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MILLIMETER AND SUBMILLIMETER WAVE SOURCES FOR RADAR APPLICATIONS

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This report presents the results of the evaluation of millimeter wave sources as candidates for components of a short range radar system.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

1. SUMMARY

A. Millimeter Source Candidates

Millimeter wave sources have been evaluated as candidates for components of a short range radar system. The frequency regions considered are centered near 94 GHz (3.2mm), 140 GHz (2.14 mm), 220 GHz (1.36 mm), 350 GHz (.850 mm), and 408 GHz (.735 mm). These regions are especially promising because of:

- Narrow beams with small antennas.
- Some existing component technology.
- Atmospheric windows at these frequencies.

B. Basis for Source Evaluation

Millimeter sources were evaluated as candidates for transmitter sources and as local oscillators. The performance parameters considered were:

- Efficiency.
- Output power.
- Volume and weight.
- Availability.
- Ruggedness.
- Frequency stability.

Efficiency and output power were of paramount importance for transmitter sources. They were less important for local oscillators.

C. Transmitter Sources

(1) Sources for Near Term Systems. Consideration of the above factors lead to the following:

- Solid State Source - Impatt diode. The Impatt diode is the only device which currently produces reasonable output power (~1w peak at 94 GHz) at the frequencies of interest. It is lightweight and rugged, but noisy.

- Tube Sources. These sources are ranked by their desirability according to the criteria above.

— Gyrotron - The gyrotron tube is not presently available in the US. However, the Soviet version produces high power (10 Kw cw, at 1.9 mm and 1 Kw at .9 mm) is very efficient (≈30% at 1.9 mm and 6% at .9 mm). US development of these tubes is essential.

— Extended Interaction Oscillator (EIO) - The EIO produces good output power (1 w cw, 20 w pulse) and is capable of coherent operation. Of the presently available sources it is the most promising.

- Travelling Wave Tube (TWT) - While the TWT is not properly a source, but an amplifier, it can be driven by a stable low power source. Hughes has developed a very powerful (1 Kw @ 94 GHz with a msec pulse) TWT operating at 94 GHz. Potential of the TWT at higher frequencies is doubtful.

• Carcinotron - This tube produces reasonable power (~1 w cw at $\lambda = 1$ mm). It has a relatively large tuning range (~20%), accompanied however by a wide variation of output power. Well designed, highly regulated power supplies are required for frequency stability.

(2) Transmitter Sources for Future Systems.

(a) Cyclotron resonance tubes. Numerous tubes under this generic name, including the above mentioned gyrotron, as well as relativistic electron beam (REB) tubes, and the free electron laser, are under development.

(b) Optically pumped molecular (OPM) lasers. These lasers, typically excited by CO_2 laser are promising as dual mode transmitter sources.

D. Local Oscillators

(1) Local Oscillators for Near Term Systems.

(a) Solid state devices - The Gunn diode currently operates at frequencies up to 100 GHz. It is a stable, low noise, presently low power (~ mw cw) source. Frequency multiplication may be required to use this device at higher frequencies.

(b) Tube - The reflex klystron is a highly developed, stable source but may also require frequency multiplication to reach higher frequencies.

(2) Local Oscillators for Future Systems.

(a) Optical pumped molecular laser (OPM laser) - The OPM laser is extremely quiet and stable, and capable of producing large amounts of power. Much packaging work would be required for it to function in a tactical system.

(b) Josephson junction - A dark horse candidate for use as a local oscillator; it requires cryogenic temperatures for operation.

E. Further Recommendations

Development of InP technology should be supported as well as the search for new high mobility solid state materials.

New techniques for producing energy in this wavelength region should be sought out and supported keeping in mind that until a source can produce more energy than a black body it is highly speculative.

2. MILLIMETER WAVE SOURCES

A. Black Body

The simplest source of 1 mm radiation is a mercury arc-lamp. The effective temperature of the plasma is $4 \times 10^{3\circ}$K. The radiation is in the Rayleigh-Jeans limit of the Planck black-body distribution, given by the power radiated from a 1 cm^2 source into 2π steradian (sr) solid angle is:

$$P = (9.6 \times 10^{-44})(\nu^2 T \Delta\nu)$$

where ν = frequency, T = temperature in degrees Kelvin and $\Delta\nu$ = bandwidth. For a bandwidth of 30 GHz the simple mercury arc can produce on the order of 1.0 u watts at 1 mm. Figure 1 shows the black body emission calculated using the full Planck equation rather than the Rayleigh-Jeans approximation.

B. Electron Beam Devices

Extension of the tube technology developed for centimeter wave generation has produced millimeter and submillimeter coherent devices. However, difficulties are met in scaling to shorter and shorter wavelengths. The basic problems are outlined below:

- The dimensions are proportional to the reciprocal of the frequency, ν^{-1}, thus as the frequency is increased machining problems multiply.

- Heat dissipation becomes more and more difficult as the frequency increases. The thermal limit seems to follow a ν^{-2} law; (it depends on the area).

- These devices operate through the interaction of a standing or propagating electromagnetic wave with an electron beam. The electric field associated with the wave must be relatively strong across the diameter of the electron beam. This requirement reduces the space for electron beam propagation and makes it very difficult to avoid unwanted interception of the electron beam by the tube body and the associated heat dissipation problems. The area over which the electron beam can interact with the electromagnetic field scales with λ^2. If the area of the beam is decreased to prevent interception, the e-beam current must increase to return the same interaction strength.

- Reduction in skin depth with frequency causes the rf circuit loss to increase as $\nu^{1/2}$. This increases the minimum beam current needed for oscillation. Combining this $\nu^{1/2}$ dependence with the ν^2 dependence on current associated with a reduction in beam area (preceding paragraph) results in the minimum current density increasing as $\nu^{5/2}$. The resulting

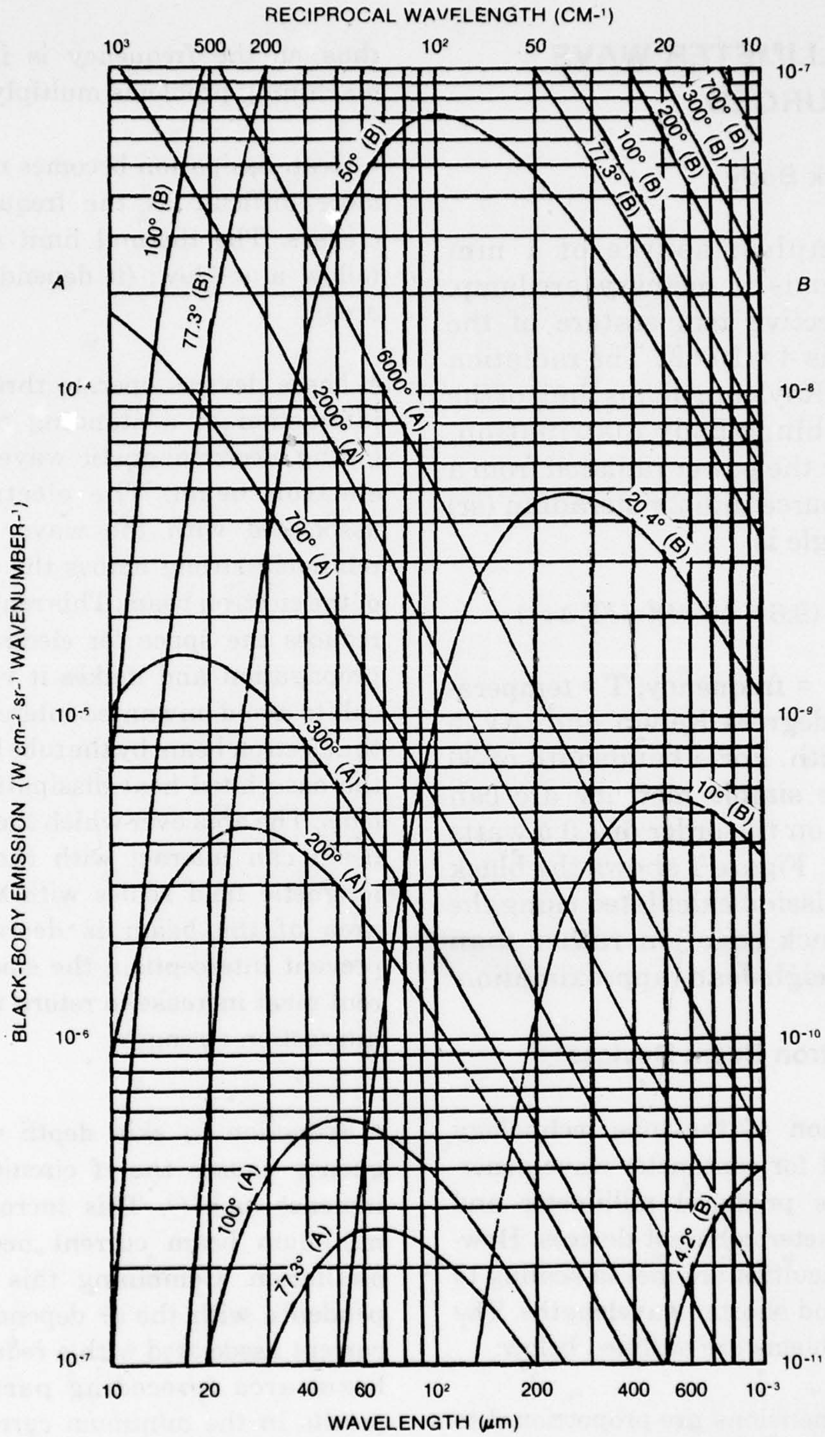


Figure 1. Black-body Emission. (The letters A and B After the Temperature Refer to the Left- and Right-hand Scales Respectively.)

required current density exceeds 100 amps/cm^2. Electrostatic focusing is required because a cathode designed to provide a reasonable lifetime (1000 hours) provides about 3 amps/cm^2 CW and 10 amps/cm^2 pulsed. Focusing increases the transverse component of velocity in the beam which increases the required size of the magnetic confining field.

- Higher voltages can be used to increase the output power but only at the expense of efficiency and weight. The size of the rf structure scales with voltage.

- At lower frequencies, M-type (crossed field) devices have efficiencies between 45 and 52%; and O-type devices (linear beam) have efficiencies less than 40%. At higher frequencies, a linear beam device is much more efficient than the crossed field device because the spent electron beam in the linear device can be dumped into a separate electrode at a depressed potential. Also a longer interaction path between the electron beam and the field is required at higher frequencies for the M-type due to their lower gain. Figure 2 shows the current limits of an M-type tube (magnetron). It is concluded that the magnetron is best used as a generator of millimeter waves under pulsed conditions. When driven with pulses of less than several microseconds duration, peak power outputs are attainable in the general range of 250-300 kW multiplied by the wavelength (in centimeters) squared.

C. Conventional Tubes

Current conventional tubes appear to have a power limitation that follows a ν^5 dependence much like the limit in gridded tubes.* Figure 3 graphically displays the frequency dependence of the output power. Solid state sources are also displayed in this figure. The solid state limit has a strong theoretical basis while the tube limit is an engineering limit. In summary the engineering problems that limit the output power in millimeter wave devices are:

- Power dissipation in fragile structures.
- Ability to manufacture small structures.
- Control of e-beam to reduce thermal dissipation.
- Control of e-beam quality from high convergent guns.
- High circuit losses (skin depth is decreasing).

*NOTE: The reasons for the gridded tube limit are: (a) grid dissipation and (b) transmit time effects across the grids. These reasons are not the same as for the beam tube limit but the end result is a similar drop in output power with frequency.

