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Submillimeter Local Oscillators for Spaceborne Heterodyne Applications

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I. INTRODUCTION

A. General Overview

The scientific mission of the Large Deployable Reflector (LDR), as currently conceived [Hollenbach, 1982], requires a detection capability in the submillimeter (300-3000 GHz) with ultra-high resolving power ($R=10^6-10^7$) over at least portions of this band. While submillimeter heterodyne detection capability is pivotal to fulfilling this requirement, such a technology has yet to be proven in space, and indeed, will require intensive development before sensors appropriate to LDR requirements can be identified.

This report addresses the particular issues of submillimeter (SMMW) heterodyne technology connected with the generation of local oscillator (LO) power over the spectral region of interest. It constitutes one section of an overall study of submillimeter heterodyne technology being conducted by NASA/Goddard at the request of the LDR Study Office at NASA/Ames.

Local oscillator power requirements are currently perceived to be in the range of 1mW using cooled GaAs Schottky mixers with broadband quasi-optical coupling, $\sim 50\mu W$ using narrowband waveguide matching, and $\sim$nW in those portions of the spectrum where superconductor-insulator-superconductor (SIS) junctions can be used as mixers. Heterodyne mixer arrays will require proportionately more LO power scaled commensurately with achievable coupling efficiency.

Medium-term prospects will be identified for a range of candidate coherent source technologies currently in varying stages of development. Our objective is to define the theoretical limitations inherent in each technology and to assess the prospects for overcoming technological impediments to advancing the state-of-the-art performance of each.The technologies listed in Table I will be compared in terms of the following criteria for receiver implementation:

LO ASSESSMENT CRITERIA FOR LDR APPLICATION

Frequency	
Linewidth	
Tunability	
Power Output	
Size, Weight	Maturity of Technology
Cryogen Requirements	
Power Efficiency	
Lifetime	
Radiation Hardness	

By comparing existing and prospective technologies on the basis of a review of the technical literature and the responses to a 1983-84 mail survey of active researchers in the field, recommendations will be advanced as to "best bet" technologies and suggested directions for further development so that viable submillimeter receivers will be available for space application in the 1990's.

TABLE I. SMMW LOCAL OSCILLATOR SOURCE TECHNOLOGIES

Primary Sources

Bulk Semiconductor:	Gunn Oscillator, Solid State Gyrotron
Semiconductor Homojunction:	IMPATT, Tunnel Diode
Semiconductor Heterostructure:	Quantum Well Device, Real-Space Transfer Device, Recombination Laser
Superlattice:	Bloch Oscillator
Josephson Point-Contact Junction:	Tunneling Oscillator, Cooper-pair Recombination Laser
Long Josephson Junction:	Fluxon Oscillator
Plasma Tube:	Free Electron Laser, Gyrotron, Orotron, Carcinotron

Frequency Conversion Sources

Solid State:	Varactor, Schottky Diodes, Non-Linear Crystals
Gas:	Optically Pumped Lasers

Self-Oscillating Mixers

Josephson Junction, SQUID, Quantum Well

B. Scope of the Report

The submillimeter has been called "the gap" in the electromagnetic spectrum in that SMMW technology has been slow to evolve, probably because it does not lie within the purview of any traditional discipline such as the "microwave" or "infrared" technologies which straddle it. Any solutions to the problems of SMMW instrumentation necessarily bridge the traditional disciplines. This report will survey, in effect, the prospects for extending optical sources to longer wavelengths and RF sources to higher frequencies. We will include concepts proposed in the open literature (but, as yet, undemonstrated) if the technological advances called for appear reasonable, given adequate support, within a 10 year time frame. As an example of a consideration outside the scope of this report, the search for and development of new materials, semiconductor alloys, etc., which possess particular properties, have traditionally taken much longer periods of time and scope of effort than are practical for the LDR application alone.

One further limitation is to SMMW sources which emit or are theoretically capable of emitting continuous wave (CW) radiation. This is because the sensitivity requirement of the astronomical application demands long observation times and a high degree of amplitude and frequency stability.

C. Surveys of Technologies Germane to the SMMW LO

The surveying of technologies has become a popular sport in the scientific community. Solymar [1972] even undertook an exhaustive review of the surveys in the field of superconductor junctions, categorizing them from highbrow to lowbrow. A number of surveys of technologies germane to the SMMW source question which have been particularly useful in this study are listed below, with a cutoff of about one decade's vintage:

1. Martin and Mizumo [1976], a survey of SMMW coherent sources with a particular emphasis on local-oscillator-type applications (considering power and linewidth criteria). While a number of technologies have either evolved significantly or emerged since that writing, the thrust of the review is still highly germaine to the LDR problem.

2. Solymar [1972] - SIS, Josephson junctions

3. Barone and Paterno [1982] - Josephson junctions

4. DeLucia, Herbst, Feld and Happer [1981] - basic mechanisms of gas-phase systems from which SMMW quanta could be extracted; it is to be hoped that a similar, interdisciplinary and broad-horizoned view be taken of the other approaches; much of this survey is outside the scope of this study since we will strive not to stray too far afield of extant technologies.

5. Button [1981, 1983] - volumes 1 and 7 of the series, Infrared and Millimeter Waves, are devoted entirely to reviews of submillimeter source technology. To cite several particularly general reviews:

a. Hirshfield [1979] - gyrotrons
b. Granatstein, Read and Barnett [1982] gyrotrons
c. DeTemple and Danielwicz [1983] optically pumped lasers
d. Bicanic [1983] tunable sideband generation
e. Nishizawa and Suto [1983] semiconductor lasers
f. Wortman and Leavitt [1983] orotron
g. Kantorowicz and Palluel [1979] - backward-wave oscillators

6. Wilson [1983] - a review of the state-of-the-art of SMMW receiver technology.

II. FUNDAMENTAL CONSIDERATIONS

In this report we survey the technologies considered for generation of local oscillator power in the 300-3000 GHz range. The limits to their power output vs. frequency as well as their emission linewidth and ultimate volume and thermal constraints derive from the physical mechanisms underlying their operation.

The predicted limitations necessarily reflect the degree to which a system is understood and characterized; often, initial estimates are shown to be unrealistic as more sophisticated analyses evolve.

A. Mechanisms of Primary Sources

It should be useful to classify the primary sources of coherent SMMW radiation (at this point we exclude passive nonlinear media of any sort in which a coherent AC field or multiple fields interact to generate another) according to three general mechanisms by which an electromagnetic field (in predominantly one mode) is generated:

1. Negative Dynamic Resistance (NDR) Devices
2. Stimulated Emission and Vortex Flow Devices
3. Electron-Beam Devices

This categorization is according to "scale", in a thermodynamic sense; in (2), the most fundamental scale of interaction is a small subsystem two of whose energy states are separated by a single quantum of the e-m field; upon occurence of a transition between the states the occupation number of the field mode changes by unity; in (1), it is a current of many electrons, a macroscopic variable, which is caused to vary sinusoidally in amplitude; (3) describes an entire class of interactions in which a beam of electrons and an oscillating electromagnetic field are coupled by any of a number of mechanisms described, in the semi-classical limit, by the relativistic Maxwell Equations. These mechanisms include single-electron as well as collective modes of interaction.

We now provide examples of devices, realized or proposed, which fall into each of these categories:

1. Negative Dynamic Resistance

    (a) Transferred-electron (TE) devices

        (1) k-space transfer (Gunn)
        (2) real-space transfer in heterojunctions

    (b) Transit-Time devices

    (c) Tunneling devices

        (1) semiconductor homojunction
        (2) quantum well heterojunction devices
        (3) superlattice Bloch oscillators
        (4) Josephson tunneling devices

2. Stimulated Emission and Vortex Flow

    (a) Semiconductor recombination lasers
    (b) Gas-phase lasers

        (1) Molecular
        (2) Atomic-Rydberg State

    (c) Resonant fluxon propagation Josephson junctions

3. Electron Beam Devices

    (a) Carcinotron
    (b) Free Electron Laser (FEL)

SUBMILLIMETER PRIMARY SOURCE LOCAL OSCILLATOR
MECHANISM/TECHNOLOGY MATRIX

	Bulk Semicon.	Semiconductor Homojunction	Semiconductor Heterostructure	Super-Lattice	Josephson		Plasma Tube
Negative Dynamic Resistance	Gunn	IMPATT Tunnel Diode	Quantum Well Real-space transfer	Bloch Oscillator	J-J Tunneling Oscillator		
Stimulated Emission and Vortex Flow			Recombination Laser		Recom. Laser	Fluxon Device	
Electron Beam	Solid State Gyrotron			Super-lattice FEL			Carcinotron FEL gyrotron orotron

(1) Electron Cyclotron Maser (ECM) - gyrotron
(2) Smith-Purcell FEL - orotron, ledatron
(3) Coherent Cerenkov radiation
(4) Magnetic bremsstrahlung FEL

(c) Solid State Gyrotron
(d) Superlattice "free-electron-laser" [Gover and Yariv, 1975]

Note that in this categorization there is no implication of a quantum- to classical- limit transition. On the contrary, in (1) where the SMMW oscillation derives from a coherent variation in amplitude of a macroscopic current of electrons, the negative dynamic resistance depends on the patently quantum-mechanical band structure of the medium or the junction.

