF energy above 300 Gc by harmonic generation. The fact that the effort has not as yet resulted in a practical harmonic generator operating below 1–2 millimeters wavelength obviously means that some limiting problem enters the picture. Excellent conversion efficiences can be obtained in the microwave range for a number of devices [48]–[79], but as soon as they are extended into the low millimeter region, the conversion rapidly deteriorates and the output signals fall below the noise.

It is well-known that in an ideal reactive element, the theoretical harmonic conversion efficiency can be 100 per cent, while for the ideal resistive element, the harmonic power output varies as n^{-2} where n is the harmonic number. In practice, the output power P_n usually varies with the fundamental power P_1 as

$$P_n = aP_1{}^s, \tag{2}$$

where a is a constant and s is greater than one. Assuming such a law held for arbitrarily large power inputs and that the nonlinear element could withstand the heat dissipation, it would seem that some scheme should succeed in breaking the submillimeter wave barrier. However, since this has not been realized, what are some of the problems that are keeping the engineer from succeeding?

First, the Q of the nonlinear reactive elements that have been suggested approaches one for frequencies of the order of 150 Gc or less and the nonlinear effect is largely lost. Resistive elements are usually only mildly nonlinear at the frequencies of interest.

Second, the nonlinear element is usually incorporated into a microwave structure with its own inherent frequency limitations. Impedance matching, attenuation and loss, fabrication and tolerance, multiresonant circuit problems, etc., have become increasingly difficult to solve.

Third, the heat dissipation, breakdown and energy storage capabilities usually prevent driving the device at favorable input power levels.

In spite of the problems, the persistent ultramicrowave engineer who loves a challenge keeps looking under another rock hoping to find an answer. This effort is not lost because many of the ideas and techniques, while not successful in the low millimeter range, are useful at lower frequencies.

At the present time, crystal diodes [51] still retain the frequency multiplication record (~0.7 mm) as they have for many years. Plasmas [68], [70], [79] and bunched electron beams appear to offer the most promise. Ferrites [50], [54], [64], [65], [74], [76], [77], ferroelectrics [71], field emitters, superconductors [69], [73], and cyclotron resonant devices seem to be best suited for low-order harmonic generation below approximately 100 Gc. Multiple photon processes [90], [192] in quantum mechanical devices offer some new approaches that could be competitive.

B. Plasmas

Microwave discharges have been known to have nonlinear properties from early work on the subject. Harmonic generation [49], [60], [68], [70], [78], [79] using ionized gases was considered over 10 years ago. However, experiments at microwave frequencies are only about 5 years old, with 35-Gc experiments being reported in the last 2 years.

In the multiplier of Baird and Coleman [68], the nonlinear mechanism is believed to be a modulation of the ionization frequency, which in turn is responsible for a modulation of the electron density and hence the current obtained from the discharge. In the multiplier of Swan [70] and Kino [78] the method of harmonic generation is believed to be based on the spatial variation of the electric field. The first mechanism is more of a resistive type of nonlinearity, while the second mechanism is more of a reactive effect with the possibility of higher efficiency.

In Fig. 11 three plasma harmonic generator configurations are shown, along with harmonic output power data obtained. It is difficult to make too close a comparison between Swan's device and that of Baird since the frequency of operation differs by over a factor of 10.

In attempting to analyze these devices, the usual

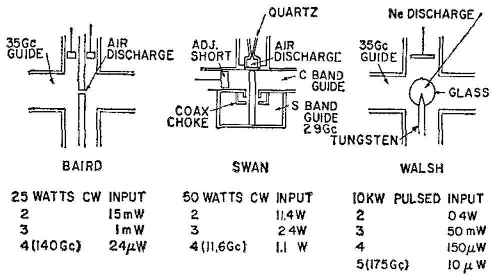

Fig. 11—Plasma harmonic generators.

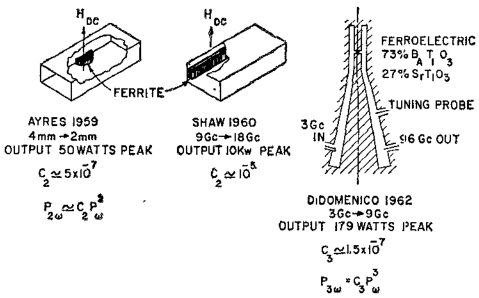

Fig. 12—Ferrite and ferroelectric harmonic generators.

approach is to solve the momentum transfer equation

$$\frac{\partial v_d}{\partial t} + (v_d \cdot \nabla) v_d + \nu_c v_d = \eta(E + v_d \times B), \tag{3}$$

along with a continuity equation for the electron density n,

$$\nabla \cdot (nev_d) + \frac{\partial \rho}{\partial t} = 0 \tag{4}$$

or

$$\frac{\partial n}{\partial t} = \gamma_i n + D \frac{\partial^2 n}{\partial x^2}, \tag{5}$$

for the case where diffusion is the dominant loss mechanism.

The microwave gas discharge with its strong nonlinearities, and large CW and pulsed power capabilities, is a strong competitor in the frequency multiplication area. Progress in the analysis of these devices has been made so that the experimental design has become more of a science than an art. This multiplier is the most efficient, high-harmonic ($n>5$), high-power, high-frequency device in the ultramicrowave region today. It is a bit strange that even more effort is not spent in this direction.

C. Ferrites and Ferroelectrics

In Fig. 12 three representative multipliers are shown, two using a ferrite and one using a ferroelectric. Considerable interest was developed when Ayres [50] achieved 50 watts peak of 2-millimeter power in 1959. In 1960, Shaw [93] and colleagues were able to achieve an output of 10 kw for an input of 30 kw at 9 Gc for an efficiency of 30 per cent. Recently DiDomenico [71] realized a conversion efficiency of 8.5 per cent in a ferroelectric tripler multiplier with a peak input power of 2.1 kw at 3 Gc.