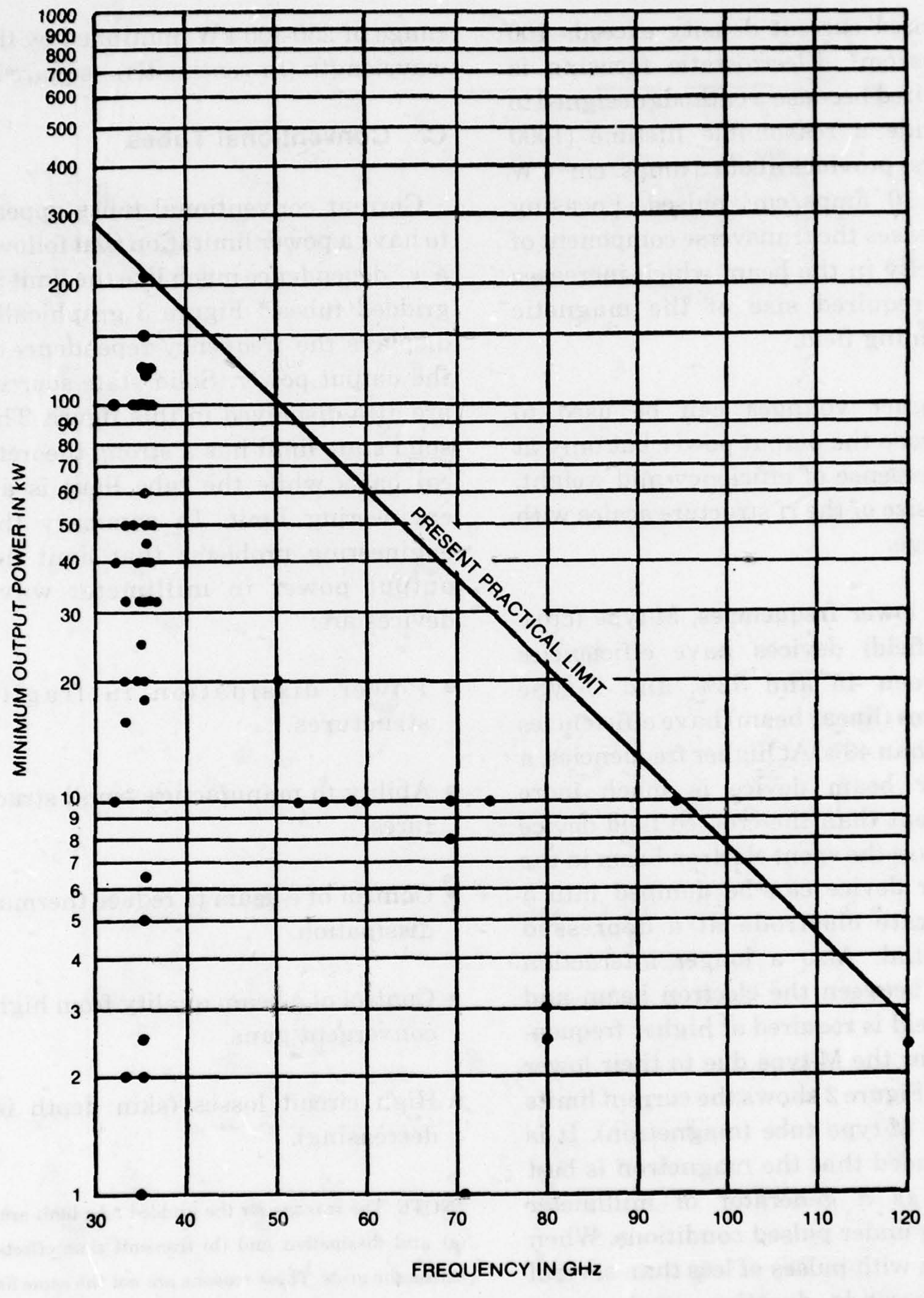


Figure 2. Commercially Available Pulsed Millimeter Magnetrons (Reference 1)

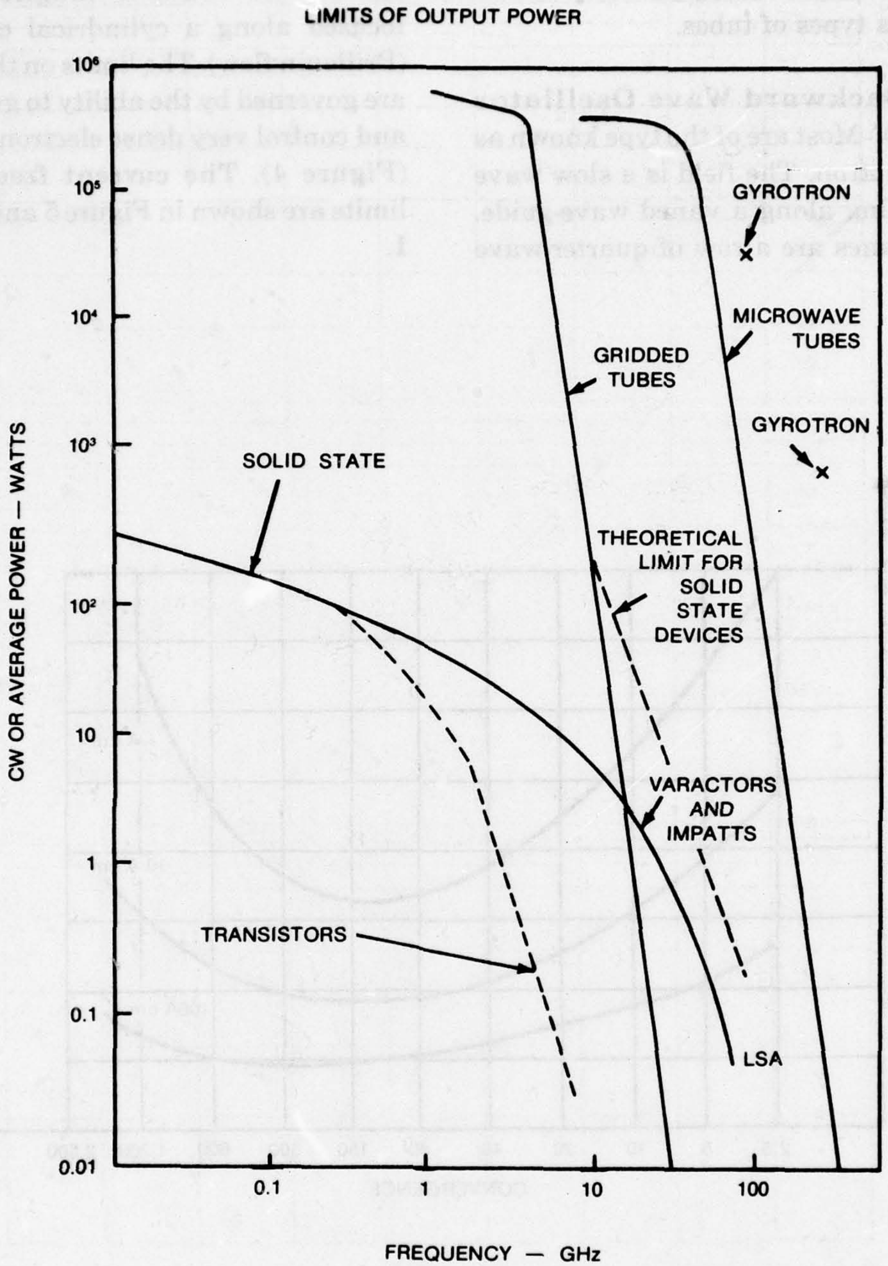


Figure 3. Power Limitations of Current Microwave Tubes and Solid State Devices

Let us now examine each of the various types of tubes.

(1) Backward Wave Oscillator (BWO): Most are of the type known as Carcinotron. The field is a slow wave travelling along a vaned wave-guide. The vanes are a row of quarter-wave stubs. The beam is magnetically *focused along a cylindrical channel* (Brillouin flow). The limits on this type are governed by the ability to generate and control very dense electron beams (Figure 4). The current frequency limits are shown in Figure 5 and Table 1.

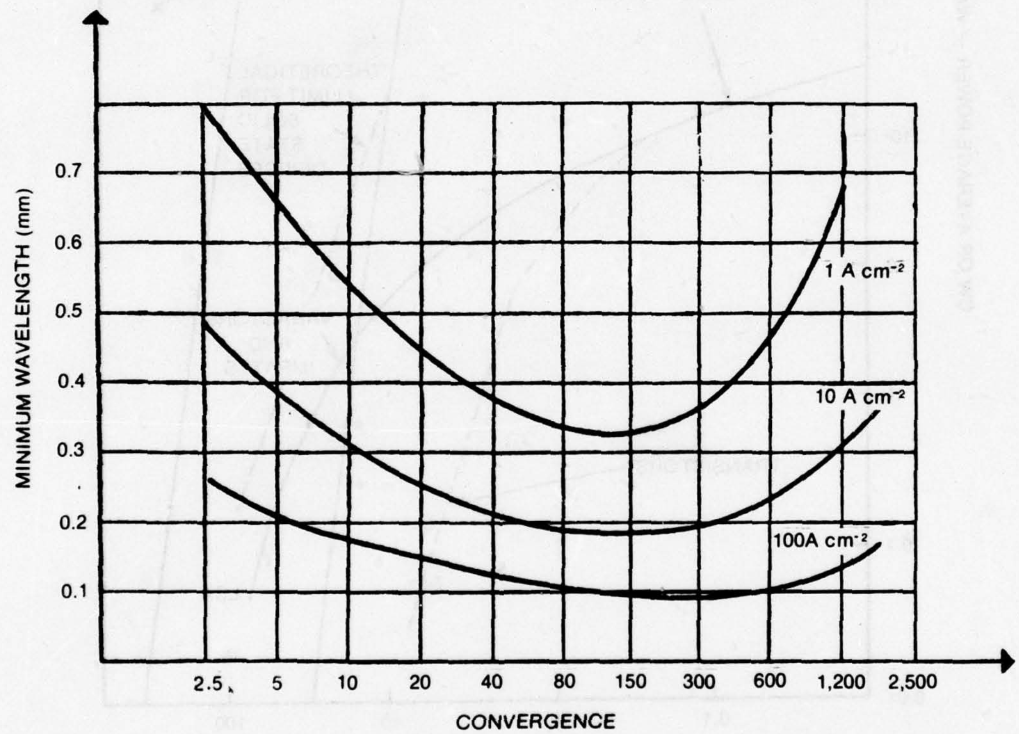


Figure 4. The Limit in Wavelength as a Function of the Gun Convergence for Different Current Densities at the Cathode of a BWO

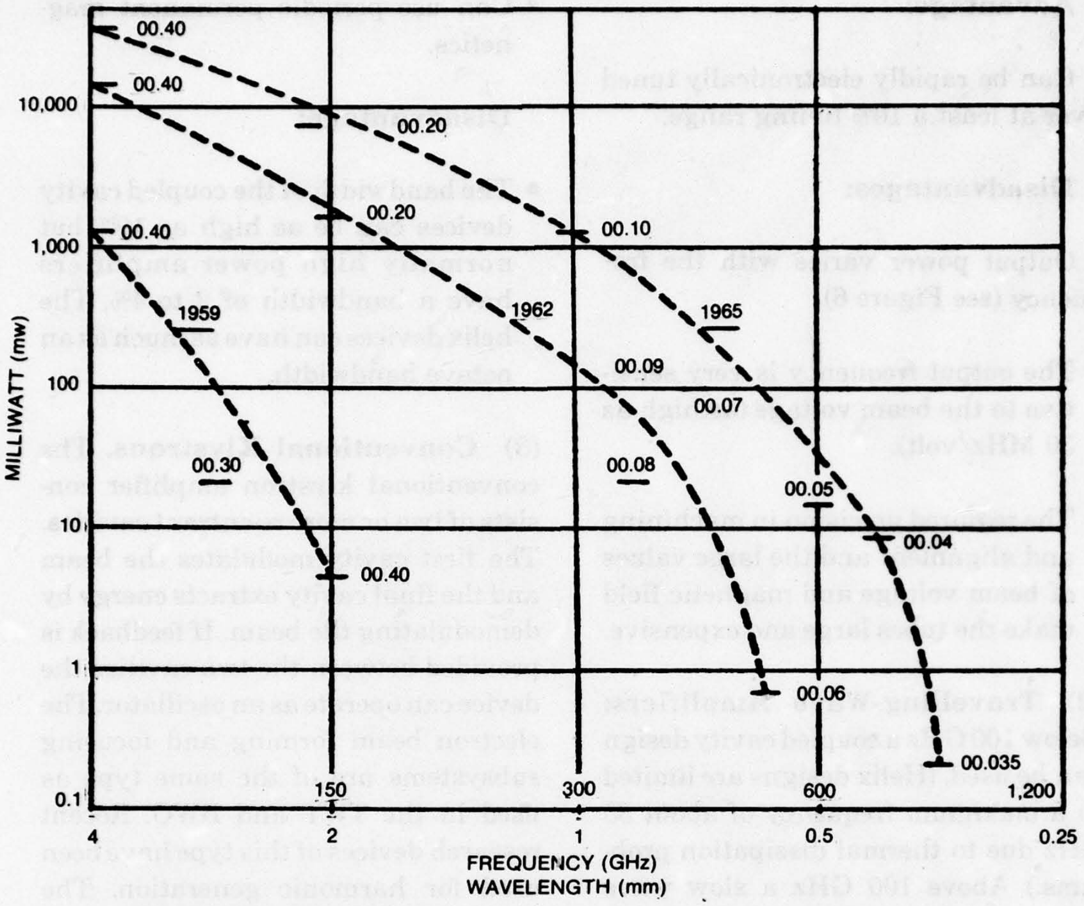


Figure 5. Maximum Powers Produced by Type 0 Carcinotrons at Different Wavelengths.