B. DC to AC Power Conversion

Having arranged the viable or potentially viable SMMW oscillator devices according to a scheme of underlying mechanisms, it becomes apparent that all involve the conversion of the kinetic energy of moving electrons to radiative energy in the SMMW electromagnetic field. The exceptions to this rule are the lasers, molecular and atomic, for which no energy deposition mechanism has been specified a priori and for which De Lucia, et al., [1981] have thoroughly analyzed the following excitation schemes:

1. Physical separation of states in a molecular beam
2. Optical pumping
3. Vibrational energy transfer
4. Chemical Excitation
5. Direct electron excitation
6. Gas dynamic excitation

In this sense, the optically pumped molecular laser is more rightly considered under the heading of Secondary, or Frequency Conversion Sources, since the pumping radiation is, itself, coherent.

It bears saying at this point that, while other excitation schemes for primary SMMW sources are not impossible (pumped by incoherent light, or by some thermal process, etc.), these are beyond the scope of this survey for the reason that they have not, to our knowledge, even been proposed, let alone advocated, and are thus not in the purview of a consideration of technologies viable for implementation within the next decade.

We now procede to say a few words about considerations which are germane to entire classes of devices.

The SMMW output which is of consequence to a local oscillator application is, of course, the power which can effectively be coupled to the mixer. Thus, a generic issue common to all oscillator devices is the design of an embedding circuit in which losses are minimized and impedance-matching to the device optimized. The design of circuits in this frequency range is an art largely in its infancy, with laws for scaling from lower frequencies poorly understood. The embedding circuit ought not to limit the bandwidth of operation unduly and must be free of unwanted resonances.

A further limitation is imposed by the device capacitance, C_d, which, coupled with the inherent series resistance, R_s, imposes a high-frequency roll-off of the power which can be coupled out of the device.

Finally, in the case of tunneling devices, a limit on the thickness of the device is imposed by the requirement that the electron wave function maintain coherence through the tunneling region, i.e., the electron must not be scattered due to collisions. This, in turn, limits the degree to which C_d can be reduced.

III. SOLID STATE BULK OSCILLATORS

A. k-Space Transferred-Electron Devices

While other mechanisms give rise to negative resistivity in bulk semiconductors [Sze, 1981, page 639], the process with relaxation times sufficiently fast to be useful in high frequency microwave oscillators is that of k-space electron transfer, the so-called Ridley-Watkins-Hilsum effect or Gunn effect. This effect hinges upon the existence of multiple valleys in the conduction band of a semiconductor, with an energetically higher-lying valley characterized by a lower electron mobility. As electrons are heated by falling through the potential across the crystal, they tend to scatter into the upper valley states giving rise to a lower average electron drift velocity and thus lower current. There are thus regimes where the device may be biased so that a positive incremental voltage results in a decreased current.

This mechanism is utilized in a number of modes for microwave generation in a tuned circuit [Sze, 1981, pp.651ff] and the operating frequency need not be limited by the transit-time across the device. On the other hand, an upper frequency limit is ultimately driven by material parameters, namely the maximum rate at which electrons are scattered between the lower and upper valleys. A thorough analysis (using Monte Carlo calculations) of the effects of material parameters in semiconductors comprised of group -III and -V elements (of which GaAs and InP have proven useful in oscillators) has been presented by Ridley, 1977. The conclusion, as shown in Figure III.1, is a calculated cutoff frequency, above which efficiency would drop precipitously, which lies in the 10-100 GHz range.

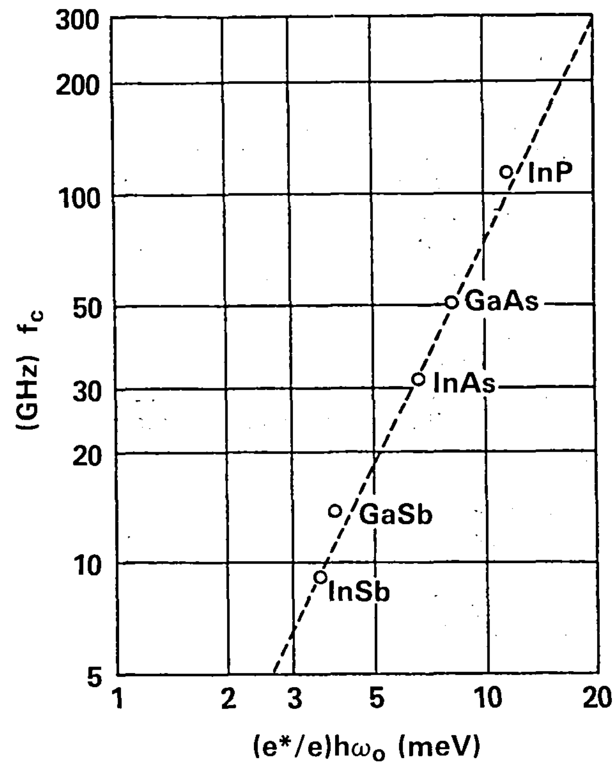


Figure III.1.
[Ridley, 1977]

GaAs Gunn devices are available which deliver 20mW at 95GHz and are attractive as sources for their tunability with bias current and cavity parameters as well as their low noise characteristics. InP Gunn devices producing 30-40mW at 95 GHz are also being manufactured. However, barring development of materials with suitable two-valley properties and, additionally, significantly shorter relaxation times, there are no prospects for extending the Gunn technology into the SMMW without efficient harmonic upconversion in an external device.

B. Solid State Gyrotrons

A. K. Ganguli and K. R. Chu [1978] examined the theoretical possibility of constructing a cyclotron maser based on the velocity dependence of the effective mass (band nonparabolicity) of an electron in the conduction band of a semiconductor. The mechanism for extracting energy from the transverse gyromotion of electrons in a magnetic field is, essentially, that of the free electron gyrotron, discussed more fully in Section VIII.C., below. But in this case, the role of the relativistically varying mass of the free electron is played by the effective mass of the conduction band electrons which may be much smaller than the electron rest mass, m_e. The device implication is that the magnetic field requirement is vastly reduced and Larmor frequencies in the SMMW using permanent rather than superconducting magnets become plausible.

In their analysis, Ganguli and Chu considered an InSb medium, in which the electron effective rest mass: $m_o^* = .0145\ m_e$. The effective mass, m^*, varies with electron velocity, v, as:

$$m^* = m_o^* \ (1 - v^2/v_g^{\ 2})^{-1/2} \qquad \text{(III.B.1)}$$

for $v \ll v_g = (E_g/2m_o^*)^{1/2}$; E_g = band gap energy.

This implies a required magnetic field of five kilogauss for an electron gyrofrequency of 1 THz. By invoking the threshold power requirement for oscillation as derived for the free electron gyrotron, a product of this threshold times cavity Q of $\sim$mW for electron energies $\sim 10^{-3}$eV, and an estimated Q ~ 100 would place such a device in a regime of utility for spaceborne local oscillator applications.

This technology is, however, yet to be demonstrated. The most serious obstacle appears to be that electron collisions do not allow for the phase bunching required for coherent energy transfer to the EM field. The dimension of the semiconductor parallel to the longitudinal motion of the electron beam must be shorter than the electron mean free path in the medium. The question of whether a sufficiently long mean free path is technologically or even theoretically possible in a low -m* material is currently under study [Granatstein, 1984]. It is believed that a length of $\sim 10\mu$m would be required for oscillation.

This is derived from the condition that the fractional energy, F, transferred from the beam to the field during the transit time, t, must satisfy:

$$F > \omega t/Q. \qquad \text{(III.B.2)}$$

Since the length of the medium will necessarily be much shorter than the wavelength of the oscillation, the problem of an imbedding cavity will have to be addressed.

A mechanism using stimulated transitions between Landau levels in an InSb crystal as a maser amplification device for submillimeter waves, proposed by P.A. Wolff [1964], is subject to similar caveats.

IV. SEMICONDUCTOR HOMOJUNCTION DEVICES

A. Transit-Time Diodes

The class of negative resistance devices in which the 180-degree lag of the current with respect to the applied potential is derived by the drift of one species of charge carrier across a drift region is in common use for power generation in the millimeter regime and has received considerable attention in certain quarters for possible application up to 1 THz. This mode of operation can be accomplished in a variety of structures which differ in the manner in which carriers are injected into the drift region. A representative device is the impact ionization avalanche transit time (IMPATT) diode implemented in the Read diode structure shown in Figure IV.1.