While many ferrite multiplier papers have appeared in the last four years, the work has concentrated on analysis and understanding [76] of the processes occurring in the ferrite. The associated experimental study has been concentrated at X band.

It seems unlikely that much effort, if any, on ferrite or ferroelectric low millimeter wave multipliers will be seen in the near future. Problems of small sample size, linewidth, anisotropy, waveguide circuitry, saturation, etc., appear very difficult to surmount. Unless superior materials or new techniques are discovered, multiplier work in this area will be confined to lower frequencies.

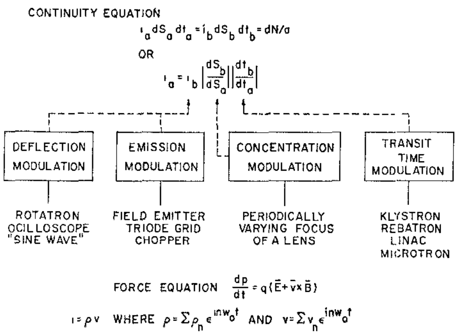

Fig. 13.—Bunched electron beams.

D. Diodes

The semiconductor diode is the oldest, most convenient to use, and most dependable multiplier element yet devised for low-level production of low millimeter waves. The paper by Ohl and associates [51] in 1959 remains the classic work in the area.

While varactor diodes have been improved and the cutoff frequency increased, relatively few papers on parametric harmonic generation [55], [58], [59], [62] in the millimeter range have appeared. The state of the art conversion in multiplying from 24 to 48 Gc is about 9 db.

E. Electron Beams

A bunched electron beam [27], [28], [67] represents the most nonlinear element that has been found for frequency multiplication. Usable harmonic current amplitudes in the range of harmonic number 30–50 have been obtained from Rebatrons and specially designed low energy linear accelerators. Microtrons [28] also have usable current harmonics up to approximately the 20th harmonic.

Referring to Fig. 13, it has been shown by Gabor in 1944 [*J.IEE* (*London*), vol. 91, part III; 1944], that only four "pure" or basic methods of bunching a beam exist. These methods may be identified by reference to the equation of continuity.

If $\boldsymbol{u}$ is the velocity with which a cathode spot belonging to the element of area dS sweeps over the cathode, and ∇i is the two-dimensional gradient of i over the cathode surface, then the total rate of change of i is

$$\frac{di}{dt} = \frac{\partial i}{\partial t} + \boldsymbol{u} \cdot \nabla i, \tag{6}$$

where the first term represents emission and the last, deflection modulation. The other two types of modulation, concentration and transit time, are easily deduced from the ratio terms for the areas and times.

It is important to draw attention to two points: 1) the bunching action resulting from a nonlinear, relativistic force equation can be quite different than for a linear equation; and 2) classical electronics is inherently a nonlinear business, since it is difficult to avoid having both the charge density ρ and velocity v being Fourier series which, when multiplied together to yield the current i, do not yield a new Fourier series wherein only the first two terms are important.

IV. Quantum Electronic Devices

A. General Considerations

Almost every person interested in ultramicrowaves is optimistic that quantum electronics [80]–[112] will sooner or later provide an answer to the generation problem. The microwave-infrared gap has been already bracketed but not spanned by a maser device.

At least three things contributed to making a laser possible: 1) the optical spectroscopy of ruby was well-known; 2) the broad absorption bands of ruby in the green and blue, plus good quantum efficiency, made incoherent radiation pumping practical; and 3) a resonator structure, the Fabry-Perot interferometer, provided a low-loss, high-Q feedback system for stimulated emission. Sufficient knowledge of only one of these problems, the F-P resonator, is available at the present time for the ultramicrowave region.

Far infrared spectroscopy, using a black body radiator as a source, is possible at the present time for resolving lines with a Q of 100 or greater. Activity in this area is rapidly increasing so that data on materials should be appearing at an accelerated rate. Once the energy levels, linewidths, oscillator strengths, etc., are known, the possibilities of maser schemes can be logically pursued. At the moment there are just too many unknowns in the problem.

Pumping appears to be a very difficult problem. Incoherent, optical radiation pumping would most probably result in poor quantum efficiency. Laser light pumping would seem to offer attractive possibilities. In fact, laser light has already been successfully employed to pump a microwave, ruby maser [104]. Coherent, low millimeter wave energy could be used in a quantum harmonic generation system, but it is doubtful if a multiplication by a factor greater than 5 is practical.

The most exciting quantum electronics device [112] to recently appear is the GaAs p-n junction, wherein the coherent radiation is believed to result from transitions between the conduction band and a Zn acceptor level. These devices are driven with current pulses of up to 190 amperes in some cases, yielding current densities of the order of 10^4 a/cm^2. Thus the energy conversion is from dc or video energy to coherent optical energy, the optimum situation. It remains to be seen whether a semiconductor can be made with the appropriate energy levels or band gap for the ultramicrowave region.

Optical mixing of laser light [106]–[108] to produce submillimeter wave beat notes is an interesting thought if appropriate nonlinear media can be found. Unfortunately, most nonlinear quantum effects are high level phenomena so that efficient conversion of energy is unlikely. The quality of the signal, if it could be obtained, leaves something to be desired if it results from two lasers whose output is spiking. Under these conditions the beat notes would appear at somewhat random times in microsecond spikes.

As a summarizing remark, it may be fair to state that while quantum electronics has not yet provided an answer to the submillimeter wave problem, the possibilities for doing so appear most encouraging. Perhaps it will require a great deal more work before the time is ripe but the optimistic feeling is that the answer will come.