TABLE 1. CHARACTRISTICS OF AVAILABLE CARCINOTRONS

WAVELENGTH (mm)	CURRENT (mA)	VOLTAGE (kV)	POWER (W)	EFFICIENCY (%)
4	65	6	38	11
2	45	6	8	4
1	30	10	1.4	0.5
0.5	35	10	15×10^{-3}	4×10^{-3}
0.4	35	10	9×10^{-3}	2×10^{-3}
0.35	45	10	0.25×10^{-3}	6×10^{-5}

Advantage:

- Can be rapidly electronically tuned over at least a 10% tuning range.

Disadvantages:

- Output power varies with the frequency (see Figure 6).
- The output frequency is very sensitive to the beam voltage (as high as 30 MHz/volt).
- The required precision in machining and alignment and the large values of beam voltage and magnetic field make the tubes large and expensive.

(2) Travelling-Wave Amplifiers: Below 100 GHz a coupled cavity design can be used. (Helix designs are limited to a maximum frequency of about 35 GHz due to thermal dissipation problems.) Above 100 GHz a slow wave structure is preferred. The same beam focusing method as use in the BWO is used for the TWT.

Advantages:

- Up to three orders of magnitude more power is expected from a TWT than a BWO at a given operating voltage. 1-5 kW has been produced at 94 GHz.
- High efficiency is obtained by the use of depressed collector voltage.
- Can use periodic permanent magnetics.

Disadvantage:

- The bandwidth of the coupled cavity devices can be as high as 10% but normally high power amplifiers have a bandwidth of 2 to 4%. The helix devices can have as much as an octave bandwidth.

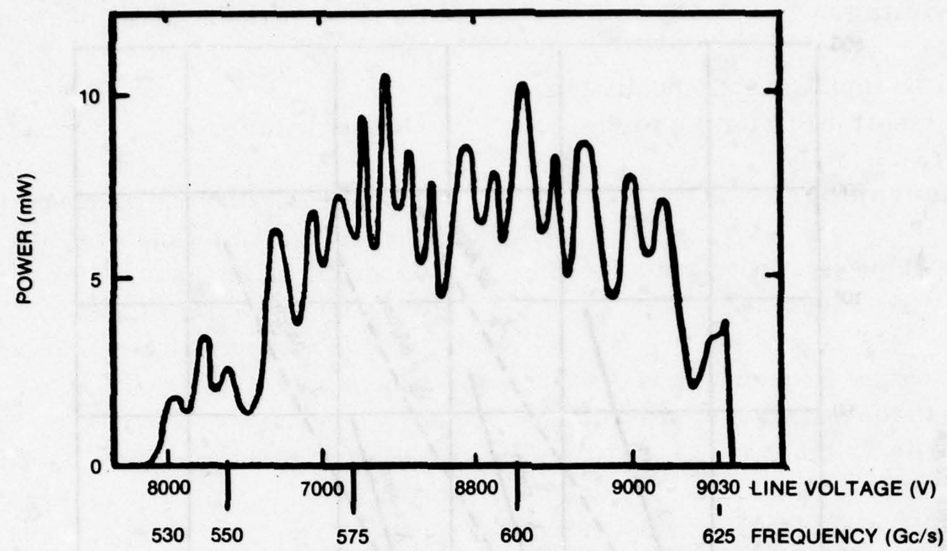
(3) Conventional Klystrons. The conventional klystron amplifier consists of two or more re-entrant cavities. The first cavity modulates the beam and the final cavity extracts energy by demodulating the beam. If feedback is provided between the two cavities the device can operate as an oscillator. The electron beam forming and focusing subsystems are of the same type as used in the TWT and BWO. Recent research devices of this type have been used for harmonic generation. The energy extraction cavity couples out harmonics of the fundamental frequency. Figure 7 shows theoretical limits on this type of tube.

Advantage:

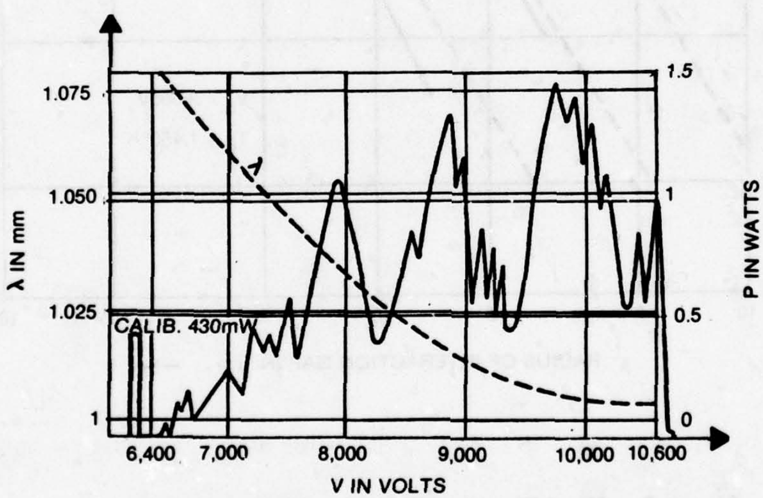
- Stable single frequency source.

Disadvantages:

- Cavity losses at higher frequencies make it increasingly difficult to approach ideal efficiencies.



A. Output power as a function of line voltage for a C.S.F. 0.5 mm tube.



B. Power and frequency tuning range of a 1 mm tube.

Figure 6. Frequency and power as a function of tube voltage for two typical BWO's (Reference 1)

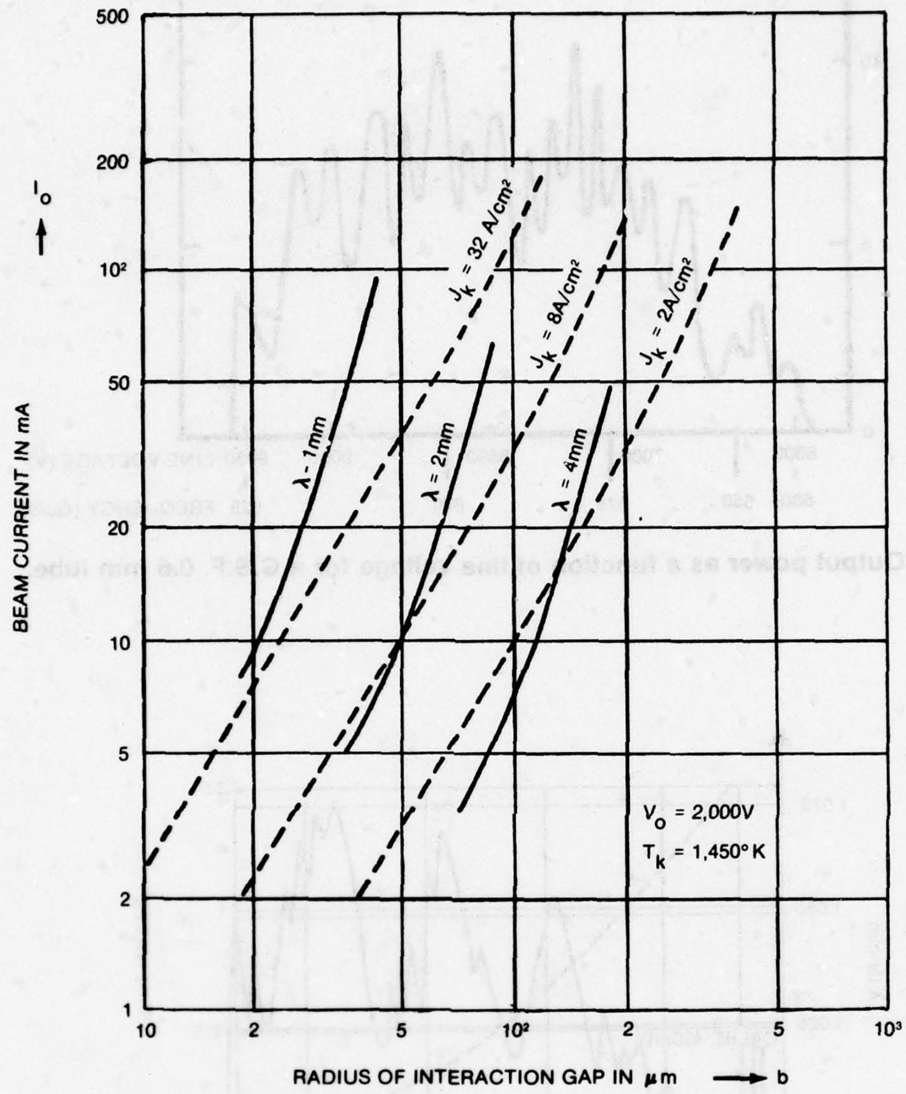


Figure 7. Short Wavelength Limit of Reflex Klystron

(From van Iperen, B. B., Philips tech. Rev. 21, 226 (1960)). Broken curves show the theoretic maximum available beam current. The minimum current for oscillation is shown by the solid lines. To obtain oscillations it is necessary to be able to choose a gap diameter b where the available current (broken curve) exceeds the minimum required current (solid curve).

- The tuning range and instantaneous bandwidth is limited, typically less than 2%.

- Limited lifetime on the order of 100 hours where high powers are required.

(4) Extended Interaction Oscillators. These devices are klystrons with a single cavity formed from a section of slow wave structure short-circuited at each end (see Figure 8). The interaction between the beam and the field occurs in the same way as it does for a TWT or a klystron. The power modes of this device are very similar to those of a reflex klystron, which leads to the possibility of "double moding".

Advantages:

- Higher power than the reflex klystron (1 watt CW and 20 watts pulsed at 280 GHz). Power is limited by e-beam current densities obtainable.

- Lifetime on the order of 1000 hours.

- Good output power and frequency stability.

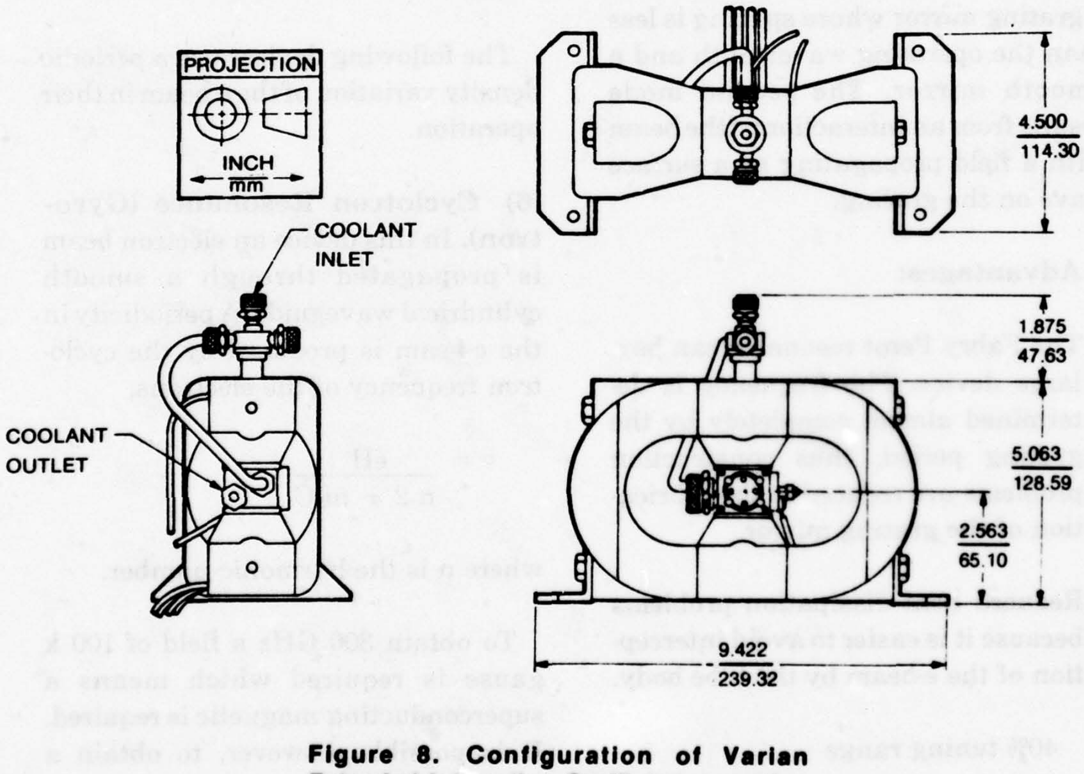


Figure 8. Configuration of Varian Extended Interaction Oscillators operating in the 140-230 GHz range.