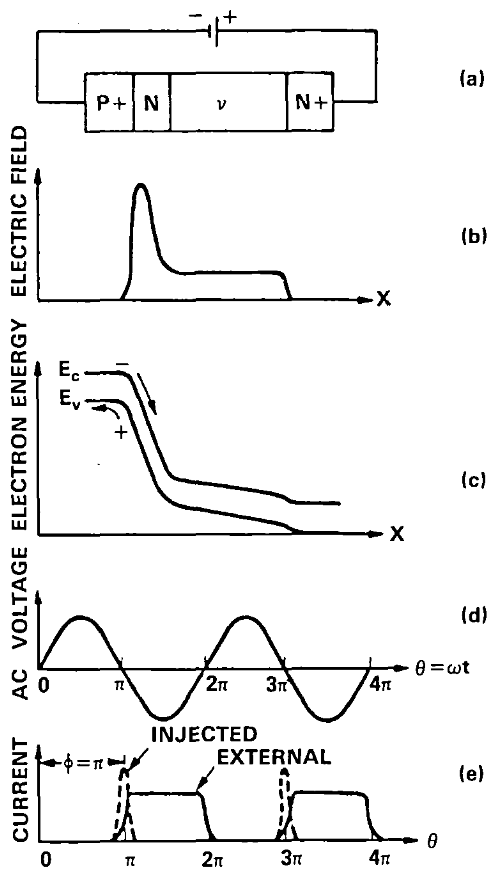


Figure IV.1
[Sze, 1981]

The heavily doped external layers, in silicon, say, allow ohmic contact to the external circuit. Under reverse bias, the electric field is sharply peaked at the junction between the heavily doped p-region and the moderately doped n-region. Impact ionization of atoms occurs in this region as the applied potential swings in the direction of increasing negative bias. Avalanche breakdown results in a burst of generated charge carriers; the holes are collected at the p+ contact while the electrons drift across the intrinsic (ν) region at the saturation drift velocity. The current vs. voltage phase delay is a combination of the avalanche delay ($\sim 90°$) and the delay due to transit time across the drift region.

The drawbacks to the IMPATT as local oscillator are two and they are severe: since the current due to an avalanche process is both pulsed and statistical in nature, IMPATTs tend to be far too noisy for LO applications. Furthermore, the combined limitations of the breakdown voltage and saturation velocity in a particular semiconductor material lead [see Sze, 1981] to a $1/f^2$ frequency dependence of extractable power. This is borne out in the empirical data of Figure IV.2.

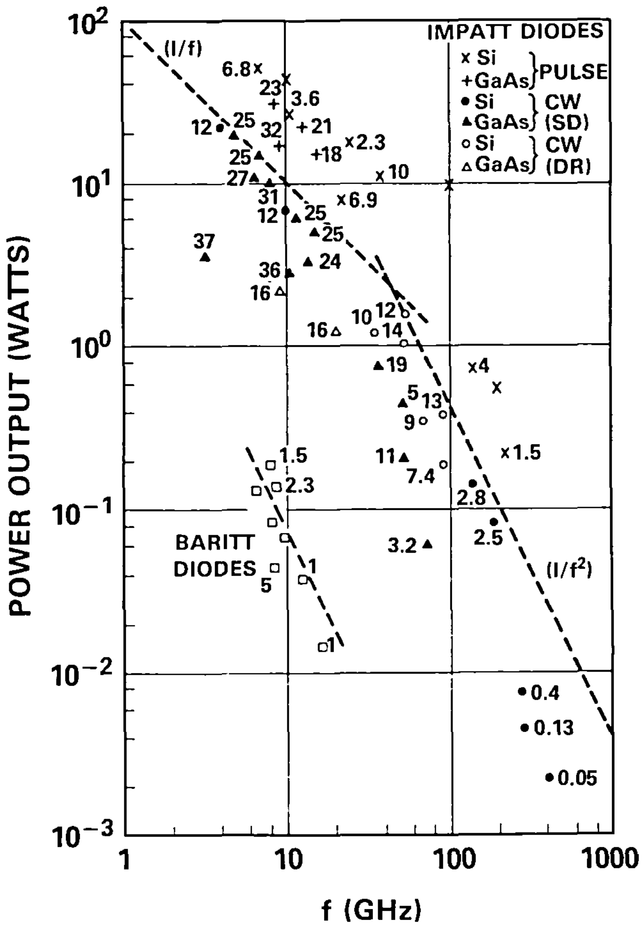


Figure IV.2
[Sze, 1981]

Barrier injection transit time (BARITT) diodes, in which carriers are thermionically injected, are much less noisy devices than the IMPATT but are not useful in our frequency regime.

In the TUNNETT (tunnel injection transit time) diode depicted in Figure IV.3, current is generated by means of electron tunneling from the valence band of the heavily-doped p+ region to the conduction band of the heavily-doped n+ region.

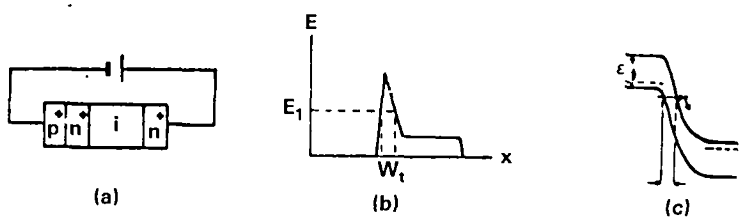


Figure IV.3.
[Nishizawa, 1982]

While such a device was first fabricated in 1968 and while operation to 1 THz has been predicted [Nishizawa, 1982], cw operation, even at low frequencies, has yet to be achieved. Serious device fabrication problems having to do, for one thing, with impurities in the drift region, have precluded predicted performance. The mechanism is inherently low-noise, so the prospect of a solid-state fundamental LO source is tantalizing. A hybrid mode diode, the MITATT, was demonstrated in cw operation at 150 GHz by Elta, et al., 1980.

B. Submillimeter Three-Terminal Devices

A device variously called a permeable base transistor [Bozler and Alley, 1980] or static induction transistor [Nishizawa, 1982, and references therein] has been posited to be applicable as a low noise oscillator to 1 THz. This structure has been realized using the latest GaAs crystal growth and X-ray lithographic techniques, and operation at 17 GHz has been demonstrated [Bozler and Alley, 1980]. The development of this device is just beginning, and technological impediments appear formidable.

V. SEMICONDUCTOR HETEROSTRUCTURE DEVICES

A. Quantum Well Tunneling Devices

Early work by Tsu and Esaki [1973] demonstrated that alternating layers of GaAs and $Ga_{1-x}Al_xAs$ can be grown with thicknesses less than 100 Å which exhibit the quantum mechanical tunneling behavior to be expected of a one dimensional periodic potential. Both the theory and fabrication technology (primarily using molecular beam epitaxial growth techniques) of such structures have progressed rapidly during the past decade as the vast potential applications of a "tailorable" artificial lattice are appreciated.

By judicious choice of the barrier height (by means of the ternary alloy composition) and well thickness in the single well structure shown in Figure V.1, the Schroedinger equation for a particle in the well admits of one or more bound state resonances. The probability of an electron injected at the left tunneling through the structure is enhanced when the electron energy is resonant with the quantum well bound state.

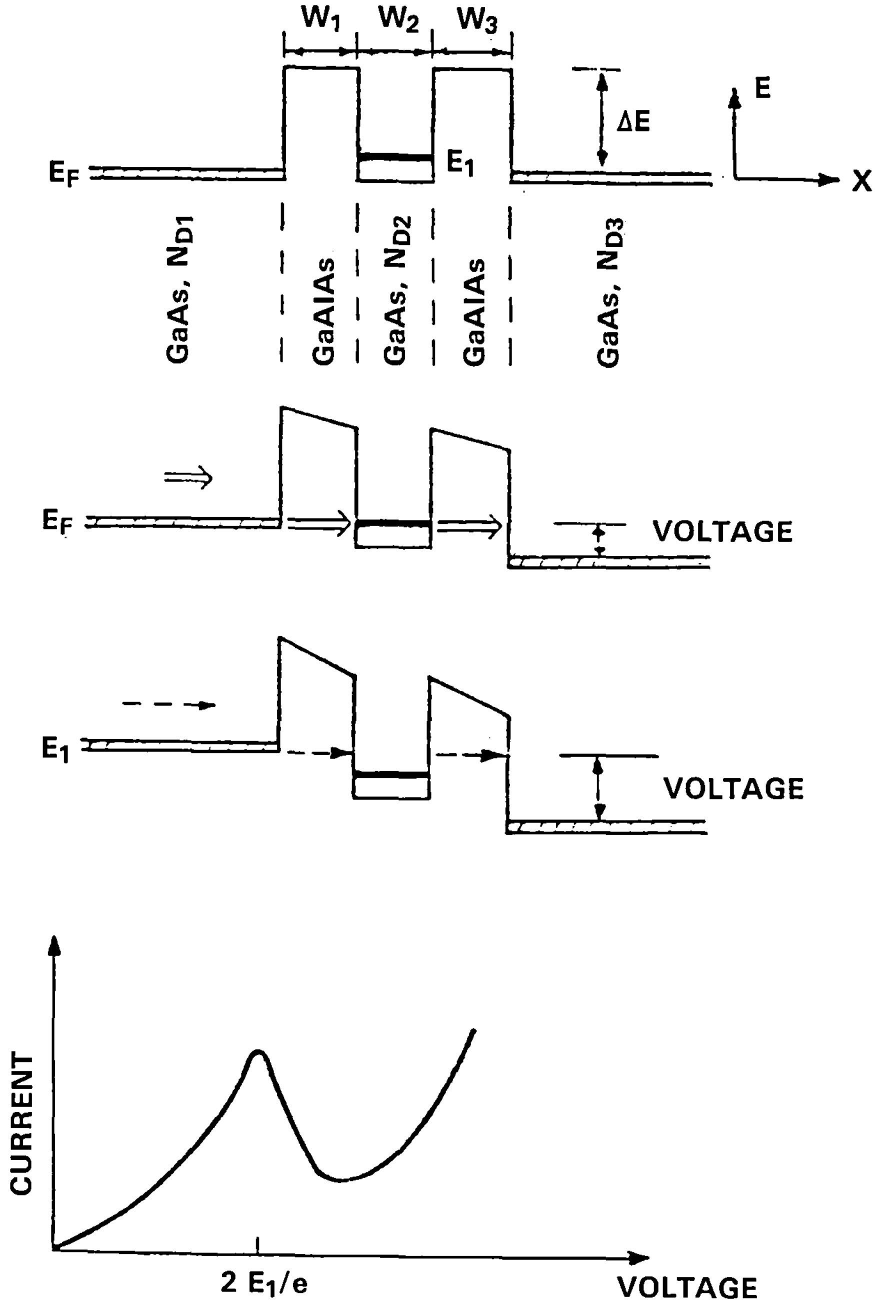


Figure V.1.
[Sollner, et al., 1983]

The net current through the structure is obtained by integrating the tunneling probability vs. electron energy over the Fermi distribution of electron energies in the injection layer. The relative energy of the bound state resonance in the well is varied as a potential is applied across the structure, as shown in Figure V.1.