B. Tunnel Diodes

Quantum tunneling in abrupt junction, highly doped diodes gives rise to negative resistance for small forward bias voltages. Since tunneling is a majority carrier effect with no limitation of minority carrier drift time, the tunnel diode should be expected to operate at very high frequencies [82], [84], [85], [98]. Since the bias voltage level is of the order of tenths of a volt, large output powers are not expected.

Fig. 14 shows a tunnel diode oscillator and amplifier reported by Burrus and Trambarulo [84], [85], [98]. The problems in the design of these devices are of course the diode and the circuit.

A tunnel diode has a very low impedance; hence it must be operated in a low impedance circuit. An estimate of the maximum frequency f_{max} of oscillation that can be obtained is given by the expression $(R/r_t)^{1/2} f_c/2\pi$ where r_t is the total ac dissipative resistance of the oscillator circuit. Typical values of the electrical quantities [98] might be

$$I_1 \simeq 2I_0 = 4 \times 10^{-3}\text{a} \qquad P_{out} = \tfrac{1}{2} I_1^2 r_t \simeq 0.24\ \mu\text{watts}$$

$$r_t \simeq 0.03 \text{ ohm} \qquad R \simeq 0.6 \text{ ohm}$$

and

$$f_c \simeq 180 \text{ Gc} \qquad f_{max} \simeq 130 \text{ Gc}.$$

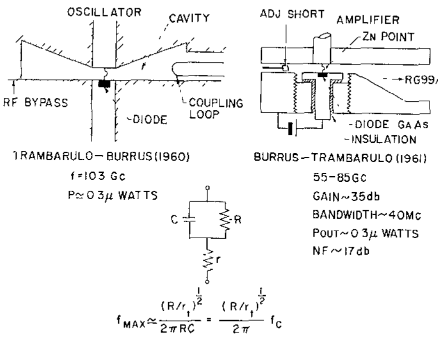

Fig. 14—Tunnel diode devices.

Trambarulo and Burrus [98], using a zinc contact, heavily doped n-type, gallium arsenide diode, achieved oscillations at 103 Gc. By fighting the problem of low-Q millimeter wave circuitry, the upper frequency limit could be extended further. The tunnel diode oscillator is a very interesting device in the spectra range in which it can operate. However, it does not appear that a diode mounted in a microwave circuit will go beyond 300 Gc.

C. Nonlinear Quantum Effects

Basically the Maxwell-Newton problem in classical electronics and the Schrödinger-Maxwell problem in quantum electronics are nonlinear. While Maxwell's equations are linear, the forcing functions or driving terms are nonlinear and hence produce nonlinear and/or parametric effects.

In classical electronics, the current J is the driving function for Maxwell's equations

$$\nabla \times E + \dot{B} = 0$$
$$\nabla \times H - \dot{D} = J = \rho v. \tag{7}$$

As pointed out previously, if both ρ and v are a Fourier series, then their product is also a Fourier series. A linear response is obtained by neglecting all but the first two terms (the dc and ac fundamental) in the expression for J.

In quantum mechanics, either the electric and/or magnetic polarizations P and M are the driving functions for Maxwell's equations

$$\nabla \times E + \dot{B} = 0$$
$$\nabla \times B - \epsilon_0\mu_0\dot{E} = \mu_0(\dot{P} + \nabla \times M). \tag{8}$$

If a time-dependent Schrödinger calculation on the interaction of the radiation with the material is made, then in the perturbation theory a linear P or M will be obtained only on the basis that higher order terms can be neglected. The ultramicrowave engineer, whose quantum mechanics knowledge may be a bit rusty, is often not aware of this fact. Also he may have the opinion that to obtain a nonlinear effect, the quantum system must be driven on resonance or the natural transition frequencies of the material.

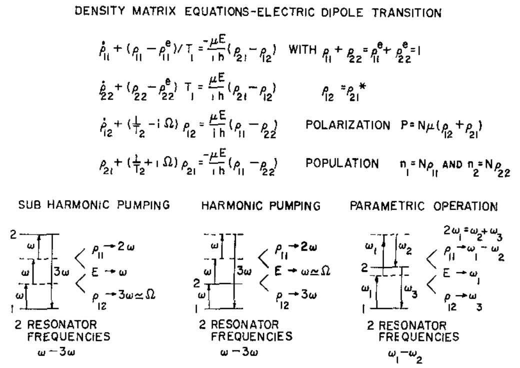

Fig. 15—Nonlinear quantum effects.

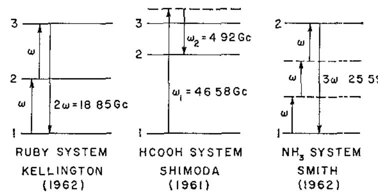

Fig. 16—Multi quantum effects.

It is a bit difficult to point out all the features of a given problem since almost all nonlinear effects are tedious to analyze mathematically [90], [102]. However, at the expense of a little mathematics, consider a two-level system having an electric dipole transition.

The density matrix equations are given in Fig. 15, where μ is the electric dipole moment, E the electric field, T_1 and T_2 the relaxation times, Ω the natural transition frequency, P the electric polarization, N the density of molecules, and n_1 and n_2 the populations of the two states.

Consider the first example of subharmonic pumping of the two-level system. The driving term for the ρ_{12} equation has the factor $E(\rho_{11}-\rho_{22})$. If E varies as ω and ρ_{11}, ρ_{22} as 2ω, then ρ_{12} can be driven at 3ω. These conditions will be consistent with the ρ_{11} equation which has in the driving term the factor $E(\rho_{12}-\rho_{21})$. Hence with E varying as ω and ρ_{12}, ρ_{21} as 3ω, the difference frequency driving ρ_{11} will be 2ω. The reason for the third subharmonic response is that the perturbation is third order. The other two examples can be explained in a similar fashion.