- **Length of the slow wave structure is only a fraction of that of a BWO resulting in a smaller tube and focusing magnet.**

Disadvantages:

- **Tuning range is not as broad as it is for a BWO.**

- **Cannot be used as an amplifier.**

(5) Ledatron. This device has two modes of operation. In the first mode, the electron beam interacts with a field in a Fabry Perot cavity whose axis is transverse to the beam current. The Fabry Perot cavity is constructed with a grating mirror whose spacing is less than the operating wavelength and a smooth mirror. The second mode results from an interaction of the beam with a field propagating as a surface wave on the grating.

Advantages:

- **The Fabry Perot resonator can be a large device. The frequency is determined almost completely by the grating period, thus construction problems are reduced to the fabrication of the grating mirror.**

- **Reduced heat dissipation problems because it is easier to avoid interception of the e-beam by the tube body.**

- **40% tuning range**

- **Output coupling is easy.**

Disadvantages:

- **Starting currents are high.**

- **Magnetic fields on the order of several kilogauss are required.**

The tubes described above require ultra-high precision manufacturing techniques to obtain a periodic structure that generates a varying electromagnetic field. An alternative approach is to propagate the electron beam along a magnetic field in a smooth cylindrical wave guide (see Figure 9) and produce the required periodicity by causing the e-beam to "bunch".

The following devices use a periodic density variation of the e-beam in their operation.

(6) Cyclotron Resonance (Gyrotron). In this device an electron beam is propagated through a smooth cylindrical waveguide. A periodicity in the e-beam is produced by the cyclotron frequency of the electrons,

$$\nu = \frac{eH}{n\, 2\, \pi\, m C}$$

where n is the harmonic number.

To obtain 300 GHz a field of 100 k gauss is required which means a superconducting magnetic is required. It is possible, however, to obtain a harmonic of the cyclotron frequency reducing the required magnetic field.

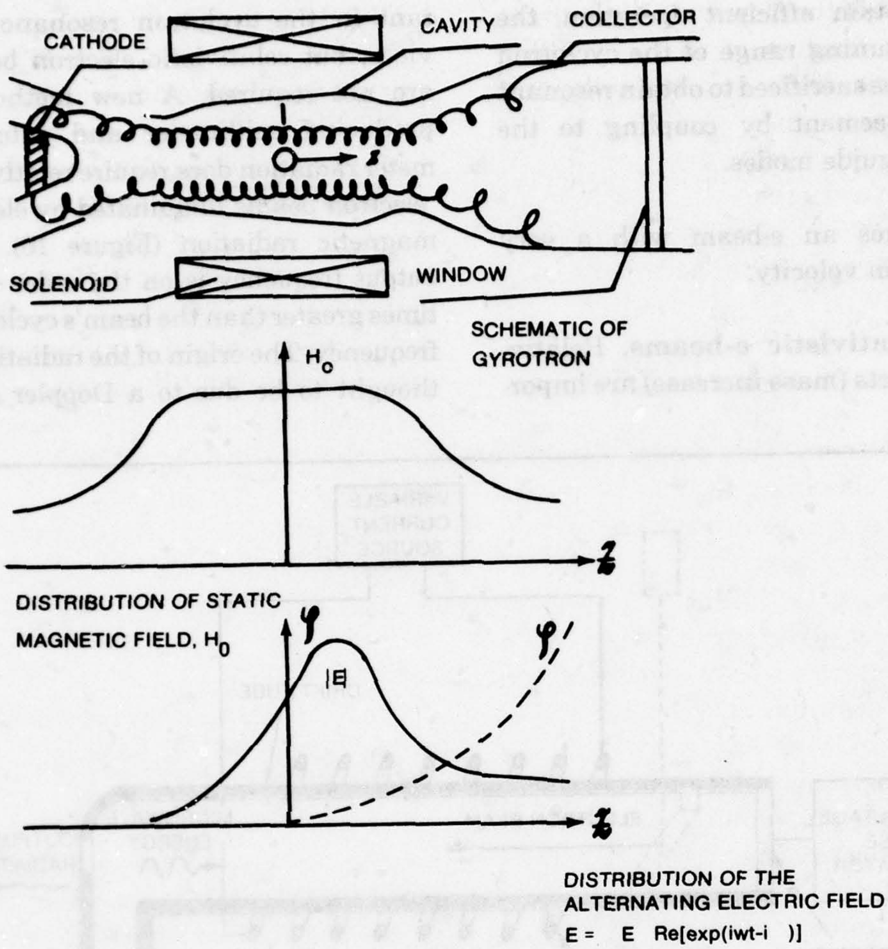


Figure 9. Gyrotron Characteritics

Advantages:

- **High efficiency — 43% has been obtained.**
- **In principle a wide tuning range should be possible, but multiple modes of the overmoded wave guide used in the gyrotron limit the tuning range substantially.**
- **High power: at 1.9 mm, 10 kW at 30% efficiency; at 0.9 mm, 1 kW at 6% efficiency.**

Disadvantages:

- **Large, spatially uniform magnetic fields are required.**

- To obtain efficient operation, the wide tuning range of the cyclotron must be sacrificed to obtain resonant enhancement by coupling to the wave guide modes.

- Requires an e-beam with a very uniform velocity.

(7) Relativistic e-beams. Relativistic effects (mass increase) are important in the cyclotron resonance devices, but relativistic electron beams are not required. A new method of producing millimeter and submillimeter radiation does require relativistic electron beams illuminated by electromagnetic radiation (Figure 10). The output frequency is on the order of 75 times greater than the beam's cyclotron frequency. The origin of the radiation is thought to be due to a Doppler shift

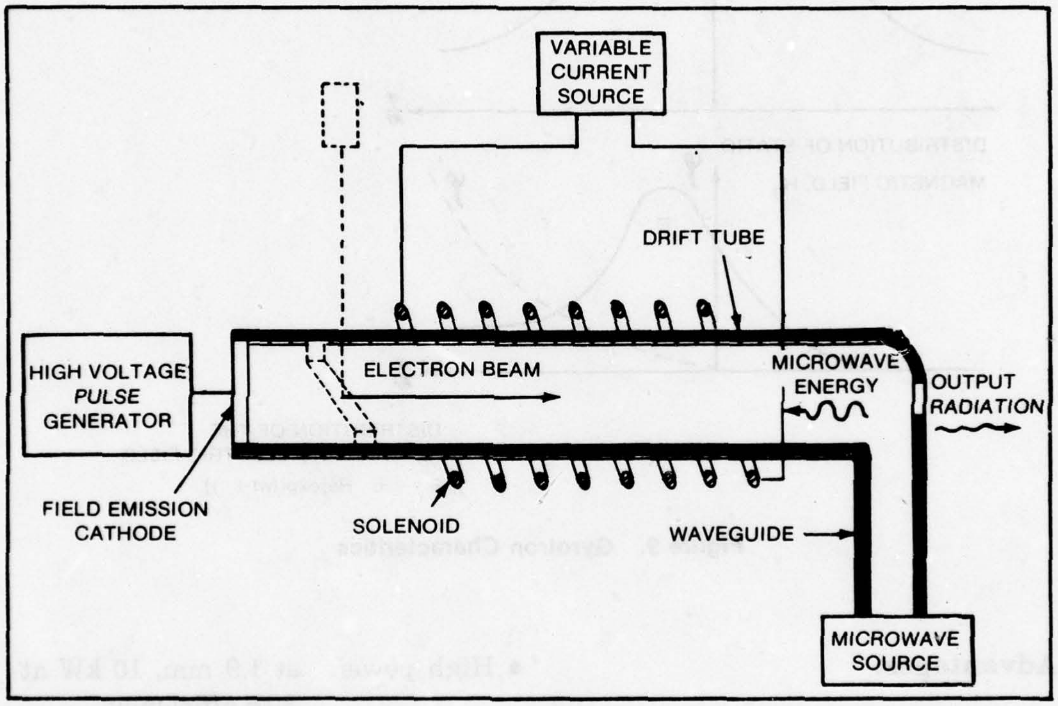


Figure 10. Cutaway View of a Relativistic E-Beam Submillimeter generator (Reference 4)

The output is obtained through a window that passes only the reflected signal. The dotted sections indicated an input scheme necessary to operate the device as an amplifier.

when the radiation is scattered by the electron beam. Two different types of scattering occur. Scattering from the beam-vacuum interface produces short pulses. Scattering due to the production of plasma oscillations in the e-beam by the electromagnetic wave produces pulses whose duration is limited by the e-beam current pulse.

Advantages:

- High power upconverter.
- Requires magnetic fields on the order of 1 k gauss.

Disadvantages:

- High currents (5×10^4 - 10^6 amps) are required. These currents are presently produced only in short pulses.
- Accelerating voltages of 2 M V are needed to obtain relativistic velocities (Figure 11).

(8) Ubitron. (Figure 12) A smooth wave guide is used in this device as in the gyrotron and the beam propagating through the wave guide is given a periodic disturbance by using a spatially periodic magnetic field. The beam is bunched longitudinally in the Ubitron and transversely in the Gyrotron. Efficiencies between 3 and 6% have been obtained without a depressed collector.

Advantages:

- Does not require a high magnetic field.
- A very high power device by virtue of the use of hollow beam magnetron guns to obtain high beam currents.
- Wide bandwidth.

Disadvantages:

- Requires high operating voltages.
- Periodic H-field is needed.

D. Solid State Devices

All solid state oscillators which depend on transport of charge carriers suffer the power output limitation known as the Johnson DeLoach relationship. This relationship states that the power output of the device multiplied by its reactance is inversely proportional to the frequency squared. Because reactance is also dependent on impedence matching requirements, the relationship reduces to the power depending upon υ^2, (Figures 3 and 13). Arrays of coupled solid state oscillators could be used at a penalty of increased complexity.

(1) Tunnel Diodes. This was the first active two terminal semiconductor device to generate coherent radiation in the millimeter region. The maximum frequency of this device is determined by its junction diameter. At high frequencies the lifetimes are short and the output powers are on the order of what can be obtained from a Hg arc source.

(2) Gunn Diode. In materials such as GaAs and InP the electronic configuration is such that above some minimum applied field a negative resistivity is observed. This is due to a change in mobility (increase in effective mass) of the electrons. The negative resistance can be used to produce oscillation in a tuned rf circuit. The maximum obtainable frequency is

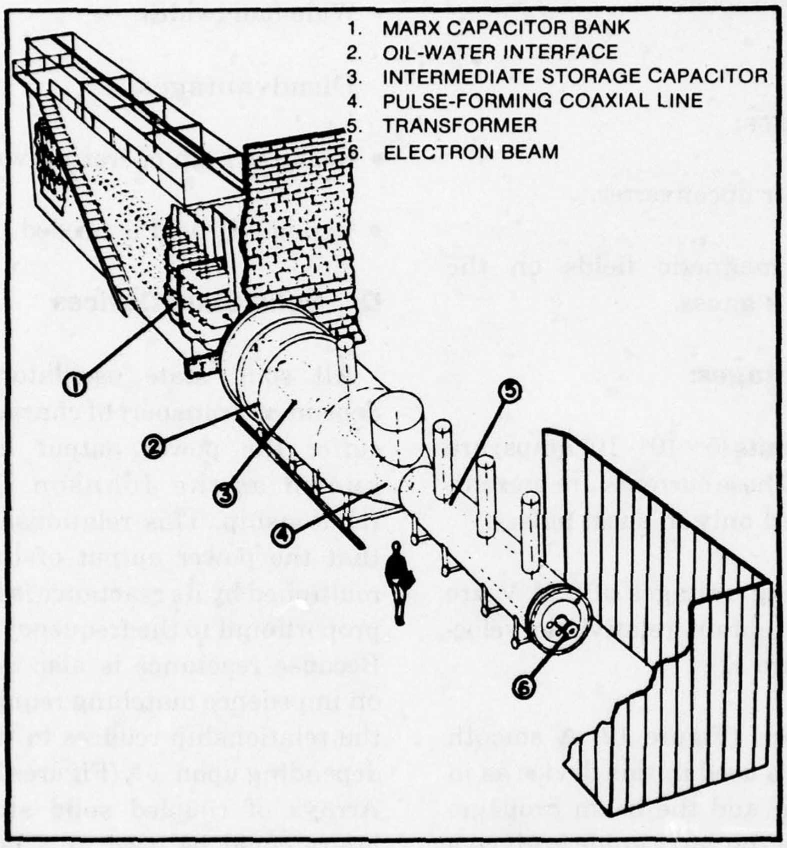


Figure 11. Typical Relativistic e-Beam Device

The Naval Research Laboratory's Gamble II, a typical relativistic e-beam device (REB). Most of the components illustrated are common to all REB's. The size of the device is determined by energy requirements.

given by the relaxation of the mobility states. GaAs and InP will not be useful at frequencies higher than 300 GHz. InP is a more promising material for high frequency operation by virtue of its higher mobility. More effort needs to be spent on its development. Materials with much shorter relaxation times (and preferably higher mobilities) must be found. Gunn diodes are available that operate up to 100 GHz with powers on the order of 10 mW. They are of interest as local oscillators due to their low noise.