Sollner, et al. [1983] demonstrated the resonant tunneling effect in a room temperature single well structure. Using the parameters of their quantum well structure, the transmission probability (showing two resonances) and current density vs. applied potential were calculated as shown in Figures V.2 and V.3, in the zero temperature limit.

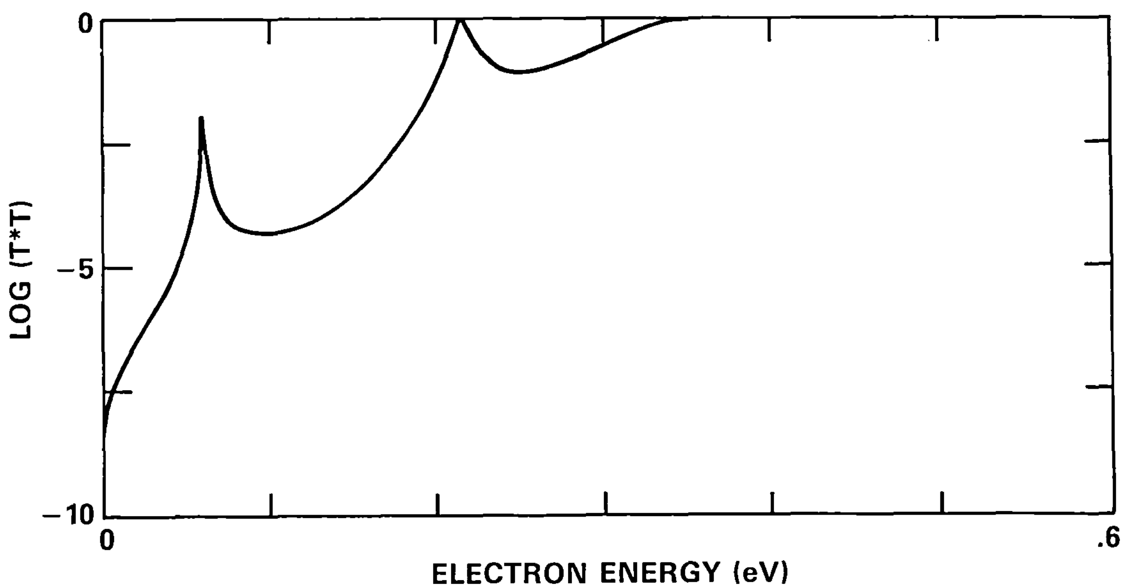


Figure V.2.

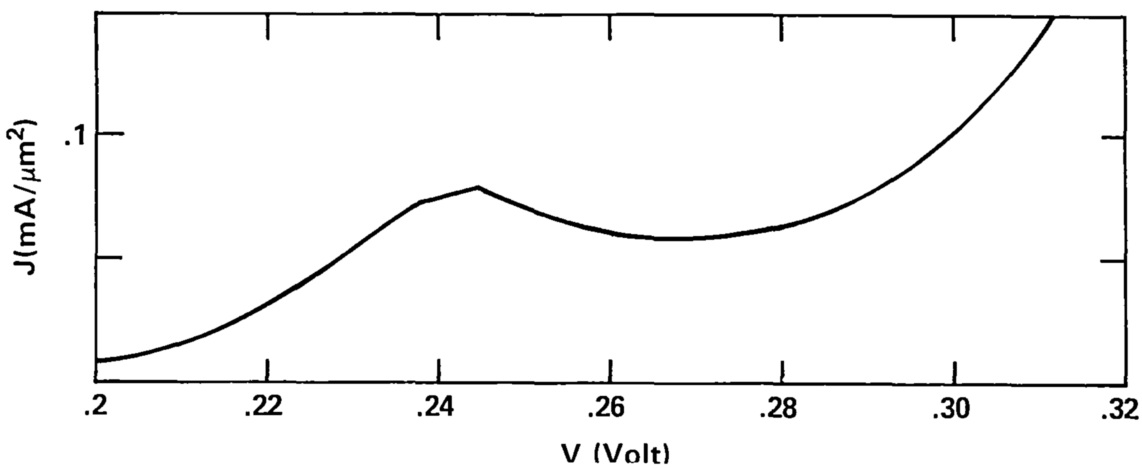


Figure V.3.

It is clear from Figure V.3 that a regime of negative resistance exists in the I-V curve of the device, as was observed by Sollner, et al. at low temperatures. It must be said, however, that the quantum mechanical model applied to the calculation was of the most primitive sort in that abrupt barriers were assumed and the effects of band bending neglected.

The experiment of Sollner, et al., substantiated that their device could be used for heterodyne mixing up to 2.5 THz, thus allowing charge transport times faster than 10^{-13}s to be inferred.

Much research has to be done on very fundamental aspects of this technology. It is unclear how the device capacitance can be significantly reduced, since series configuration of multiple wells will eventually exceed the mean free path of the tunneling electrons. Optimization of materials and structures for particular applications, even under naive theoretical assumptions, is just beginning.

Sollner, et al., proposes the application of a quantum well heterostructure device to SMM oscillator applications and are currently studying the design of such a device. An estimate of extractable power, from a structure such as the one in which they demonstrated mixing, is microwatt, based on a circuit model such as applied to a negative resistance device by Sterzer, 1964.

B. Real-space Transfer Devices

The operation of the real-space transfer device hinges on the transfer of heated electrons to a regime of lower mobility giving rise, as in the Gunn device (see Section III.A., above) to negative resistance. The distinction lies in the fact that the transfer occurs not through scattering into higher-lying states of the same material, but by via diffusion in real space across a heterojunction into a material of lower bulk mobility. This effect was first proposed in 1979 [Hess, et al., 1979] and has since been demonstrated to give rise to oscillations when a three-layer heterostructure was incorporated in an LC circuit tuned to 25 MHz [Coleman et al., 1982].

The device reported by Coleman, et al. is comprised of alternating layers of GaAs, 1000Å wide, and n-doped $Al_xGa_{1-x}As$ (x = 0.2), 250Å wide. An electric field is applied parallel to the junctions between electrodes spaced 50μm apart, as shown schematically in Figure V.4.

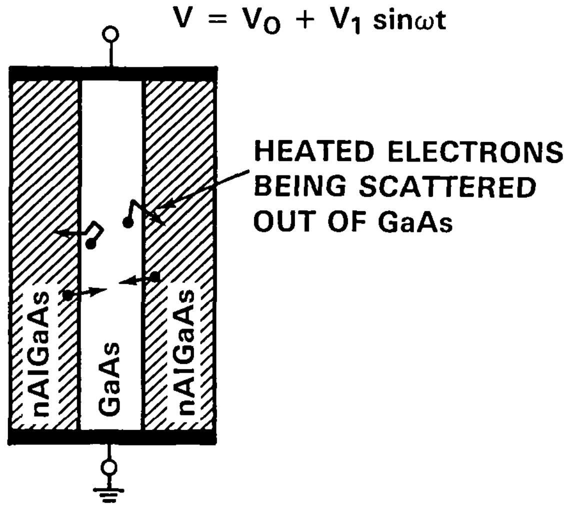


Figure V.4.
[Coleman, et al., 1982]

The principle of operation is that the high mobility of GaAs (enhanced by an undoped AlGaAs buffer) ($\gtrsim 5000$ cm^2/V-s) accounts for the current flow at low electric fields. Under high electric fields, however, thermonic emission of the hot high-mobility electrons into the AlGaAs region, where their mobility is an order of magnitude lower, results in negative resistance. This results in current 180° out of phase with the applied voltage and, thus, in oscillation.

The status of this device is that oscillation up to 1 GHz [Coleman, 1984] has been observed and tentatively attributed to this effect. Much basic research is required before the actual relaxation and transport properties are sufficiently well understood to make intelligent predictions of frequency and power limitations. It has been suggested [Hess, et al., 1979] that the frequency limitation is the time required for the cooled electrons to fall back to the high-mobility (GaAs) layer and this is estimated to be on the order of $< 10^{-11}$s. This estimate would place the high frequency limit within our region of interest.

Work has not begun on consideration of optimizing geometries, materials, and temperature regimes for particular applications. The generic problem of imbedding-circuit design, common to all solid-state devices, has not been addressed and it is too soon to speculate how the power output of 32mW, quasi-CW, at 25MHz will scale with increased frequency. The question of how many heterojunctions may be driven in parallel (maintaining a constant RC product, it would seem) has also not been addressed.