It is readily seen from the density matrix formulation that ρ_{12} and ρ_{21}, which determine the polarization P_1, result from the driving field. Pumping near natural resonances or conserving energy in each step will result in greater response of the system but it is not required. Also population inversions are not necessary to achieve a coherent nonlinear effect. Moreover, in many cases short relaxation times are desirable as opposed to long relaxation times for some maser problems. There is a great amount of fertile ground for exploration in this area.

Three examples of recently reported work on multiple quantum effects are shown in Fig. 16.

D. *Optical Frequency Pumping and Mixing*

With over 10 kilowatts of pulsed, coherent power available from lasers, it is obvious that attention would quickly be directed to investigating methods of using the light to pump lower frequency masers and methods of beating two lasers together in a nonlinear medium to produce ultramicrowave beat note energy. Fig. 17(a) illustrates three very recent efforts along this line of attack on the problem.

Devor [104] and associates produced a population inversion in the ground state of C_r^{3+} by driving the ruby with laser light. By adjusting the angle of the applied dc magnetic field with the c axis of the crystal and applying the proper magnitude of field, the $1/2(\boldsymbol{E}) \rightarrow +1/2(4A_2)$ transition matched the $\boldsymbol{E} \rightarrow \pm 1/2(4A_2)$ component of the laser spectrum. Then, saturating the $+1/2(4A_2) \rightarrow -1/2(\boldsymbol{E})$ pump transition depletes the $+1/2(4A_2)$ state sufficiently far below its normal Boltzmann population to achieve an inversion with the $+3/2(4A_2)$ state as illustrated. The microwave transition $+3/2(4A_2) \rightarrow +1/2(4A_2)$ occurs at 22.4 Gc. Measured values of $-Q_m$ were the order of 75.

Population inversion of the $+3/2(4A_2)$ and $+1/2(4A_2)$ lines could, of course, be obtained by microwave pumping. The ultramicrowave problem would be to find a material with lines separated by a frequency of 300 to 3000 Gc and invert their population by a similar technique. If the two levels involved were sufficiently far above the lowest ground state, then their normal populations could be quite small, if not zero, at sufficiently low temperature. Hence the problem would be to establish enough population in the higher of the two levels to overcome the losses. Just how this could be done in the face of competing processes is the question to be answered.

Siegman [106], [107] and colleagues have mixed the Fabry-Perot mode frequencies of a single ruby laser in a photocathode and photodiode and obtained beat note frequencies in the 1 to 10 Gc range. A schematic of the photodiode experiment is shown in Fig. 17(b). They indicated that the IF frequency limit would be determined by the transit time of the electrons and holes through the intrinsic region of the junction. In their diode, the transit time was the order of 10^{-10} seconds. The peak power output of the X-band signal was -50 to -60 dbm (10^{-8} to 10^{-9} watts), indicating a rather poor conversion efficiency.

Pantell [102] and associates recently achieved optical frequency mixing in a bulk CdSe semiconductor in the experimental setup illustrated in Fig. 17(c). Beat note signals in the microwave region of less than -10 dbm (10^{-4} watts) were obtained.

Coleman and Svelto are presently studying several possible explanations of Pantell's results, one based on bulk photoconductive mixing and a second based on the Franz-Keldysh effect of the shift of band edge in a semiconductor with applied electric field.

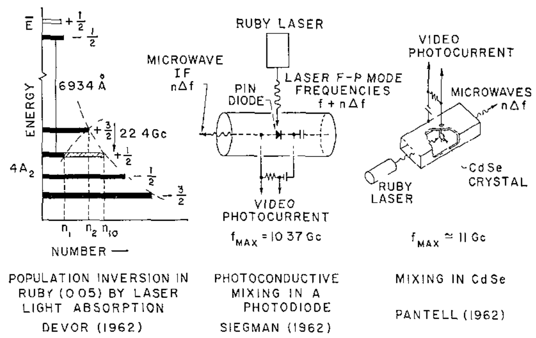

Fig. 17—Optical frequency mixing.

The problems of mixing two laser frequencies to obtain ultramicrowave frequency beat notes are basically the same as those encountered in microwave frequency mixing except they may appear in a different form. From a macroscopic electromagnetic field point of view, the first thing required is a nonlinear medium represented by either a nonlinear polarization $\boldsymbol{P}$ or a conduction current J. In terms of tensor susceptibilities and/or tensor conductivities, $\boldsymbol{P}$ and J may be expressed as

$$\boldsymbol{P} = \epsilon_0{}^2\chi_1 \cdot \boldsymbol{E} + \epsilon_0({}^3\chi_2 \cdot \boldsymbol{E}) \cdot \boldsymbol{E} + \cdots \tag{9}$$

or

$$J = {}^2\mathfrak{d}_1 \cdot \boldsymbol{E} + ({}^3\mathfrak{d}_2 \cdot \boldsymbol{E}) \cdot \boldsymbol{E} + \cdots . \tag{10}$$

Thus, as in all nonlinear problems, the analysis will be rather complicated in spite of the fact the nonlinearity will not be nearly as large as desired for operation of the device at modest field strengths. A consideration of the conversion properties of nonlinear dielectric and resistivity media indicates for this large down conversion of frequencies that a resistive medium with a theoretical efficiency of 25 per cent is preferable. However, in this case the problem of heat dissipation capability immediately enters the scene since the ideal resistive medium will not be found, thus requiring the realizable medium to be driven hard.

Given two laser beams with wave vectors $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ and the difference wave with wave vector $\boldsymbol{k}_D$, then, as in a corresponding microwave problem, the conditions

$$\boldsymbol{k}_1 = \boldsymbol{k}_2 + \boldsymbol{k}_D \quad \text{and} \quad \omega_1 = \omega_2 + \omega_D \tag{11}$$

must be met if efficient operation is to be obtained. Bloembergen [110] has pointed out that diffraction-limited light beams will be essential to generate beats at small difference frequencies since momentum matching will be a first order effect in the aperture.