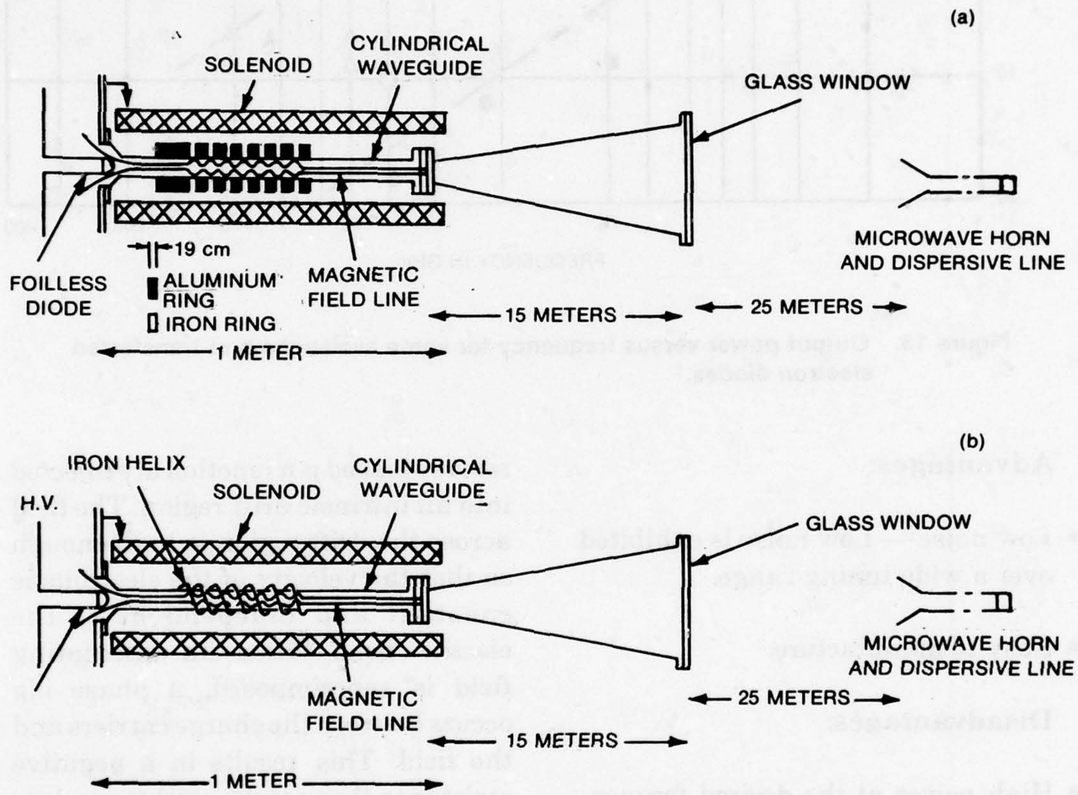


Figure 12. Ubitron

Two methods of spatial modulation are shown: a) a rippled magnetic field produced by inserting aluminum and iron inside the solenoid, and b) a helically perturbed field produced by an iron helix inside the solenoid.

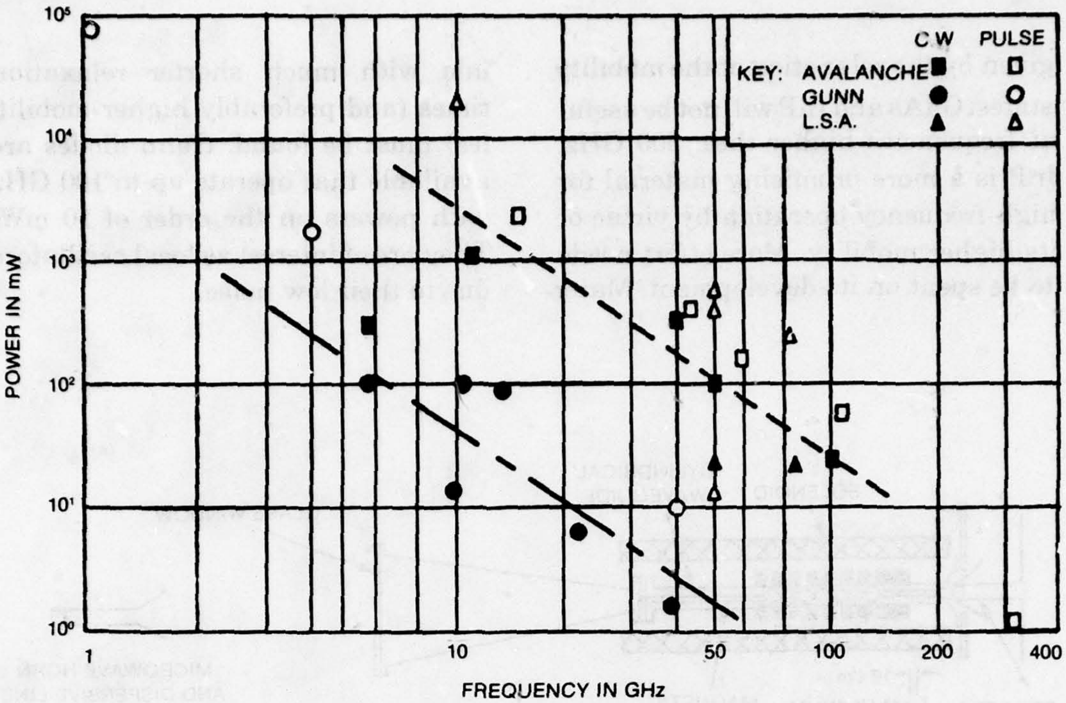


Figure 13. Output power versus frequency for some avalanche and transferred electron diodes.

Advantages:

- **Low noise — Low noise is exhibited over a wide tuning range.**
- **Easy to manufacture.**

Disadvantages:

- **High power at the desired frequencies is not available due to material limitations.**

(3) IMPATT Diode (Impact Avalanche and Transit Time). (Figure 14) In this device (constructed in Silicon or GaAs), carriers from a reverse biased p-n junction are injected into an intrinsic drift region. The field across the drift region is high enough so that the velocity of the electrons is constant and independent of the electric field. When an alternating field is superimposed, a phase lag occurs between the charge carriers and the field. This results in a negative resistance that can be used to produce oscillation. The maximum frequency is dependent on the thickness of the drift layer and the thickness of the depletion layer at the avalanche junction. It is difficult to fabricate and cool very thin drift layers. Very thin depletion layers can lead to breakdown

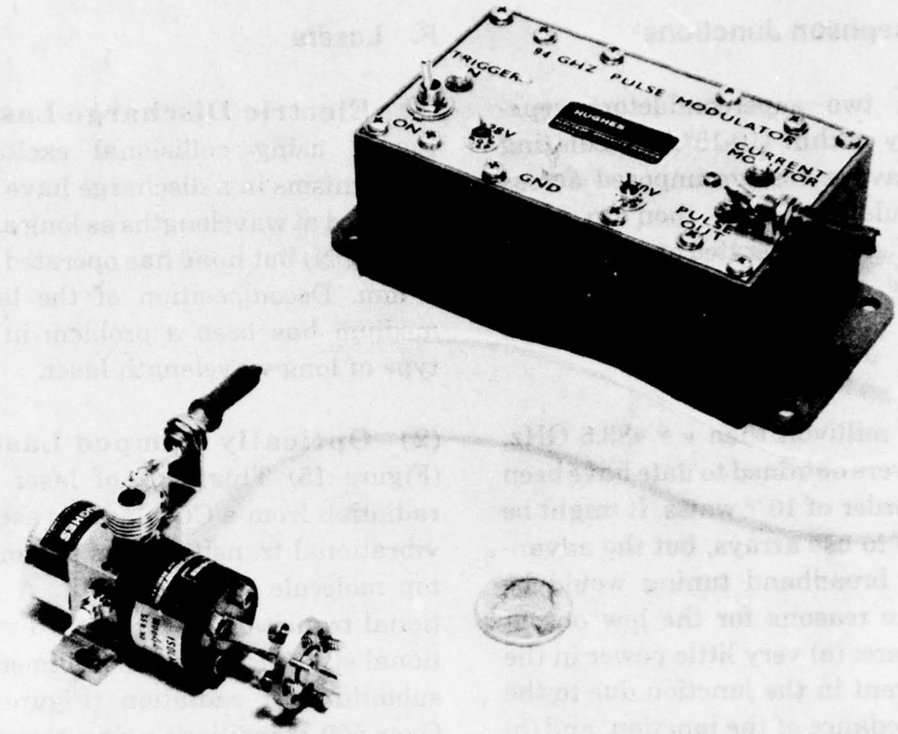


Figure 14. 94 GHz Impatt Diode

or tunneling. These limitations lead to a rapid fall-off of efficiency above about 100 GHz. New high-mobility materials are needed to obtain high efficiencies above 100 GHz.

Hughes Electron Dynamics Division has obtained 520 mW over a chirp frequency range of 211 to 215 GHz at a 2.6% efficiency. To reduce the reactance of the device to reach this high operating frequency, it was necessary to eliminate the Impatt package and make the diode an integral part of the waveguide circuit.

Advantage:

- **Higher output power than a Gunn oscillator.**

Disadvantages:

- **Low efficiency in the region of interest.**
- **Noisy and the noise varies over the tuning range.**
- **When operated as a pulsed source at high power, frequency stability is lost due to heating during a pulse.**

E. Josephson Junctions

When two superconductors separated by a thin (10-15°A) insulating layer have a voltage imposed across the insulating layer, then an alternating field is generated at a frequency given by

$$\nu = 2\ eV/h$$

if V = 1 millivolt then ν = 483.6 GHz. The powers obtained to date have been on the order of 10^{-9} watts. It might be possible to use arrays, but the advantage of broadband tuning would be lost. The reasons for the low output powers are: (a) very little power in the a.c. current in the junction due to the low impedance of the junction, and (b) it is difficult to match the low impedance source to free space or to a waveguide.

Advantages:

- Broadband tuning is possible but it is difficult to design a junction to realize this advantage.

Disadvantages:

- Low output power.
- Must be operated below 23°K.
- Difficult to couple energy out of the junction.

F. Lasers

(1) Electric Discharge Lasers. Lasers using collisional excitation mechanisms in a discharge have been operated at wavelengths as long as 337 um (HCN) but none has operated near 1 mm. Decomposition of the lasing medium has been a problem in this type of long wavelength laser.

(2) Optically Pumped Lasers. (Figure 15) This type of laser uses radiation from a CO_2 laser to excite a vibrational transition in a symmetric top molecule such as CH_3F. A rotational transition in the excited vibrational state produces the millimeter or submillimeter radiation (Figure 16). Over 500 transitions using this technique have been observed. This technique is still in the research stage.

Advantages:

- *Very stable frequency source.*
- No known power limitations but efficiencies are limited.
- Can operate either pulsed of CW.

Disadvantages:

- Not continuously tunable; in fact, several different gases would be required to change frequencies over an atmospheric window. It should be pointed out that changing gases is a very easy operation.