C. Recombination Lasers

Stimulated emission due to population inversion between energy bands of semiconductors is the mechanism responsible for infrared light generation at .8μm in the GaAs diode lasers which are the most widely used lasers at this time. The inversion is produced by injection of minority carriers into a p-n junction which recombine with the majority carriers giving rise to radiative transitions. This mechanism implies direct radiative recombination across the energy gap and is thus limited in wavelength by how small a band gap is available. Wavelengths out to $\sim 30\mu$m are attained in $Pb_{1-x}Sn_xTe$, cooled to liquid helium temperatures. Longer wavelength emission would require transitions between donor and acceptor levels and the valence band in doped semiconductors. Such radiation has been observed [Gornik, 1972] but research over the course of the last 20 years gives scant reason for hope of a practical technology in the medium term.

VI. JOSEPHSON POINT-CONTACT JUNCTIONS

A. Phenemenology

A tunneling structure comprised of layers of superconductor-barrier-superconductor has been known, since 1960, to exhibit highly nonlinear behavior which has found a variety of applications including high frequency generation and mixing. The following review of the Josephson phenomenon follows the exposition and notation of Barone and Paterno [1982] who summarize the theoretical and experimental work in the field over the past two decades.

A superconductor is characterized as a macroscopic Fermion ground state: all the condensed electron-hole pairs are at the Fermi level and a minimum threshold energy, ϵ, is required for an excitation (creation of an electron-hole Cooper pair). Let ψ_L and ψ_R be the pair wave functions in the superconductors on either side of a thin tunneling barrier. In particular, let:

$$\psi_j \equiv \rho_j^{\frac{1}{2}} e^{i\varphi_j}, \; j = L,R \qquad \text{(VI.A.1)}$$

where ρ_j is the Cooper pair density.

The Schroedinger equation,

$$i\hbar|\dot{\psi}\rangle = \mathcal{H}|\psi\rangle \;, \qquad \text{(VI.A.2)}$$

with an applied potential, V, across the junction. leads to, for example:

$$i\hbar\,\dot{\psi}_R = -eV\,\psi_R + K\,\psi_L, \qquad \text{(VI.A.3)}$$

where K is the coupling amplitude associated with the interaction (tunneling) component of the Hamiltonian. Solving the resulting time-dependent equations simultaneously, with the assumption of a constant pair density ρ_1, the pair <u>current</u> density,

$$j = \dot{\rho}_L = -\dot{\rho}_R , \qquad \text{(VI.A.4)}$$

which is not zero by virtue of current in an external circuit replacing pairs which tunnel across the barrier, becomes:

$$J = J_1 \sin \varphi , \qquad \text{(VI.A.5)}$$

where $J_1 \equiv {}^{2K}/\hbar\rho_1$; $\varphi \equiv \varphi_L - \varphi_R$.

Solving for the phase leads to $\dot{\varphi} = 2eV/\hbar$, and, thus, to a sinusoidal current for an applied DC voltage:

$$J = J_1 \sin (\varphi_o + 2eVt/\hbar). \qquad \text{(VI.A.6)}$$

This depicts the so-called <u>AC Josephson effect</u>. Since φ_o is not necessarily zero, supercurrents $< J_1$ arise for V = 0 (DC Josephson effect). Inclusion of the magnetic field dependence:

$$\partial\varphi/\partial x = 2eH_y d, \qquad \text{(VI.A.7)}$$

where $d \equiv \lambda_L + \lambda_R + t$;

λ_i = Landau depths;

t = barrier thickness,

leads to a spatial distribution of the current, and, in particular, to confinement of the DC Josephson currents to a depth of:

$$\lambda_j = (\hbar c^2/8\pi edJ_1)^{\frac{1}{2}}, \qquad \text{(VI.A.8)}$$

the Josephson penetration depth.

The behavior which has been described gives rise to a highly nonlinear I-V curve shown in Figure VI.1, reputedly "the greatest nonlinearity in nature." This accounts for the demonstrated superior performance of SIS mixers at 115 GHz [S.-K. Pan. et al., 1983] and 450 GHz [Blaney, et al., 1982].

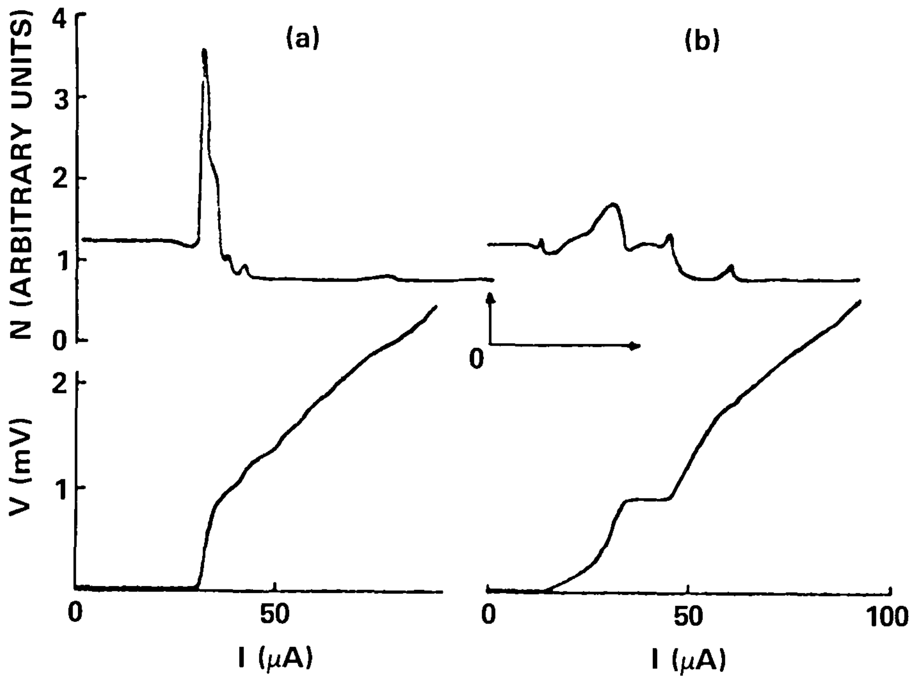


Figure VI.1. [Blaney, et al., 1982]
450-GHz Point-Contact SIS Mixer.

It might be expected that internal absorption (breaking Cooper pairs and forming free electrons) would mitigate against operation at frequencies above the energy gap, though the precise rolloff has not been determined empirically.

B. Short Junction Oscillators

A great deal of research has gone into the development of Josephson junctions of varying geometries and these are summarized by Barone and Paterno [1982]. For our purposes, these can be broadly grouped as "short" or "long" junctions according to whether the length of the junction is less than or much greater than the Josephson penetration depth. The representative technology involves the desposition of a layer of superconducting metal, formation of a thin oxide layer of the metal, followed by deposition of a point contact of the same or another superconducting metal.

The study of oscillations in short Josephson junctions has been limited, primarily, to frequencies below 20 GHz and has been characterized by power output $< 10^{-9}$W and large ($\sim$GHz) linewidths for devices with dynamical resistances greater than 1Ω [Vernet and Adde, 1971]. To our knowledge, the only evidence of oscillation at submillimeter frequencies has been indirect: by operation in a self-oscillating mixer mode.

Stimulated emission was suggested, though never confirmed, as responsible for radiation in a superconductor/normal metal structure [Leopold, 1969].

C. Josephson Self-Oscillating Mixer

An appealing alternative to supplying local oscillator power to the mixer from an external radiation source would be use of an internal oscillation of the mixer itself. This has been demonstrated at 891 GHz in a niobium point contact Josephson junction by Vernet, et al. [1977]. The major obstacle to this technology for heterodyne detection applications is the inherent linewidth of the internal LO which, in the Vernet experiment, was GHz. This linewidth is tantamount to phase noise which is due to low-frequency noise in the junction which frequency modulates the Josephson current. Vernet, et al., proposes a scheme for shunting the low frequency noise (which would be feasible if the IF were to be kept relatively high), though this concept has not been demonstrated, to our knowledge. The impedance matching problems presented by a shunted low impedance device are formidable.

A means of surmounting the inherent linewidth problem has been explored by Verschueren, et al. [1984]. A DC resistive superconducting quantum interference device (RSQUID) comprised of a thin niobium wire contacting two blobs of Pb-Sn solder attached to a piece of normal (resistive) metal provides inherently narrow-band internal oscillation up to 400 GHz. A linewidth of 100 kHz was observed and partially attributed to inadequate current stability in the external circuit. While "only" an experimental proof-of-concept, this appears to be a promising avenue of research. A major problem to be addressed is the efficient coupling of the external signal radiation into the junction.