Ultramicrowave beat frequencies from two laser beams will be produced but not before some hard work is spent on the problems involved.

E. *High Magnetic Fields*

Any generation scheme of producing electromagnetic radiation requires some characteristic frequency to be present to establish where in the spectrum the device will operate. It is very well-known that a free electron in vacuum in a magnetic field has a characteristic cyclotron resonance frequency f_c of 28 Gc per weber per meter squared while the spin resonance frequency f_s of an electron in a ferrite [97], for example, is also 28 Gc per weber per meter squared.

With pulsed magnetic fields of 10 w/m² or greater now attainable, characteristic frequencies above 300 Gc can be realized. Two schemes based on this approach are the Tornadotron device of Weibel [111] and the pulsed ferrite device of Shaw [93] illustrated in Fig. 18.

The cycle of operation of these two devices is the same. A low magnetic field resonance is first established at 3 Gc, after which the high magnetic field is pulsed on increasing either the orbital or precessional motion. The energy stored in the system is then radiated away at the high frequency. Both systems are inherently pulsed devices.

The practical problems are: 1) storing the maximum energy in the system, 2) having the rise time of the pulsed magnetic field short compared to the relaxation times of the systems, and 3) having the radiation time of the RF pulse short compared to the relaxation times.

While the ferrite system has a very large density of spins, it suffers from having to use a small volume ferrite sphere and having to work with small precession angles θ of the order of 2 degrees, thereby limiting the energy storage to the order of 10^{-8} joules. Since short radiation times T_R of the order of 10^{-8} seconds are present, the peak pulsed output power can be the order of 1 watt. Repetition rates of 10 pulses per second could be achieved with a husky power supply since ferrite heating is not excessive. The present ferrite system illustrated in the lower right-hand portion of Fig. 18 has been operated to 50 Gc. From the experimental point of view, the pulsed ferrite system of Shaw has the minimum complexity that could be expected in a high magnetic field device.

As orginally conceived, the Tornadotron was to radiate its stored energy at the peak cyclotron frequency associated with the peak magnetic field. However, when the experiment was performed, only outputs at certain discrete frequencies as the magnetic field was increasing were obtained. This behavior was explained by assuming the swirling electron cloud was not radiating in a free space fashion but was interacting with the resonant modes of the electron chamber as schematically illustrated in the lower left-hand portion of Fig. 18. At time $t=0$, the electrons were driven against the field in a negative vertical direction. One half cycle later, the electrons had moved to the left and are now being again driven against the field in a positive vertical direction, thereby achieving a net exchange of energy. Obviously, the proper field configuration must be obtained in the chamber to obtain this favorable interaction.

Compared to a pulsed ferrite, the Tornadotron is a far more complicated device. However, both schemes have many practical problems to solve if they are to reach frequencies above 300 Gc. It is doubtful if these devices have answered the question of how best to exploit a high magnetic field approach to the ultramicrowave problem.

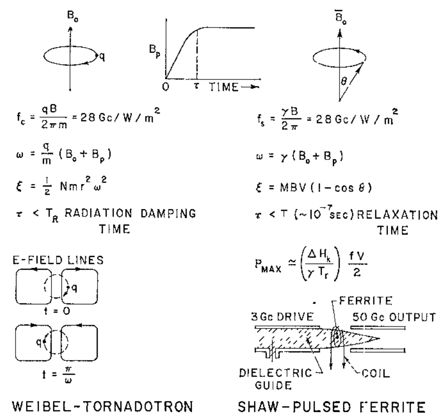

Fig. 18—Electron cyclotron and electron spin resonance generators.

F. Masers

The objective in searching for a source of coherent energy is to find a principle which will permit the efficient conversion of cheap, available power into the premium desirable power. Since in a typical maser, coherent power at one frequency is converted into coherent power at a lower frequency, the only reasons one might wish to pursue this attack would be that the higher frequency pump power was available while the lower frequency signal power was not or that the coherence quality of the signal was improved by the conversion. In the maser amplifier different considerations would apply.

Various schemes have been devised to have the pump frequency smaller than the signal frequency but the ratio of the two frequencies is usually less than 1 to 3 so that extending this technique well into the ultramicrowave region does not appear feasible.

The typical microwave maser crystal consists of a paramagnetic ion such as Cr^{3+} or Fe^{3+} in a host material such as Al_2O_3 or TiO_2. For low millimeter wave applications, one searches for a material where the zero field energy level separation is as large as possible so that the applied dc magnetic field needed to further separate the levels is of reasonable size. Here again, the high magnetic field problem limitation is encountered.

Two examples of solid state millimeter masers are given in Fig. 19. In the pulsed field millimeter wave maser of Foner, the pump frequency f_p used to obtain the population inversion is substantially less than the signal frequency f_s. Here the crystal is biased at H_0 and levels 1–3 saturated by the pump at frequency 12.7 Gc. A rapidly increasing pulse field H_p is then applied to increase the energy difference between the inverted levels 1 and 2 where masering occurs. By using peak

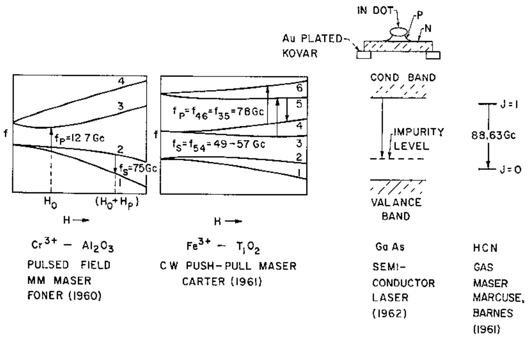

Fig. 19—Masers.