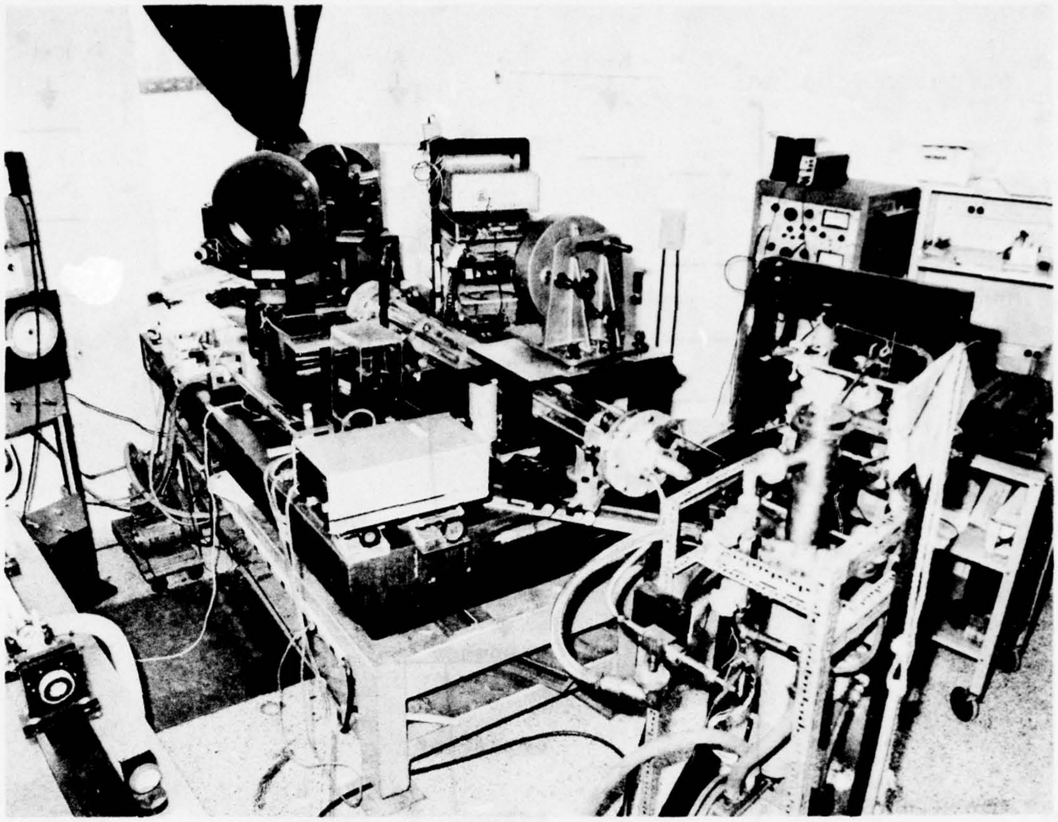


Figure 15. Submillimeter waveguide laser

The CO_2 pump laser is on the left. The submillimeter laser is on the right. The equipment shown is being used for propagation measurements.

- One photon at 10.6 um is expended for each photon at 1 mm.

- The technology is in its infancy.

(3) Rydberg States. It has been postulated that a laser could be made by optically pumping Rydberg states. It has yet to be proven.

(4) Free Electron Laser. A relativistic e-beam is passed through a periodic magnetic field (Figure 17). This beam will amplify radiation moving with the beam through the field. Radiation is also absorbed by the electrons. The wavelength for absorption is shorter than the wavelength for stimulated emission (amplification) by the fraction

$$2 h\nu/\gamma mc^2$$

The relationship between the lineshapes for emission and absorption are illustrated schematically in Figure

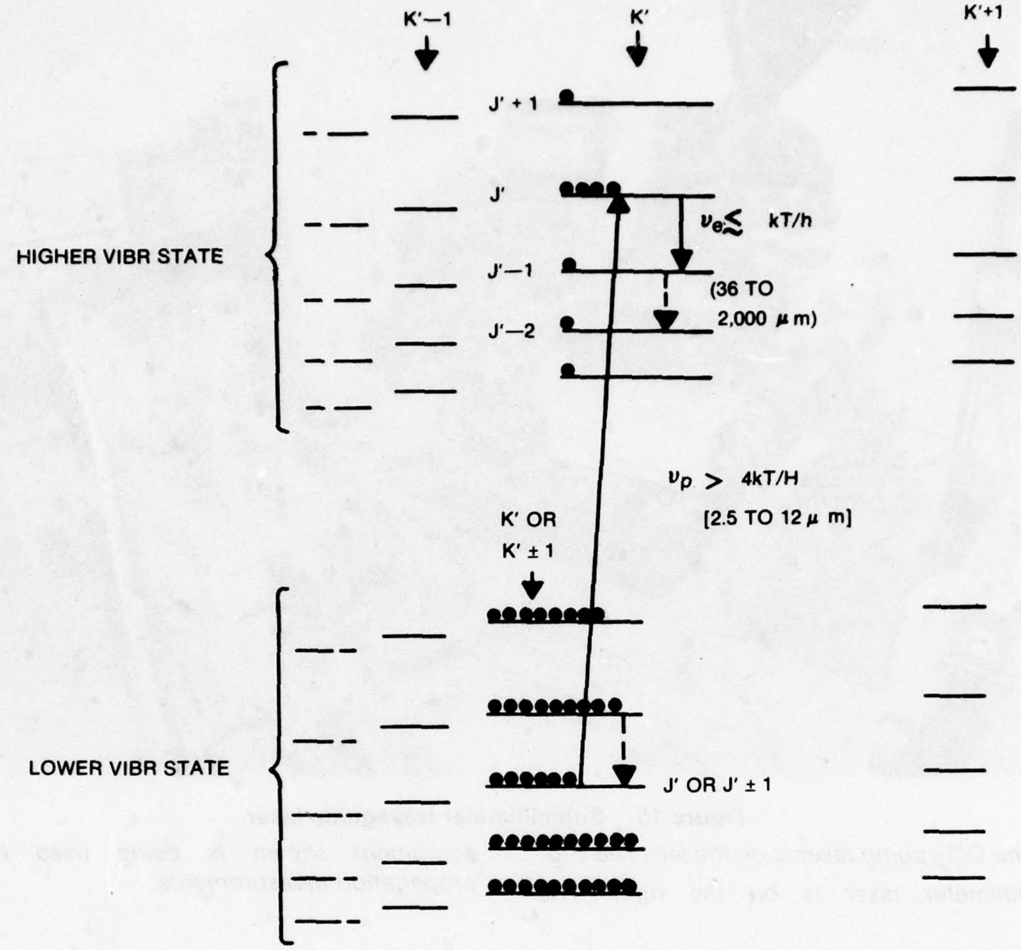


Figure 16. Rotational transitions suitable for lasing in a symmetric top molecule.

18. The output frequency increases as the square of the electron beam energy. This type of laser is still in its infancy. 0.36 watts average power and 7 kW peak power has been produced at 3.9 μm using a 34 M eV e-beam and a 2.4 k Gauss magnetic field. Work has also been done at 10.6 μm Longer wavelengths would require lower e-beam energies.

Advantages:

- Tunable source.
- Potential for high power.

Disadvantages:

- Present efficiencies are quite low. Improved efficiencies should be ob-

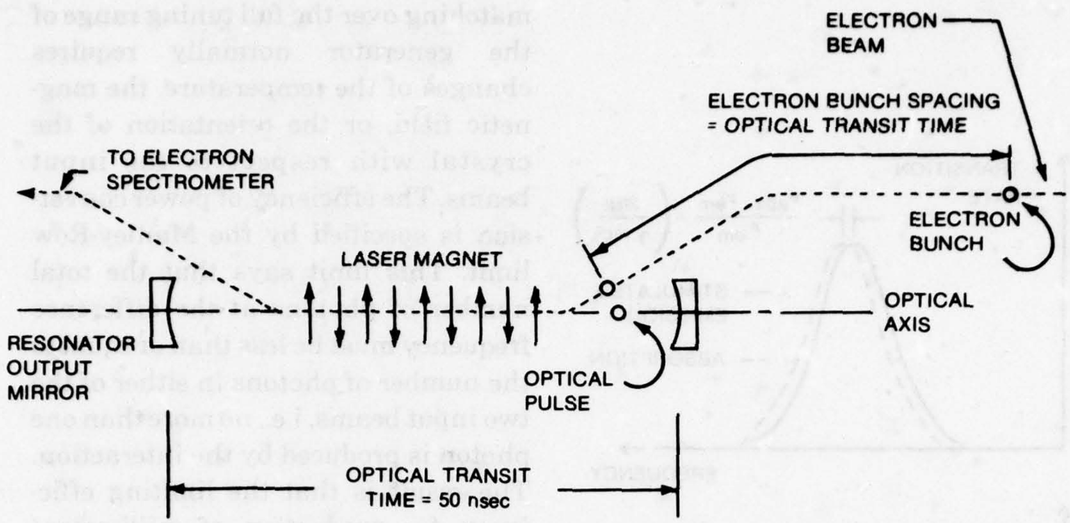


Figure 17. Typical free electron laser **Reference: (D.A.G. Deacon, et al)**

tainable with a storage ring but it has not yet been demonstrated.

G. Frequency Converters

(1) Diodes. Ideally, a non-linear contact would produce harmonic power proportional to $1/n^2$ where n is the harmonic number. Non-linear junctions can be formed between metal-semiconductor, phosphorous and carbon-ion bombarded silicon, and GaAs. To get to high frequencies requires very small contact areas reducing the allowable pump power (Figures 19-21).

Metal-Oxide-Metal (and Josephson junctions) require very thin oxide layers. This makes it very difficult to couple energy out of the junction.

Metal-Plasma. This junction is virtually indestructible. The output power and efficiency should be higher than in a semiconductor junction; however the intense heat generated by the plasma and the plasma's stability are problems.

(2) Difference Frequency Generation. (Figure 22) Two frequencies are input to an optical material with a non-linear index of refraction at the two frequencies. The output frequency is equal to the difference between the two input frequencies. An additional requirement is "phase-matching". This requirement is imposed because mixing must take place over distances much greater than a wavelength and is equivalent to requiring conservation of momentum. To maintain phase matching over the full tuning range of the generator normally requires changes of the temperature, the magnetic field, or the orientation of the crystal with respect to the input beams. The efficiency of power conversion is specified by the Manley-Row limit. This limit says that the total number of photons at the difference frequency must be less than or equal to the number of photons in either of the two input beams, i.e., no more than one photon is produced by the interaction. *The result is that the limiting efficiency* for production of millimeter/submillimeter radiation with visible or near infrared radiation is about 10^{-3}. Typical materials are InSb, ZnGePa, GaAs, LiNbO2, and ZnO.

Advantages:

- The CW device is very coherent.
- Can be tuned over a wide frequency range; the actual range is material dependent.

Disadvantages:

- The pulsed device is not very coherent and there is a large variation in the pulse to pulse output power.
- Extremely limited in output power. Crystal heating is one limitation but another is material properties.
- Two pump frequencies are required.