VII. FLUXON OSCILLATORS

A. Phenomenology

The fundamental physics of a Josephson junction have been reviewed in Section VI. In a Josephson junction whose dimensions are comparable to, or greater than, the Josephson penetration depth (hundreds of microns), the self field due to the current flowing in the junction becomes significant. As shown in Barone and Paterno [1982], the electrodynamics of such a junction are described by a sine-Gordon equation of the form:

$$\phi_{xx} - \phi_{tt} = \sin\phi , \qquad \text{(VII.A.1)}$$

where x is the longitudinal dimension in units of the Josephson penetration depth, λ_j, t is a normalized time variable, and is either the phase difference, $\varphi = \varphi_L - \varphi_R$, or a normalized measure of the magnetic flux. There is a voluminous literature dealing with solutions to this equation (which is of considerable mathematical interest in its own right; see, for example [Scott, et al., 1976], [Enpuku, et al., 1980]); suffice it to say that the equation admits of traveling wave solutions which are solitons, i.e., "packets" of flux which maintain their profile on propagation. Similarly, given appropriate boundary conditions, bound-state oscillations are also possible: "fluxons" shuttling back and forth between the boundaries, either singly or in multiples. The fact that moving fluxons produce radiation has been invoked as a mechanism for the generation of submillimeter LO power.

B. Flux-Flow Device

The resonant-propagating flux flow mode in which the junction acts like an open-ended microwave cavity, has been investigated both theoretically and experimentally, and Erne' and Parmentier [1981a] conclude that "it would seem that the requirements for local oscillator power (a few nanowatts) [this assumes a SIS mixer] and linewidth (less than a few hundreds of kilohertz) might well be within the reach of Josephson junction fluxon oscillators." However, due to the resonant cavity nature of this phenomenon, operation above 100 GHz appears unlikely [Nagatsuma, et al., 1983], though operation in higher order longitudinal modes has not, to our knowledge, been investigated. Preliminary analysis has begun on the major problem of coupling such a device to an ionbedding circuit in order to extract the generated power [Erne and Parmentier, 1981b].

A flux-flow oscillator using unidirectional propagation of a vortex array along a long tunnel junction has recently been demonstrated to provide power up to 1 microwatt in the range between 100 and 400 GHz [Nagatsuma, et al., 1983]. It is suggested that operation up to the gap frequency in the lead-alloy superconductor might be possible but not observed due to the size-constrained frequency limitation on the integral SIS detector which was used. Nagatsuma, et al. [1983] surmounted the power coupling problem by fabricating both oscillator and detector on a single substrate as shown in Figure VII.1.

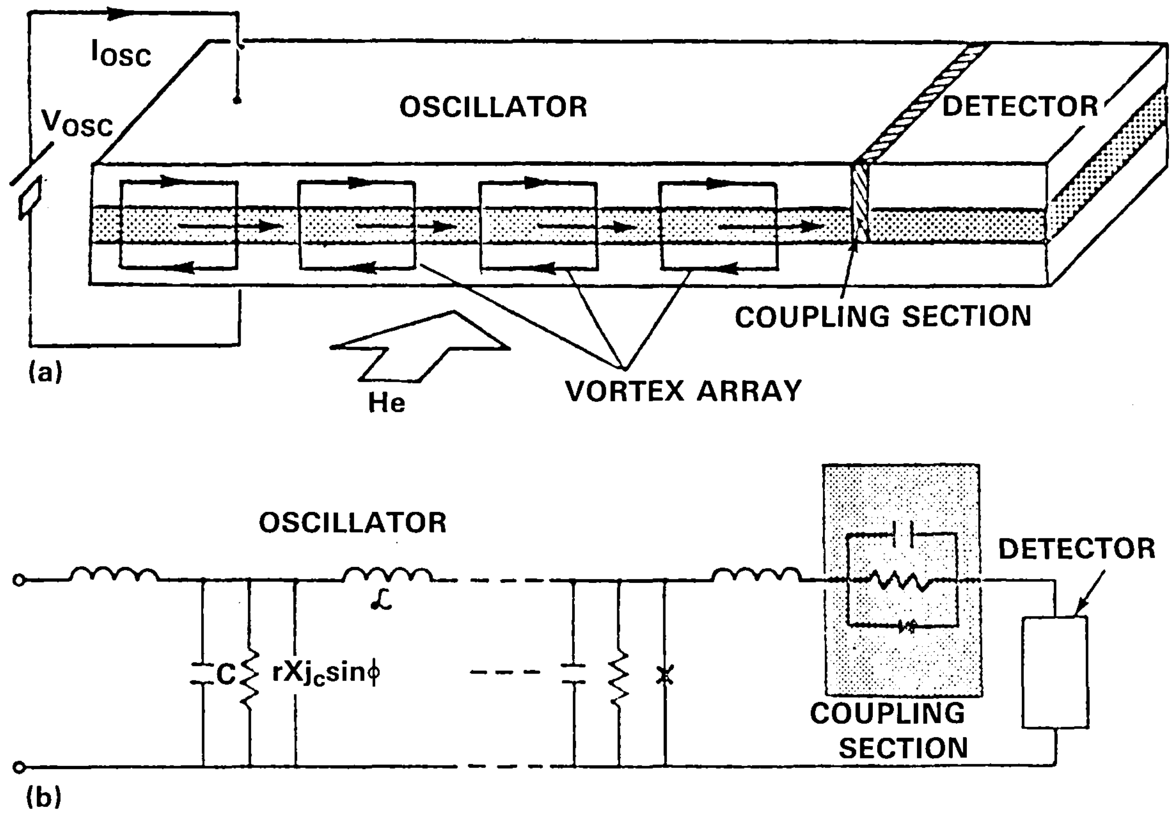


Figure VII.1.
[Nagatsuma, et al., 1983]

The circuit was fabricated using lead alloys deposited with a photolithographic liftoff process, with the barrier formed by RF plasma oxidation. Electro-magnetic coupling of the oscillator and detector sections is provided via an edge oxide section. Oscillation was detected by comparing the detector I-V curve under varying oscillator conditions.

It must be said that this is a complicated system, the understanding of which is at a very fundamental stage. The radiation power depends on the flux flow velocity which is, in turn, determined by both the bias voltage and the applied magnetic field. The emission linewidth question has not been addressed, nor is there an understanding of behavior to be expected as the energy gap ($\sim$1 THz) of the superconductor is approached. Fabrication processes for both soft metal alloy superconductors and the higher critical temperature (9.26°K) niobium technology are currently being developed and behavior under temperature cycling is being studied.

VIII. ELECTRON BEAM DEVICES

A. Carcinotrons

Coherent radiation sources based on the extraction of energy from an electron beam propagating in free space (i.e., a vacuum tube) can, generally, be divided into two classes: slow-wave periodic circuit devices, including the Carcinotron, Orotron and Ledatron, and devices based on relativistic electron effects, including the gyrotron and free electron laser.

The generation of submillimeter waves in a Carcinotron (tradename of Thomson-CSF for a high frequency backward-wave oscillator, BWO) is an extension of conventional microwave tube technology to higher frequencies. Technological impediments due to critical machining tolerances and surface quality as well as heat dissipation constraints have made scaling tube dimensions to shorter wavelengths a tortuous development process. Kantorowicz and Palluel [1979] cite an empirical power-frequency dependence of $1/f^4$, or worse, for tubes at these frequencies.

The principle of operation of the Carcinotron is the interaction of an electron beam, guided by means of an externally applied magnetic field through a slow-wave structure with transverse dimensions on the order of the emission wavelength. The slow-wave structure supports an RF electric field with a longitudinal component periodic in the direction of the beam propagation and a group velocity comparable to the velocity of the electrons in the beam. The interaction of the bunched electron beam with the field leads to a transfer of energy to the field. The ultimate frequency limitation arises due to the minimum dimension over which collective interaction of the beam dominates electron motion, i.e., the Debye length. The limit thus imposed, with available electron densities, is on the order of 3 THz [Mizuno and Ono, 1979] and applies equally to other slow-wave electron-tube devices.

In practice, operation to about 800 GHz has been achieved, with output power on the order of 1 mW. The development of higher power and higher frequency BWO's hinges upon methodically surmounting the following technological hurdles: development of fabrication techniques to overcome problems of circuit element surface quality on the scale of the skin depth at high frequencies and circuit period irregularities; design to improve heat dissipation capacity and thus tube lifetime; design to improve the monoenergetic character of the beam to reduce heat dissipation requirements.

As pointed out by Kosmahl [1982], the limits to this technology are not to be found in Maxwell's equations but rather in the state-of-the-art of device design, materials and fabrication techniques. A device similar to the commercially available device shown in Figure VIII-1. incorporates a permanent magnetic field of 8-9 kG, an accelerating potential of 10 kV, and delivers .25 mW output at .35 mm [Kantorowicz and Palluel, 1979]. The performance of a device based on the design proposed by Kosmahl [1982] has not, to our knowledge, yet been published.