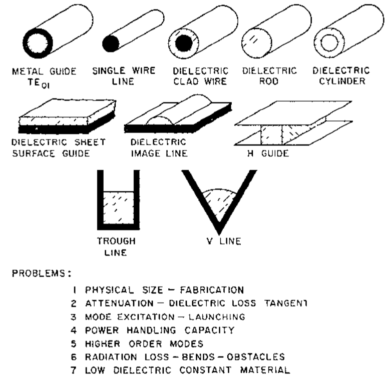

Fig. 20—Transmission systems.

magnetic fields of the order of 25–29 kg, output signals at 75 Gc were obtained. In principle, by using higher magnetic fields, still higher signal frequencies could be obtained.

Carter [96] used push-pull pumping in Fe^{3+} in TiO_2 to obtain maser signals in the range 49–57 Gc. Here levels 3–5 and 4–6, which are adjusted by means of an applied magnetic field to have the same frequency, are pumped with a coherent source at 78 Gc. Population inversion for the levels 5–4 is obtained. The magnetic bias fields used were in the range 5.5–7.2 kg. This scheme has the obvious difficulty of requiring a high frequency pump; hence it would not be capable of generating signals higher than existing pump tubes.

The third example of a millimeter maser is the HCN gas maser operating at 88.63 Gc as reported by Marcuse [99] and Barnes [101]. In this original type of maser device, the normal Boltzmann population of the $J=1$ level is supplied by thermal radiation. By using a separator, the molecules in the $J=0$ level are removed while the molecules in the $J=1$ level are retained, thereby achieving the inversion. While the beam type maser does not require a coherent pump source, it does suffer from low, molecular beam densities and hence produces very little output power, usually the order of 10^{-9} watts.

The last example in Fig. 19 illustrates the stimulated emission of radiation from GaAs *p-n* junctions. This diode device is particularly significant since it converts dc or video energy into coherent optical energy, the best imaginable process. The observed line at approximately 8375 Å is believed due to transitions between the conduction band and a Zn acceptor level. While this frequency is orders of magnitude greater than those in the ultramicrowave region, one can always hope that narrow energy level materials might be found where a similar effect might be used.

V. Transmission Systems and Resonators

A. Smooth Waveguide Structures

Smooth, dielectric-metal, waveguide structures consist of essentially two types. In the first type [121], the electromagnetic field is confined inside a region surrounded by metal walls. In the second type [114], [116], [119], [120], [132], the electromagnetic fields are bound to a surface, but extend to infinity in the transverse direction. By appropriate design, the rate of decrease of the fields in the transverse direction can be controlled so that most of the energy is confined in the immediate neighborhood of the structure.

The various types of guides [118] that have been developed are shown in Fig. 20. Most of the ideas associated with these structures go back more than ten years. However, research and development of extending their frequency of operation above 100 Gc continues at a brisk pace.

The general problems associated with the design of such guides are listed in the lower part of Fig. 20. They are the old familiar basic difficulties that also appear in classical electronics generation systems, except here the requirement of matching beam-wave phase velocities is absent.

Of the guides listed, the TE_{01} mode circular metal guide and the *H* guide [113] have special interest. Assuming the dielectric has negligible loss, the attenuation of these guides decreases as the frequency increases.

If one were to hazard a guess as to the present and near future state of the waveguide art, the opinion might be that guides of the type illustrated will be the standard methods of transmitting power up to frequencies approaching 300 Gc. Beyond this point, practical problems will make it difficult to compete with quasi-optical and optical types of transmission systems.

B. Optical Systems

The beam emitted by a highly directional antenna has, within the Fresnel region, a substantially uniform diameter. The variations of cross-sectional amplitude and phase distributions along the path of the beam depend on the field distribution at the antenna.

Fig. 21 illustrates three optical transmission systems that have been studied recently.

In the system of Sobel and colleagues [130], a phase-reversing Fresnel zone plate is used. By making the plates large in diameter *D* compared to the wavelength, the Fresnel region can be made to extend an appreciable distance from the aperture. This distance may be con-

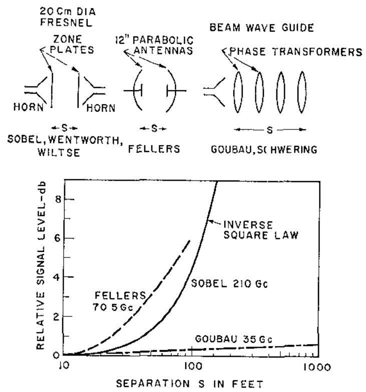

Fig. 21—Optical systems.

sidered to be about one half the Rayleigh distance $R=D^2/\lambda$. For $D=20$ cm and $\lambda=0.14$ cm, then $R=28.5$ meters = 95 feet. In the graph of Fig. 21, it is seen that only 2-db loss is obtained for distance of the order of 55 feet.

Fellers [141] has studied the transmission loss between pairs of parabolic antennas having diameters D of 6 in and 12 in. One of his curves taken for a wavelength 0.425 cm is also shown in the graph of Fig. 21. The Rayleigh distance R for his system is 73 feet. For separations up to the order of 100 feet, the db loss in this system is more than twice that of Sobel's Fresnel zone system.

The third system shown in Fig. 21 is the beam waveguide of Goubau and Schwering [129], [133]. By having the proper field distribution over the first aperture, it is possible for the beam to have the cross-sectional amplitude distribution repeated at a certain distance from the origin of the beam. By adding suitable phase shifting means, the original phase distribution can be reconstituted and a new Fresnel region formed which has the same field configuration as the original one. By repeating this iteration process, the beam can be guided without expansion of energy. Thus the field distribution varies along the guide, but is periodically repeated at discrete intervals.