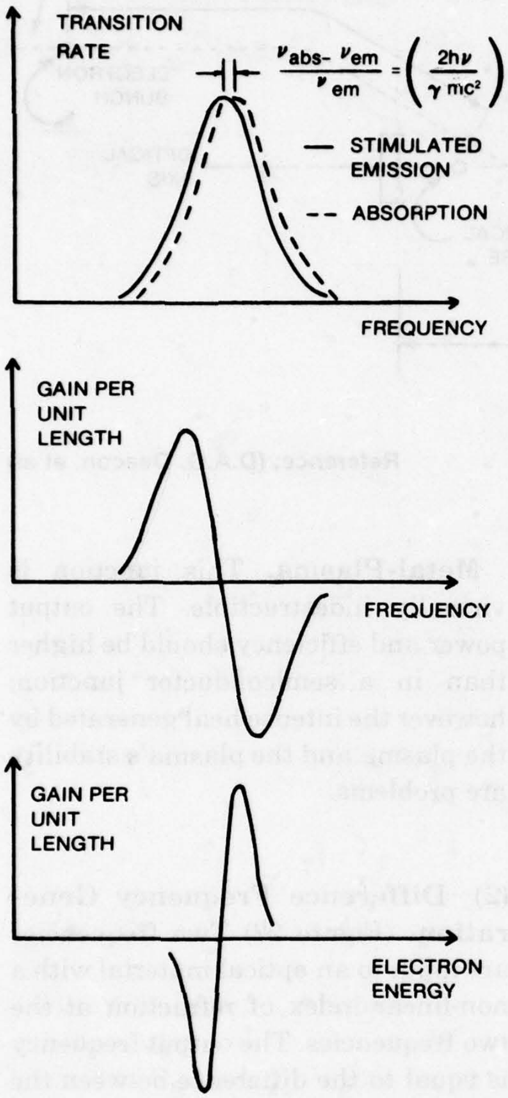


Figure 18. Relationship between line shapes for emission and absorption

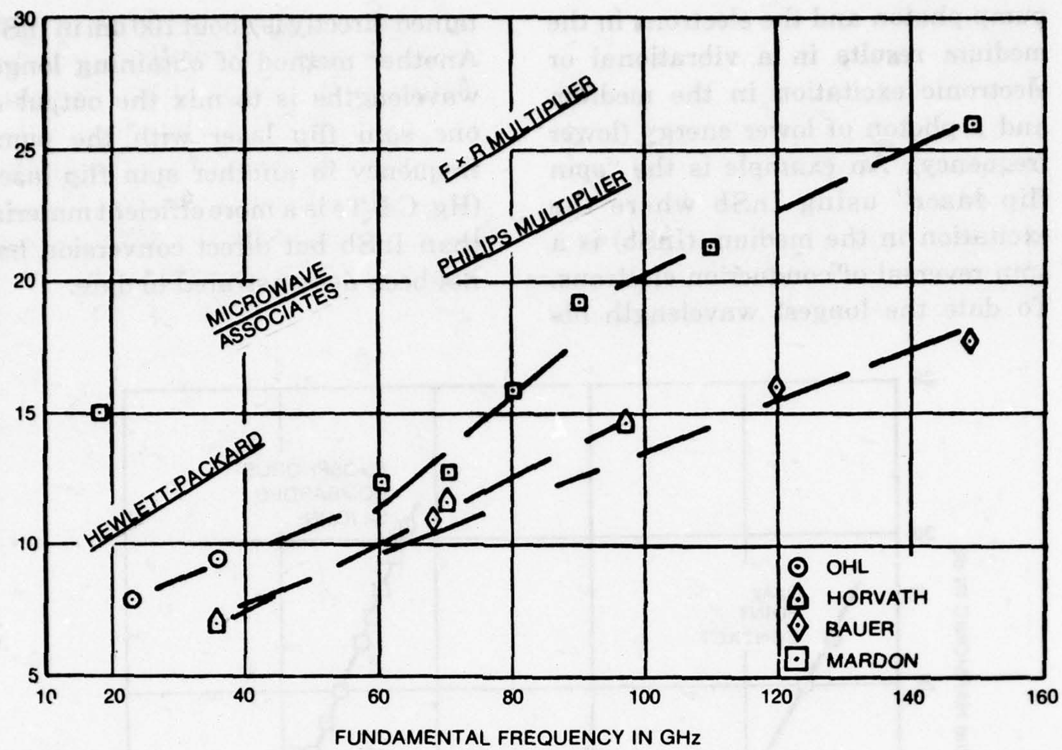


Figure 19. Second harmonic conversion loss versus fundamental frequency for point contact diodes (Reference 1)

(3) Parametric Oscillators. This device requires a material with a large quadratic non-linearity. Crystals without a center of inversion symmetry meet this requirement. Examples are $LiNbO_3$, and $LiIO_3$. Both the idler (the 2nd pump frequency) and output frequency are produced by the pump field in this device. Very high pump power densities are required. The Manley-Rowe limit applies to this device.

Advantages:

- Tunable.
- A simpler system than the difference frequency generator. Only one *pumping frequency is required.*

Disadvantages:

- Power density requirements rule out CW operation. Pump power densities are as high as 50 MW/cm^2.
- Difficult to achieve high coherence.

(4) Stimulated Raman Scattering. A cubic non-linearity is important here as well as a resonant scattering process. An interaction between the pump photon and the electrons in the medium results in a vibrational or electronic excitation in the medium and a photon of lower energy (lower frequency). An example is the "spin flip laser" using InSb where the excitation in the medium (InSb) is a spin reversal of conduction electrons. To date the longest wavelength obtained directly is about 100 um in InSb. Another method of obtaining longer wavelengths is to mix the output of one spin flip laser with the pump frequency in another spin flip laser. (Hg, Cd) Te is a more efficient material than InSb but direct conversion has not been demonstrated to date.

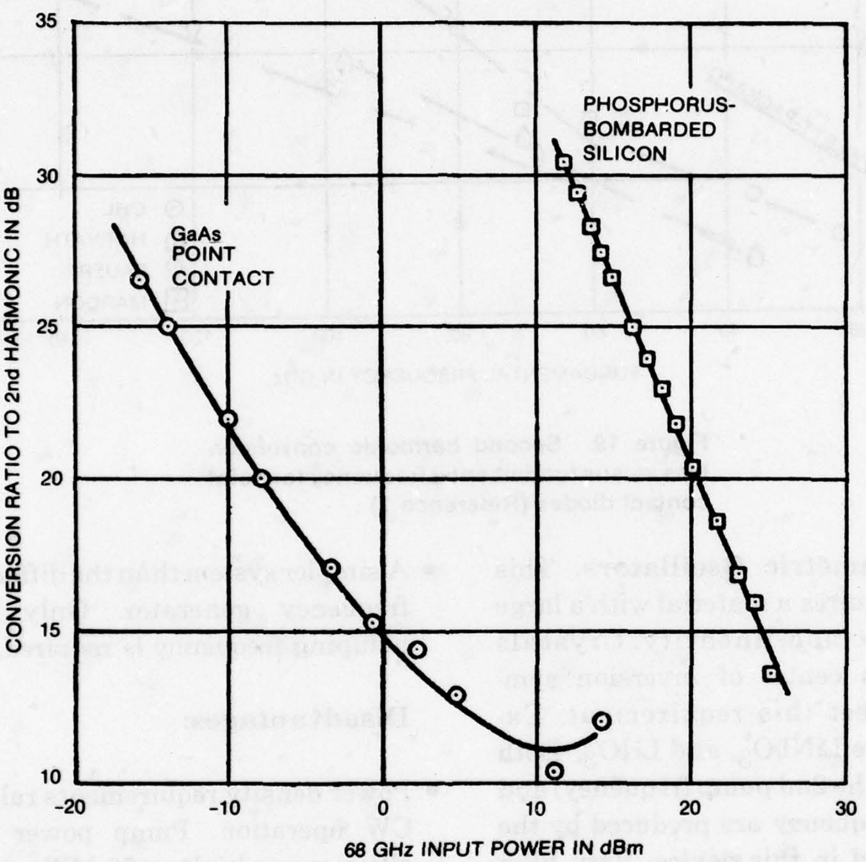


Figure 20. Second harmonic conversion efficiency versus input power of P-Si and GaAs (Reference 1)

3. COMPARISON OF CANDIDATE SOURCES FOR A MILLIMETER WAVE RADAR SYSTEM.

Three frequency regions are presently of particular interest for the operation of near future millimeter wave systems. The atmospheric windows centered at 94, 140, and 220 GHz, possess transmissivities such that one can envision operation of radar systems of moderate range (1-6 km) at these frequencies. Beamwidths at these frequencies can be made rather narrow with an antenna of moderate size (Figure 23). The diffraction limited beamwidths ($\theta_{3db} = \frac{\lambda}{D}$) for a one meter antenna at 94, 140, and 220 GHz are then 32, 21, and 13 milliradians respectively and can be obtained from the nomograph in Figure 23. At these

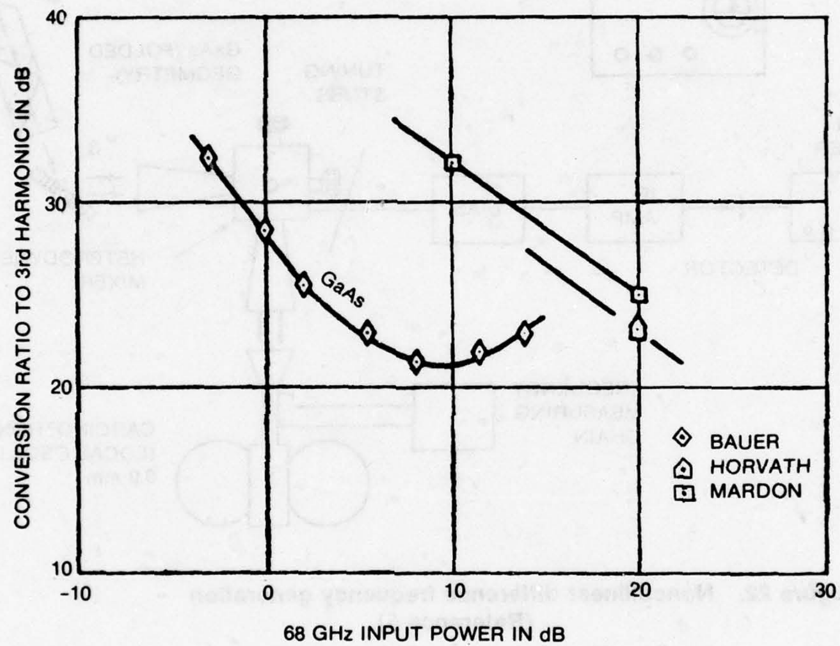


Figure 21. Third harmonic conversion efficiency of P-Si and GaAs (Reference 1)

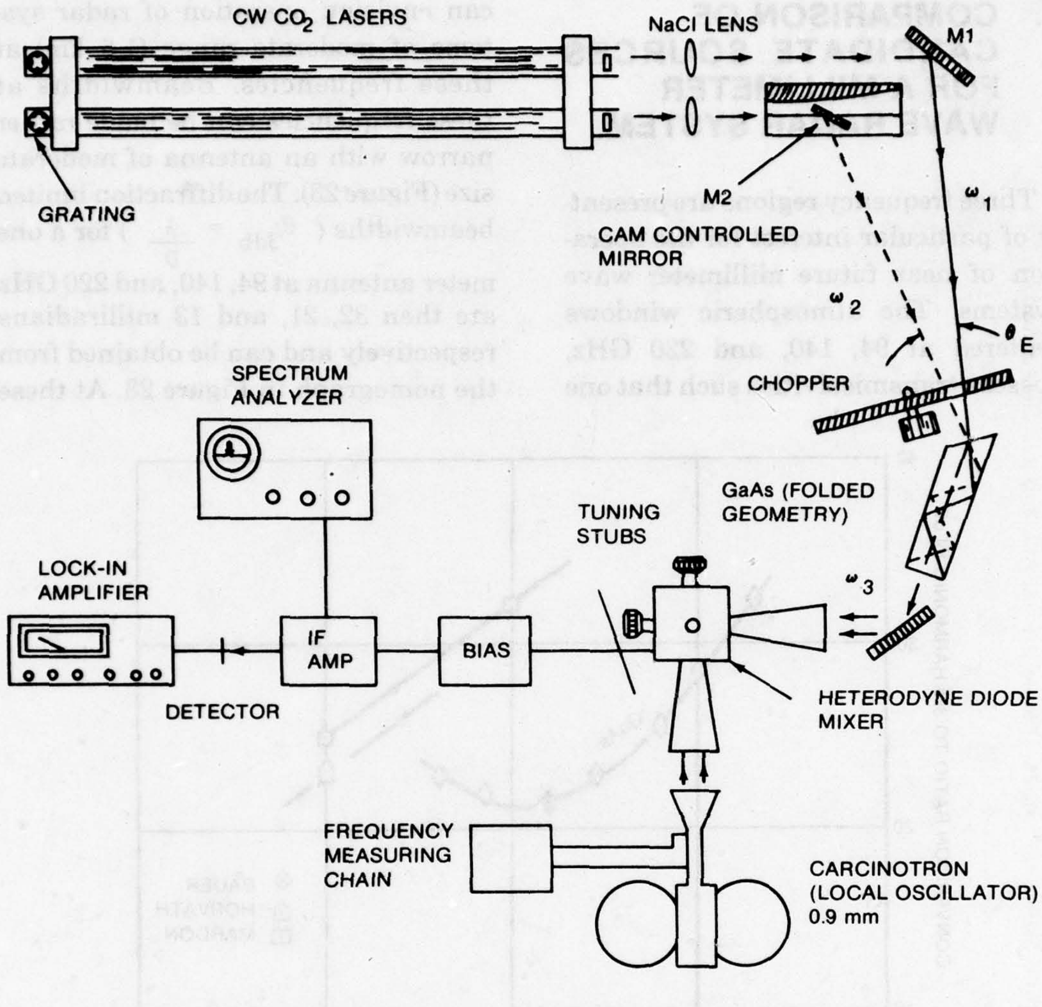


Figure 22. Noncollinear difference frequency generation (Reference 5)

beamwidths, a practical radar system can engage targets in a surface to surface mode at moderate range without undue difficulties due to target to background signal ratio or multipath. Finally, a technology exists at all three frequencies. The component technology is fairly well developed at 94 GHz. At 220 GHz, the component technology is considerably less developed despite the obvious payoff of much improved tracking capability at this frequency. The 140 GHz technology is, as might be expected, less developed than that of 94 GHz and more developed than that of 220 GHz.