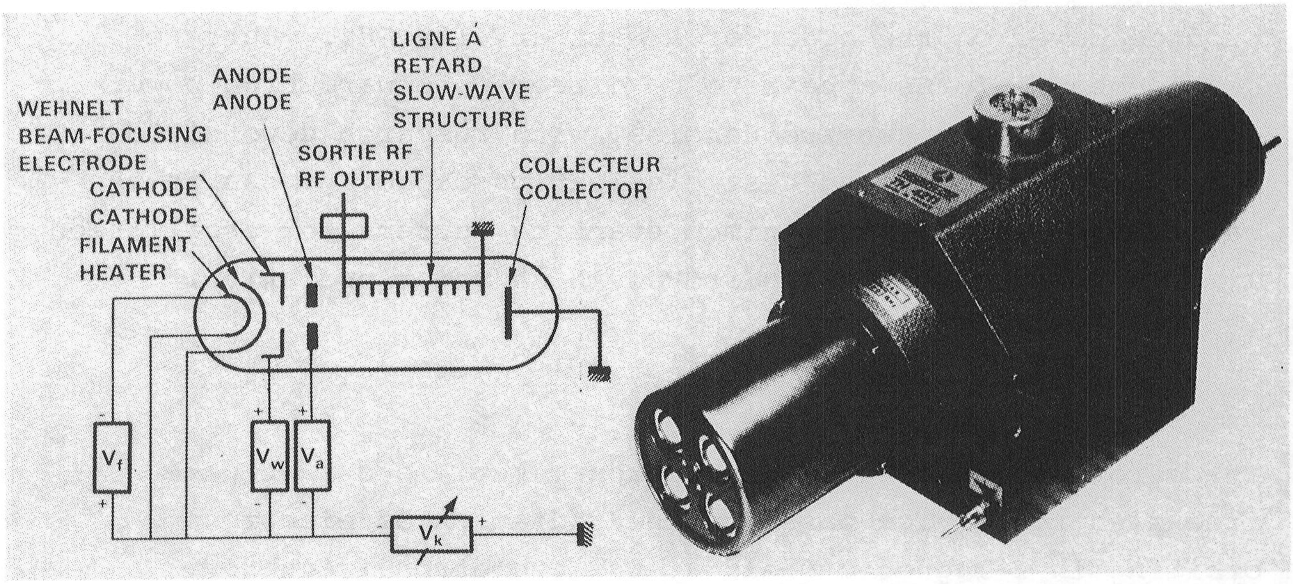


Figure VIII.1. [Thomson-CSF]

B. Orotron, Ledatron

Other configuration of slow-wave periodic circuit devices involve overall structures not limited by the dimensions of the emitted wavelength in which feedback is provided either by a Fabry-Perot resonator or a surface-wave (distributed feedback) interaction, in which latter case the principle of operation is like that of the BWO. Otherwise known as Smith-Purcell Free Electron Lasers, the Orotron and Ledatron differ in that one of the reflectors forming the Fabry-Perot resonator is curved in the former and flat in the latter. The opposing reflector is flat and its surface comprises a reflecting diffraction grating across which a flat electron beam is injected, with focus maintained by a magnetic field.

As in the case for BWO's, the extension of the operation of these devices to high frequencies is a combination of a large number of technological challenges. State-of-the-art devices in the U.S., the U.S.S.R., and Japan [Wortman and Leavitt, 1983] produce power on the order of a watt at 100 GHz. Current development efforts appear to be directed forward high power devices at millimeter frequencies, with research devoted to grating efficiency, and heat dissipation capacity. As in the case of gyrotrons, the minimum starting current for oscillation limits these devices to relatively high power operation.

C. Gyrotrons

The gyrotron, or electron cyclotron maser, is a fast-wave free-electron device based on the radiation of electrons orbiting in a magnetic field at the cyclotron frequency:

$$\omega_c = B\ q/m, \qquad \text{(VIII.C.1)}$$

or its harmonics, where q/m is the electronic charge-to-mass ratio, and B is the applied magnetic field.

The electron motion is coupled to either a standing or travelling electromagnetic wave in such a way, due to relativistic effects, as to transfer energy coherently to the wave. Such a device was first realized by Hirshfield and Wachtel [1964], and, to date, tubes have been developed with CW powers exceeding 200 kW, efficiencies exceeding 50 percent, and frequencies to 375 GHz [Granatstein and Park, 1983].

The operation of a gyrotron is typically as follows: An annular electron beam is injected, by means of an electron gun, into a linear waveguide structure of circular cross-section. The axis (z) of the beam coincides with the axis of the cavity. A strong, uniform magnetic field is applied along the z axis, causing the electrons to execute helical trajectories about the field lines with a Larmor frequency of rotation of:

$$\Omega^{o} = B(q/m)\,\gamma_o^{-1}, \qquad \text{(VIII.C.2)}$$

with the relativistic mass correction:

$$\gamma_o = \left[1 - \frac{(v_\perp)_o^2 + v_z^2}{c^2}\right]^{-1/2},$$

where v_z and $(v_\perp)_o$ are the initial longitudinal and transverse electron velocities. An accelerating potential of several kilovolts suffices for the relativistic electron mass to vary with electron energy to an adequate degree for electron <u>bunching</u> to occur.

Considering a component, $\vec{E}\exp(i\omega t)$, of the electric field circularly polarized in the sense of helical motion of the electrons (the interaction with the counterrotating component is negligible), this field acts with force qE on each of the electrons. The effect of this force is to accelerate those electrons which are in certain phases of their orbits and to decelerate others. The relativistic consequence is that the mass of the accelerated electrons increases and, thus, so does their cyclotron frequency, so they move more quickly around their orbits. Conversely, the mass and cyclotron frequency of the decelerated electrons decreases so these electrons move more slowly around their orbits. After a sufficient number of orbits, the electrons are effectively "bunched," orbiting in synchrony, at a Larmor frequency, ω.

Taking the bunch as a single entity, if, at time $t - 2\pi n/\omega$ (n = integer), the phase of the bunch is such that it <u>leads</u> the phase of the field (i.e., $\Omega > \omega$), the bunch will be accelerated, i.e., it will absorb energy from the field. Under the condition of the bunch lagging in phase ($\Omega<\omega$), energy is radiated to the field.

While $\Omega<\omega$ is the condition for field gain, it is also true that if the field and gyromotion were to be much out of phase, the positive and negative energy exchange periods would tend to cancel, as is shown in the rigorous treatment of Hirshfield [1979]. This implies a limitation on the energy extractable from the electron beam by this mechanism since electrons slowed beyond a certain Ω_{crit} will no longer interact significantly with the field. Conversely, it can be shown that if ω does not fall below Ω_{crit}, there will come a point at which the wave energy will have reached its saturation value beyond which the bunch will begin to recover energy from the field.

The task in designing a gyrotron is to optimize the transfer of beam energy to the field.

This said, there are two aspects of free-electron gyrotron operation which make this technology unsuitable for spaceborne operation:

a. Gyrotrons are inherently high-power devices with threshold powers on the order of ~kW required to initiate oscillation. This can be shown on the basis of a calculation [Durachta, 1984] following the theory of Chu [1978].

b. The magnetic field required for operation at a fundamental frequency of 1 THz is 300kG. While such a magnetic field may be produced in the laboratory using superconducting magnets, the technology involved presents formidable obstacles for spaceborne applications. The problems presented by higher-mode harmonic operation, are, again, formidable. On the one hand, design of a wave structure supporting stable, single-mode operation, especially when tunability is required, is not necessarily possible. Furthermore, such operation is inefficient and threshold power is a quadratic function of frequency regardless of the mode of operation.

D. Free Electron Laser

Coherent sources based on stimulated scattering (Compton, Raman...) of an electromagnetic wave by a relativistic electron beam have been of great interest due to their demonstrated capacity for efficient (>5%) high power ($\sim$ megawatts) generation tunable over large spectral regimes and applicable, with suitable electron acceleration methods, for operation from the submillimeter to the X-ray. These free electron lasers (FEL's), considered here in the narrow sense of devices employing wiggler magnets and of which nine are in operation or under construction worldwide, are large laboratory instruments as limited by the means required to accelerate highly relativistic electron beams. They are high-energy, almost exclusively short-pulse-devices, certainly unsuited for LO applications, and many years from any spaceborne application whatsoever.

IX. SECONDARY SOURCES

The potential attractiveness of secondary local oscillator sources derives from the observation that there are regions of the electromagnetic spectrum where coherent radiation can be generated efficiently, using proven technology and, furthermore, there are technologies, in various stages of development, which allow the conversion of this primary source radiation into the submillimeter.

A. Varactor Multipliers

The application to harmonic generation of varactor diodes, whose nonlinearity lies in the variation of capacitance with back-biasing voltage has proven fruitful in producing useful LO power up to 600 GHz [Erickson, 1983]. The state-of-the-art, as reflected in attainable conversion efficiencies, is limited by the unavailability of varactors of sufficiently low junction capacitance for efficient matching to waveguide structures. The reverse biased mixer diodes, with $C_j \sim 3$fF, have suboptimal capacitance modulation. This device problem is currently being addressed by a research effort at the University of Virginia.

The crux of multiplier development lies in the ingenuity required in the design of imbedding structures which properly match the diode to the pump radiation by resonating out the reactive component of the diode at the pump frequency and harmonic frequency and short circuit idler frequencies in the case of triplers on quarduplers. Erickson [1983] reports on the progress of this work, including doubling of 285 (GHz radiation with an efficiency of 7 percent.

B. Schottky Diode Mixers

Both the mixing in a Schottky diode of submillimeter laser radiation with microwave power up to 40 GHz to generate tunable reradiated sidebands [Blumberg, et al., 1979] and the use of a Schottky diode as a subharmonically pumped mixer [Weiss and Godone, 1984] have been demonstrated. In neither case was sufficient conversion efficiency demonstrated for serious consideration in a SMMW receiver configuration, with sideband power, in the first case, less than 10^{-7}W for an incident laser power presumably in the 10^{-2} -10^{-1}W range. A similar experiment [Petuchowski, unpublished] in which a SMMW signal was doubly heterodyned with a SMMW LO and a 90 GHz LO, all quasi-optically coupled into the same Schottky mixer exhibited conversion losses on the order of 40dB.