In theory, the loss of a Goubau line can be made arbitrarily small. In practice, one has finite diameter lenses with reflection and absorption losses. A typical attenuation curve that can be realized at 35 Gc is included in the composite graph of Fig. 21.

Several of the practical problems of a submillimeter wave optical system are obvious. The lense-optical system requires a low loss, preferably a low dielectric material, reasonably easy to fabricate for its construction. Measurements on materials in the frequency range above 300 Gc are very few in number at the present time.

All the systems described are fed by a conventional microwave horn antenna which will not be applicable above 300 Gc. Thus, new feed systems will need to be devised.

However, there is little doubt that optical systems are the appropriate ones for the infrared-microwave gap region.

C. Resonators

While the Fabry-Perot interferometer existed for many decades, a through study of this resonator [115], [117], [123], [125]–[128], [135]–[139] occurred in the last several years. This investigation was, of course, prompted by work on optical masers in which the interferometer plays a crucial part. The resonator, obviously, is also ideally suited for the ultramicrowave region.

It is of interest to note that when microwave physicists attacked the problem of the F-P resonator, they naturally searched for a discrete set of normal modes similar to those found in microwave systems. However, instead of the problem being one associated with the eigenvalues of a differential equation, it was found to be one of an integral equation. The type of equation involved is shown in Fig. 22 along with diagrams of three F-P resonator configurations and three types of reflectors that can be employed.

Detailed numerical calculations on the integral equation eigenvalue problem have been performed by Fox, Li, Boyd, Gordon, and Culshaw. The diffraction problem is now well understood and the features of various configurations known.

By proper choice of dimensions, the reflector losses can be made to predominate over diffraction loss. Hence, a design of a Fabry-Perot resonator mainly involves problems of finding suitable reflectors and coupling schemes for getting energy into and out of the resonator. Three coupler schemes, 1) the thin, metal plate, hole grating, 2) the quarter-wave transmission line coupler, and 3) the quarter-wave composite dielectric sheet coupler, are shown in the lower half of Fig. 22. The usual technique is to determine the coupler dimensions from a transmission line-impedance matching point of view.

For example, let R_s be the normalized surface resistance of one reflector. Transforming this impedance by a line of electrical length θ and then adding in series, the second reflector resistance R_s, yields the expression

$$Z = R_s + \frac{R_s + j\tan\theta}{1 + jR_s\tan\theta} \simeq \frac{2R_s + j\tan\theta}{1 + jR_s\tan\theta}. \qquad (12)$$

By adding the susceptance $-jB$ and applying the condition for a match, one obtains

$$1 = -jB + \frac{1 + jR_s\tan\theta}{2R_s + j\tan\theta}. \qquad (13)$$

Assuming $R_s \ll 1$ gives the result

$$\tan\theta \simeq \sqrt{2R_s} \quad \text{and} \quad B \simeq \frac{1}{\sqrt{2R_s}}. \qquad (14)$$

Several mode patterns for the lowest F-P modes along

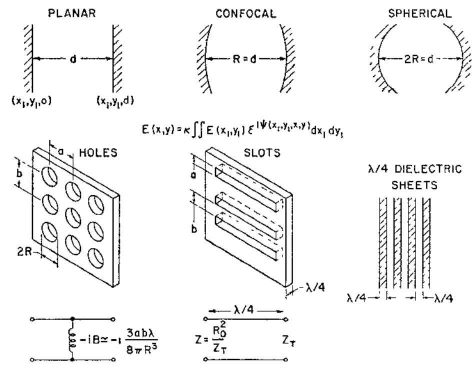

Fig. 22—Fabry-Perot resonators.

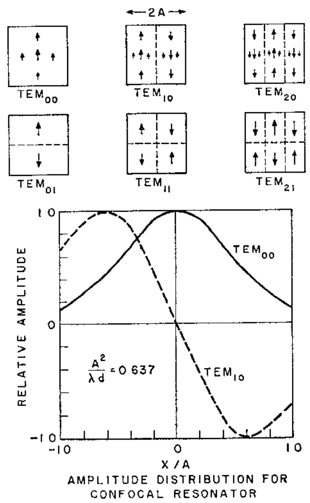

Fig. 23—Mode pattern for Fabry-Perot resonators.

with a relative field amplitude distribution are given in Fig. 23. It is observed that the dominant mode field intensity decreases as the edge of the reflector is approached, causing the power loss by diffraction to be small. A plane wave would not have this property and hence could not be a normal mode of the system.

Confocal resonators have been found to have a high degenerate mode behavior, but the diffraction losses can be orders of magnitude smaller than the planar resonator. This does permit the reflector apertures to be reduced in size and, hence, make the confocal resonator attractive in the low millimeter region. Integrating this resonator into other optical and quasioptical component systems will engage the attention of workers in the ultramicrowave region for some time in the future.

VI. Detectors

A. Submillimeter Devices

The only practical detectors which presently span the infrared [156] microwave gap [142], [151], [153] are heat-sensing devices or thermal detectors [143]. However, Putley [147], [148] has recently described an InSb photodetector which responds to radiation from infrared to the low millimeter range which may change this situation.