Table 2 illustrates the present performance capabilities of sources which show promise for implemen-

Table 2. Performance capabilities of sources at the 94, 140, and 220 GHz windows.

	AVAILABILITY	FREQ. STABILITY	OUTPUT POWER CW/PULSE	EFFICIENCY CW/PULSE	CUBE/ WEIGHT	MFTR	COST
94 GHz							
Klystron	Catalog	Good	300 mW/		11 in³/ 1 lb	Several.	$3-4K
TWT	Catalog	Good	100 W (long, 1 ms pulse)	5%/	.94 ft³/ 40 lb	Hughes E/D	$3-4K
BWO	Catalog	Good				CSF (France)	$6K
EIO	Catalog	Good	50 w/10 Kw	3%/.08%	17 lb/ 29 lb	Varian	$5-6K
Gunn Diode	Catalog	Good	50 mW				
Impatt Diode	Catalog	Noisy	50 mW/1.3 W			Hughes E/D	$500
140 GHz							
Klystron	Catalog	Good	100 mw/		11 in³/ 1 lb	Several	
BWO	Catalog		3 w*/	.53%	.5 ft³/ 70 lb	CSF (France)	
EIO	Catalog	Good	150 mw/	1.8%	17 lb/	Varian	
Impatt Diode	Special Order	Noisy	3.5 mW/.48 W			Hughes E/D	$5K
220 GHz							
Klystron	Catalog	Good	15 mw		11 in³/ 1 lb	Several	
BWO			1.4 w	0.5%		CSF (France)	$10-12K
EIO	Catalog	Good	1 w	1%	17 lb/	Varian	$10-12K
Cyclotron Resonance	Lab Device	Good	kW-MW pulse		Presently very large		
Impatt Diode	SPECIAL ORDER	Noisy	/400 mw*	/2.6%		Hughes E/D	$5K
OPM Laser	LAB DEVICE		10 mw/1 Mw		Presently large		

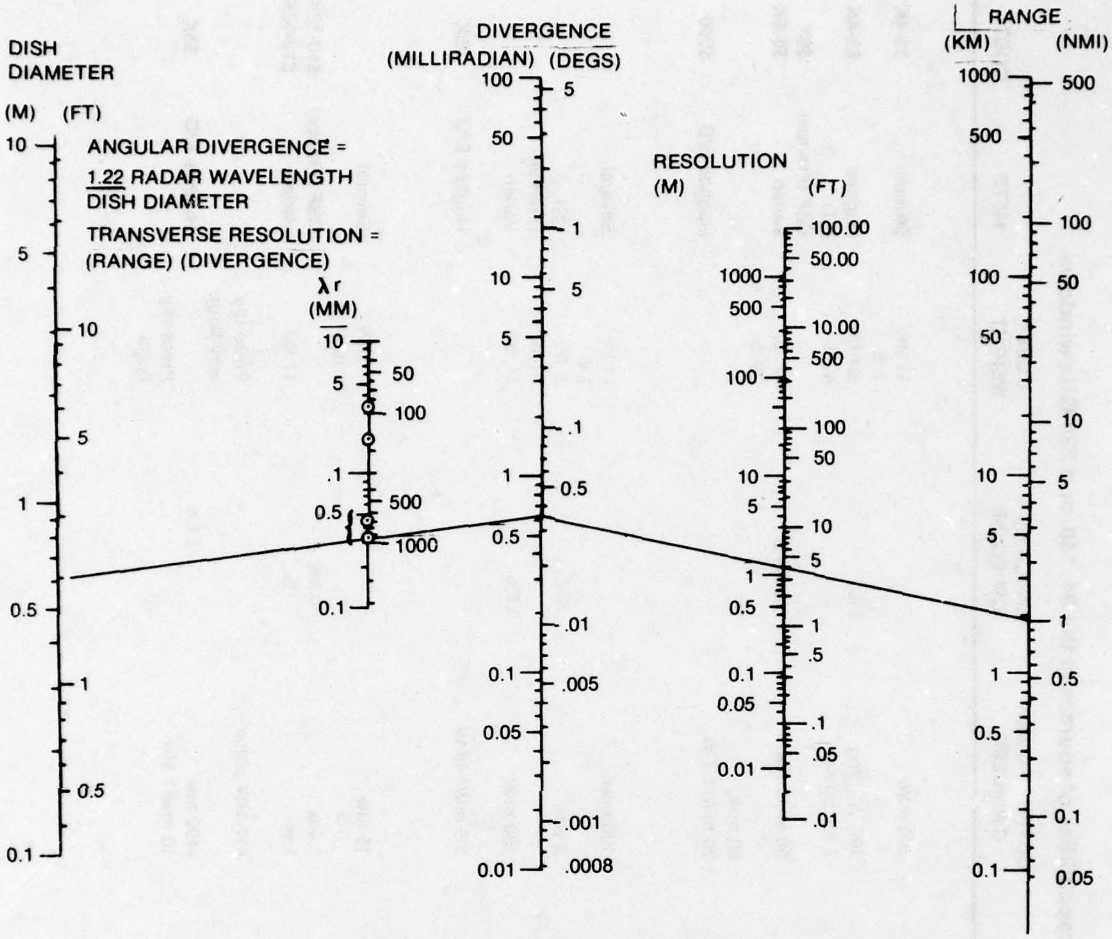


Figure 23. Submillimeter Radar Resolution Nomograph

tation in millimeter wave systems either immediately or in the near future.

Present US cyclotron resonance devices are both too bulky and too inefficient to be considered for implementation in a tactical mm radar system. The Soviets are developing cyclotron resonance devices (under the generic name of gyrotrons) which show promise of being reduced to practical size and weight for tactical systems, as well as being very efficient. This fact, coupled with the rapid advance of US technology in the development of these devices suggested the inclusion of such devices in Table 3, which predicts the near term growth of the technology for these devices.

Table 3. Projected, Cyclotron-Maser, Millimeter-Wave Sources

DEVICE	1	2	3	4
Development Time	2 years	3 years	4 years	4 years
Wavelength	8 mm	8 mm	3-4 mm	0.8 mm
Peak Power	100 kW	10 MW	10 MW	2 MW
Power Variability	full	full	full	none
Average Power	25 kW	10 kW	10 kW	1 W
Pulse Length	100 sec	1 sec	1 sec	50 ns
Rep. Rate	2500 pps	1000 pps	1000 pps	10 pps
Waveguide Mode	TE^{o}_{01}	TE^{o}_{01}	TE^{o}_{02}	
Amplifier/Oscillator	amplf.	amplf.	amplf.	osc.
Gain	20 dB	20 dB	20 dB	N.A.
Bandwidth	1%	10%	10%	10%
Tunability	5%	30%	30%	30%
Device Efficiency	40%	25%	25%	
Phase/0.1% Voltage Change	4 deg.	4 deg.	6 deg.	N.A.
Cyclotron Harmonic	fundamental	2nd	fundamental	
Magnetic Field	15 kG	12 kG	48-64 kG	
Noise Figure	30 dB	30 dB	30 dB	N.A.
Device Weight	120 lbs.	100 lbs.	100 lbs.	

The optically pumped molecular lasers are presently limited to use as laboratory tools. There are, however, several reasons for closely monitoring the state of the art of these devices. There is no fundamental upper limit on the power of these devices, and they are inherently very coherent. The OPM laser is quite obviously a good candidate for inclusion in a dual mode system, since it is inherently dual mode, the pumping device typically being a medium power CO_2 laser, operating around 10.6 μm, coaxial with the millimeter wave lasing cavity.

It is seen from Table 2 that reflex klystron power output at the frequencies of interest is extremely low. Reflex klystrons are, however, very stable sources, especially when controlled by a crystal oscillator, so the reflex klystron is a good candidate for a stable local oscillator in a mixer, or perhaps for frequency stabilization of some more powerful source, such as a backward wave oscillator. The 94 GHz magnetron listed in Table 2 is a reasonably powerful source. Magnetrons are, of course, generally far less amenable to frequency stabilization than klystrons, so use of a magnetron to obtain doppler information from the target might require a noncoherent MTI technique. The powerful travelling wave tube mentioned in Table 2 is a Hughes development. This tube is phase locked to a Gunn diode and is obviously an excellent candidate for a coherent, CW source at 94 GHz. TWT developments above 94 GHz are yet to come, the feeling in the industry being that seed money would be needed to work at higher frequencies.

Progress in the technology of solid state devices has been quite rapid, particularly with regard to IMPATT diodes, thanks to the Hughes efforts in general, and especially at high frequency. The 140 and 220 GHz IMPATT transmitters were developed by Hughes as part of BRL's systems efforts at these frequencies. The situation at present is such that IMPATT's are the only solid state devices which produce enough power to operate as transmitters at the frequencies of interest. IMPATT power output may be increased beyond the levels shown by operation of several of the devices in parallel (power combi-combination). The chief problem with IMPATT's is frequency stability. The devices are not presently coherent enough to permit doppler detection, unless, as in the magnetron case, noncoherent MTI techniques can be utilized. Gunn diodes, which presently have very low power outputs, are potentially very useful sources, since they are quite stable and capable of CW operation. They are presently used as local oscillators in millimeter wave mixer circuits.

Generally then, the solid state devices are lightweight, rugged, and potentially inexpensive. They presently suffer from low power outputs and, in the case of the IMPATT diodes, frequency stabilization needs much improvement.

The most notable BWO's are the CSF (France) carcinotrons. Carcinotrons produce sufficient power at 94 and 140 GHz. Frequency stabilization may be achievable by a phase locking technique, utilizing a cascaded phase locked system. It is seen that output efficiencies are rather low, and that the carcinotron BWO is rather heavy (40 lb). A further disadvantage is the high voltage power supply required to drive this tube. Present power supplies for these tubes weigh several hundred pounds. (The extended interaction oscillator of Varian (Canada) is somewhat more efficient as well as being considerably lighter in weight.)

4. RECOMMENDATIONS

The current situation is, that Impatt diodes can be implemented in near term systems, and are lightweight and rugged, but are presently too noisy for coherent operation, as well as rather low in power. Tube sources, especially the CSF carcinotron, the Varian Extended Interaction Oscillator, and the Hughes TWT, are capable of coherent, CW operation, and are capable of producing sufficient power for the mm radar application. Near term systems should undoubtedly utilize the Impatt or some variant of the tube sources just mentioned. The current experimental work with Impatts, pioneered by BRL, should be expanded, and a parallel development effort should be put into the tube source development. Seed money expended on frequency stabilization for tubes and power supply development, in addition to tube development, should provide considerable improvement in tube performance in a short time.

Current efforts on REB's and cyclotron maser type devices, as well as the free electron laser, should be monitored closely, and application of funds should be made in areas which would enhance the potential of these devices for short range radar systems. Relativistic electron beam devices (this does not include the gyrotron), however, may not be expected to provide an immediate payoff for a short range radar. Efforts in laser development should be considered in the same light as REB's and cyclotron masers. The millimeter laser systems presently in existence are laboratory devices, and as such are large and delicate compared to the desired end source. The inherent frequency stability of lasers and their promise as dual mode IR/mm sources does make laser development work attractive. The magnetron tube is probably not a promising candidate for a millimeter source. Reflex klystrons and Gunn diodes are both too low in power to be effective mm wave transmitter sources, but both may function well as local oscillators, both in receivers, and for phase control of the more powerful tubes. InP technology needs support to allow it to develop to level comparable to GaAs in technology.

In sum, then, near term (next seven years) systems must use either the Impatt diode (if size and weight are the dominant factor) or one of three tube sources, TWT, BWO, or EIO, if coherent operation and power output are the most important factors. The relativistic electron beam devices, cyclotron resonance tubes and OPM lasers are promising sources for future systems. Careful consideration should be given to funding development on these devices and work for future (fifteen years) systems. Critical areas which should be addressed immediately for near term systems include:

- Doppler potential of Impatts.
- Phase noise control of BWO's and EIO's.
- Development of small rugged power supplies for mm tube sources.
- Development of improved InP devices.

Current development of mm systems at 94 GHz is especially promising, since the component technology is mature at that frequency. Operation at 220 GHz (and higher) is especially desirable in some applications since the narrow beam capability would give such a system many of the advantages of a laser system. The beginning of a component technology exists at 220 GHz, while there is none at shorter wavelengths. Therefore, the most promising frequencies for current development from a source viewpoint are 94 GHz, 140 GHz, and 220 GHz, and the most promising devices for near *term* systems are Impatts, TWT's (94 GHz), EIO's, BWO's and gyrotrons (at 220 GHz).

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