	$D^* \times 10^{-9}$	τ sec
1. CARBON RESISTOR (4°K)	3	$<10^{-3}$
2. THERMISTOR BOLOMETER	0 2	$<10^{-3}$
3. SUPERCONDUCTOR BOLOMETER	$\sim10^{-15}$ WATTS	
4 GOLAY CELL	1	$<10^{-2}$
5 PHOTODETECTOR (Ge-Zn @ 4°K) 38μ	15	$\sim10^{-3}$
6 PUTLEY PHOTODETECTOR InSb B≈5kg 77°K	200	$\sim10^{-6}$
7 Ge CYCLOTRON RES. DETECTOR (4°K)	100	$\sim10^{-6}$
8 CRYSTAL DIODE 0.77 mm	$\sim10^{-12}$ WATTS	$<10^{-2}$

$$D = \left(\frac{S}{N}\right)\left(\frac{\Delta f}{A}\right)^{1/2}/P \; \frac{\text{cm(cps)}^{1/2}}{\text{WATT}}$$

WHERE

(S/N) = SIGNAL / NOISE A = AREA

Δf = BANDWIDTH P = WATTS/cm^2

λ	0 1 mm	1 mm
T	144°K	14.4°K
hf	0 012 ev	0 0012 ev

$$EA^{1/2} \simeq E\lambda = [\eta P]^{1/2} \simeq 0\ 02 \text{ VOLTS FOR } P = 10^{-6} \text{ WATTS}$$

Fig. 24—Submillimeter detectors.

The heat detector or bolometer operates on the principle of absorbing energy, either coherent or incoherent, thereby increasing its temperature, which in turn causes a change in its electrical resistance. While the detectivity of these devices is reasonably good, the inherent thermal inertia of the element causes the response time to be large, so that the highest modulation frequency that can be detected is usually less than 1000 cycles.

Some of the problems of devising a quantum detector are obvious, since the energy of a photon for wavelengths between 0.1 mm and 1 mm varies from only 12 to 1.2 milli-electron volts. This would require the material to have very closely spaced energy levels.

In searching for a nonlinear effect to apply to a detector, the problem of field strength usually arises. Suppose there were 10^{-6} watts of coherent power focused on an area A of the order of λ^2. If the impedance of the medium η were 400 ohms, then the voltage level would be 0.02 volts. If this voltage could be impressed across a barrier distance of the order of 10^{-6} meters, then the field strength would be 20 kv/meter, a value large enough to achieve a nonlinear reponse.

In Fig. 24 are listed eight detectors [144], [156] along with their detectivity D^*, where applicable, and their approximate response time τ. It is seen that the Putley and Ge cyclotron resonance detectors have a D^* almost 100 greater than the bolometer detector. The process believed to be responsible for the operation of these detectors [154] is that energy is absorbed by the free or conduction electrons, thereby changing their mobility and, hence, the material conductivity. Along with an increased detectivity D^*, these detectors also have a shorter response time than the bolometer, probably being the order of 10^{-6} seconds.

The problem of making good, coherent detectors [149] and mixers for the submillimeter region is a difficult one, perhaps equally difficult to the generation problem. As coherent sources became available, work in the detector area will have to be given more attention,

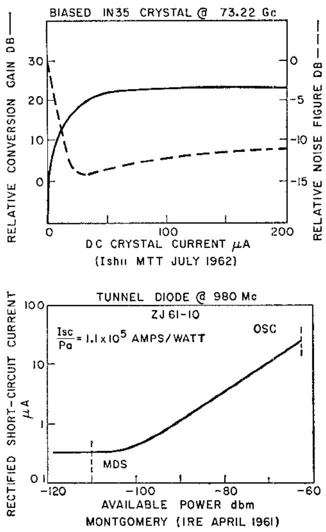

Fig. 25—Semiconductor detectors.

B. Low Millimeter Detectors

As a low level mixer and video detector for the low millimeter range, the crystal diode remains the most frequently used device. Gallium arsenide [150] has been demonstrated to have properties which make it superior to either silicon or germanium for low millimeter wave applications.

Ishii [157], in a recent study of IN53 crystal diodes, pointed out that the application of a dc bias increased the gain and sensitivity while reducing the noise. Curves taken from his paper are shown in Fig. 25. It is seen that the relativity gain increased by 23 db while the relative noise decreased by over 10 for appropriate bias current.

A tunnel diode [152], biased near oscillation and operated as a square-law detector, is a highly sensitive device in the microwave range. Fig. 25 shows a curve obtained by Montgomery on a gallium arsenide diode with an input signal at 980 Mc. The minimum detectable power of 10^{-13} watts is quite impressive. Just how high in frequency a tunnel diode detector can be made to operate remains to be seen.

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A Racetrack Microtron for Millimeter and Submillimeter Wave Generation*

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Summary—The accelerator described here is an eight-orbit four-sector racetrack microtron possessing strong focusing action. The magnet gap is only 7 mm, and the accelerating cavity is placed in one of the field-free regions. The energy gain per traversal of the cavity can be varied from 0.4 to 1.5 Mev and synchronism obtained by adjustment of the magnetic field strength and the length of the main straight section. A theoretical analysis of the synchrotron oscillations in energy and phase shows that tight bunching can be achieved at almost any point in any desired orbit by changing the frequency of the synchrotron oscillations. This can be accomplished by varying the RF power and therefore the accelerating voltage.

One particularly attractive operating region gives tight bunching in the third orbit, allowing the construction of a compact machine if desired. For the RF accelerating source used (frequency 2800 Mc) one obtains 20 per cent of the third orbit current in a bunch length of 0.1 mm using dc gun injection (no prebunching). A current of 20 ma was obtained in the third orbit (2.2 Mev) which should be sufficient for the production of milliwatt power in the submillimeter region.

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BUNCHING of an electron beam for frequency multiplication is generally achieved by energy modulating the beam, and passing it through an element with a transit time that depends in some way on the energy. At nonrelativistic energies this element can be a simple drift space (as in a klystron, for example), since at these energies the electron velocity depends strongly on the energy. A second possibility is the use of a deflecting magnetic field, which is more appropriate for relativistic velocities. In a magnetic field the angular velocity of a charged particle is inversely proportional to its total relativistic energy. Therefore the time required to deflect the particle through a certain angle is proportional to its total energy.

Kaufman and Coleman[1] first pointed out that a certain electron accelerator, the microtron or electron cyclotron, can give a highly bunched beam due to this

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