While these are potentially useful schemes to take advantage of the tunability of lower frequency sources, significant developmental effort will be required before a deployable instrument can be contemplated.

C. Optical Mixing

The possibility of using optical difference frequency generation in a nonlinear medium as a source of useful SMMW coherent radiation has intrigued researchers for over two decades. A variety of nonlinear media and conversion schemes have been proposed and investigated and are summarized in the chapters contributed to Shen [1977]. Efficient frequency conversion in a bulk medium requires the following three conditions: a large nonlinear polarization of the correct order for the process invoked; phase-matching of the generating waves and SMMW output over an appreciable interaction length; and intense generating waves. The drawback to this genus of schemes lies in the fact that nonlinear coefficients adequate for reasonable conversion efficiencies require the enhancement due to a resonance in the medium. Tunability of the emission would require concommitant tunability of the resonance in the medium and a means for maintaining a phase-matched condition. Since intense pump beams tend to be available at visible or mid-infrared wavelengths, an inherent Manley-Rowe power conversion penalty is to be paid above and beyond the inherent efficiency of the nonlinear process.

While it is possible that an efficient mixing process may, one day, be discovered, no scheme currently known would seem to offer much promise for a mid-term solution to the SMMW LO source problem.

D. Semiconductor Raman and Brillouin Lasers

The coupling of electromagnetic waves and phonons in a cryogenically cooled crystal for the generation of coherent submillimeter radiation, and, in fact, for actual heterodyne mixing, has been proposed by Nishizawa and Suto [1983, and references therein]. A parametric process would couple a strong electromagnetic "pump" wave, its scattered wave, a phonon mode, and give rise to gain at the frequency of a fourth wave. Preliminary research has demonstrated electromagnetic/acoustic coupling to 35 GHz, though gain, via the proposed parametric process or otherwise, has yet to be demonstrated.

E. Optically Pumped Molecular Gas Lasers

1. The generation of radiation at frequencies between 300GHz and 30THz by means of infrared-pumped molecular gas lasers has been demonstrated on over a thousand lines [Knight, 1981] analyzed [DeTemple and Danielewicz, 1982, and references therein], and developed by many workers in as many directions, all since its initial demonstration by Chang and Bridges [1970]. The questions to be addressed here are thus of a technological nature: is this technology capable of fulfilling the foreseen LO

requirements of the LDR heterodyne system, and can it be implemented in a manner compatible with space deployment?

2. The mechanism underlying the conversion of infrared pump power to submillimeter radiation in a molecular gas is the selective vibrational excitation of a fraction, ρ_1, of the ground-state molecules to a vibrationally excited state which is followed by their stimulated rotational deexcitation and SMMW emission. The efficiency of this process is ultimately limited to a photon-for-photon conversion (Manley-Rowe limit). This corresponds to a power conversion efficiency given by the ratio of the emitted to pump photon frequencies or 2 percent for a pump at 10 m and emission at .5mm. While schemes which emit multiple quanta per excited molecule have been discussed conceptually in analogy to the highly excited electrons of free electron devices [DeLucia, et al., 1981], the search for their implementation in a physical system in the SMMW has proven them elusive.

The technology underlying the generation of pump radiation with a carbon dioxide laser is mature with the availability of appropriate space-qualifiable hardware foreseeable within the next several years. Lifetimes of 40,000 hours have been reported [Hochuli, 1981] and the demonstration of a fully automated system for line frequency selection in an RF-excited waveguide laser is imminent [Degnan, 1984]. Actual development of a reliable tunable laser oscillator or oscillator-amplifier combination capable of providing requisite powers in a space-qualifiable package has not, to our knowledge, been undertaken but would require a straightforward effort. Wall-plug efficiencies range from 10-20 percent in both DC- and RF- excited CO_2 lasers.

3. SMMW laser output powers of up to 750 mW [Mansfield, et al., 1983] have been reported. Since substantially more power is available on a number of lines than is required of the LO of a single Schottky mixer, the prospects arise for the scaling to SMMW frequencies of imaging mixer arrays [Itoh and Stephan, 1984] and for tertiary or hybrid sources in which a strong SMMW source is mixed with a tunable microwave source with the generated sidebands serving as tunable SMMW LO's.

4. Spectral coverage - The major drawback to optically pumped gas laser local oscillators is the paucity of so-called "winner" media in which efficient conversion of pump power can be attained. This leads to a sparce distribution of usable local oscillator lines and the requirement for large-bandwidth mixers and IF electronics.

X. COMPARATIVE ASSESSMENT OF LO TECHNOLOGIES

A. Technological Assessment

While the SMMW source technologies surveyed in the preceeding sections of this report have been compared elsewhere in various other contexts, recommendations as to prospective technologies for spaceborne heterodyne LO sources must be based on the application-driven criteria cited in the Introduction. It is helpful, first, to summarize viable technology options in terms of the maturity of the technologies considered. The maturity of the respective technologies can usefully be categorized according to the following hierarchy:

0. Available, off-the-shelf, space qualified hardware: none in this frequency regime.

1. Identifiable, on-going effort, somewhere in the world, to develop a device with medium-term applicability, with prospects as identified by researchers:

   a. Straightforward development effect required:

      - Frequency-multiplied Gunn oscillators have been shown [Erikson, 1983] to provide adequate LO for a single Schottky mixer to 600 GHz. Gun oscillators are commercially available to 100 GHz; however, the doubler and tripler cascaded to sextuple the frequency require precision design, fabrication and tuning for a relatively narrow band of optimized operation, and exist, currently, as one-of-a-kind devices.

   b. Major evolutionary development effort required:

      - Backward Wave Oscillators (Carcinotrons) have been manufactured in France to beyond 1 THz with output power to fractions of a mW. Issues in this technology are high voltages, high currents, poor efficiency and thus large heat dissipation requirements. Scaling to higher frequency operation and improvement of power output will require a major development effort.

   c. Research required prior to demonstration of a laboratory prototype:

      - Optically pumped molecular gas lasers have been demonstrated as local oscillator sources for heterodyne receivers at frequencies to 2.5 THz. Compact and efficient lasers suitable for space deployment are theoretically possible, but require laboratory implementation of yet untested concepts.

2. Concept only: This category includes three classes of devices which have been shown to oscillate but not in the frequency range or power levels to be applicable as SMMW LO sources.

- A real-space transfer device has oscillated up to 1 GHz [Coleman, 1984]. Mechanisms ultimately limiting the frequency of operation are uncertain, and design of a suitable imbedding circuit for higher frequency oscillation poses a significant challenge.

- The quantum well heterostructure oscillator has been shown to provide 5μW at 18 GHz [Sollner, 1984]. Again, extrapolation to significantly higher frequencies poses formidable technological problems both in terms of optimization of parameters of the device itself and in terms of a matched imbedding circuit. Whether such problems can be overcome cannot be predicted.

- A Josephson junction fluxon oscillator output on the order of $\lesssim$ 1μW to 400 GHz has been inferred from the behavior of a coupled SIS junction [Nagatsuma, et al., 1983]. The difficulties of matching to a mixer device (necessarily an SIS device) and of optimizing a device based on this effect render premature any statements about the promise of this technology.

B. Tradeoffs

Comparison of the list of candidate SMMW LO technologies considered in the preceeding section with the summaries of deGraauw [1982] and Wilson [1983] of LO sources actually implemented in SMMW heterodyne receivers as of their respective writings suggests that research in a number of fields is opening new technological options for SMMW heterodyne instrument development. It is clear that a significantly greater portion of the SMMW spectrum can be covered and it is also clear that there will be tradeoffs to be considered.

No existing or prospective CW sources will be continuously tunable over the entire decade of interest. A mix of receivers will certainly be required and the definition of that mix will hinge both on the development of mixer and mixer array technologies and on an interactive definition of how many frequencies or frequency swatches are desirable to be covered by LDR heterodyne instrumentation.

The frequency regime over which SIS mixers will be available can be safely deemed "non-problematic," as far as LO sources for single mixers are concerned, by virtue of the low LO power requirements. It is unclear, however, how high this frequency regime extends and whether ultimate limitations arise in connection with the junction material energy gap (2.1 THz in Nb_3Sn, though the materials technology remains to be addressed) or at much lower frequencies ($\sim$300 GHz) due to Joesphson effect noise [deGraauw, 1982]. An InP Gunn oscillator, sextupled in frequency by a sequence of two varactors, has been shown to pump a Schottky diode mixer, with its higher LO power requirement, to 600 GHz. This technology is appealing because of its compactness and low power requirements. Its ruggedness, radiation hardness, and longevity remain to be demonstrated. Tunability over a bandwidth of 10 percent is feasible allowing for a factor of two degradation in output power. Thus, complete coverage of the 300-600 GHz octave, allowing for a 5 percent IF bandwidth in this range, would require 7 receiver configurations, probably with shared components.

The BWO should also be considered in this frequency regime, possibly in conjunction with a varactor doubler. Its advantages include continuous tunability over a bandwidth up to 20 percent and insensitivity to radiation. On the other hand, it is, at best, an inefficient device, requiring 100W as compared with 1W for the Gunn oscillator source; and, for the acceleration and confinement of its electron beam, it requires moderately high voltages ($\sim$10kV) and substantial magnetic fields ($\sim$10kG).

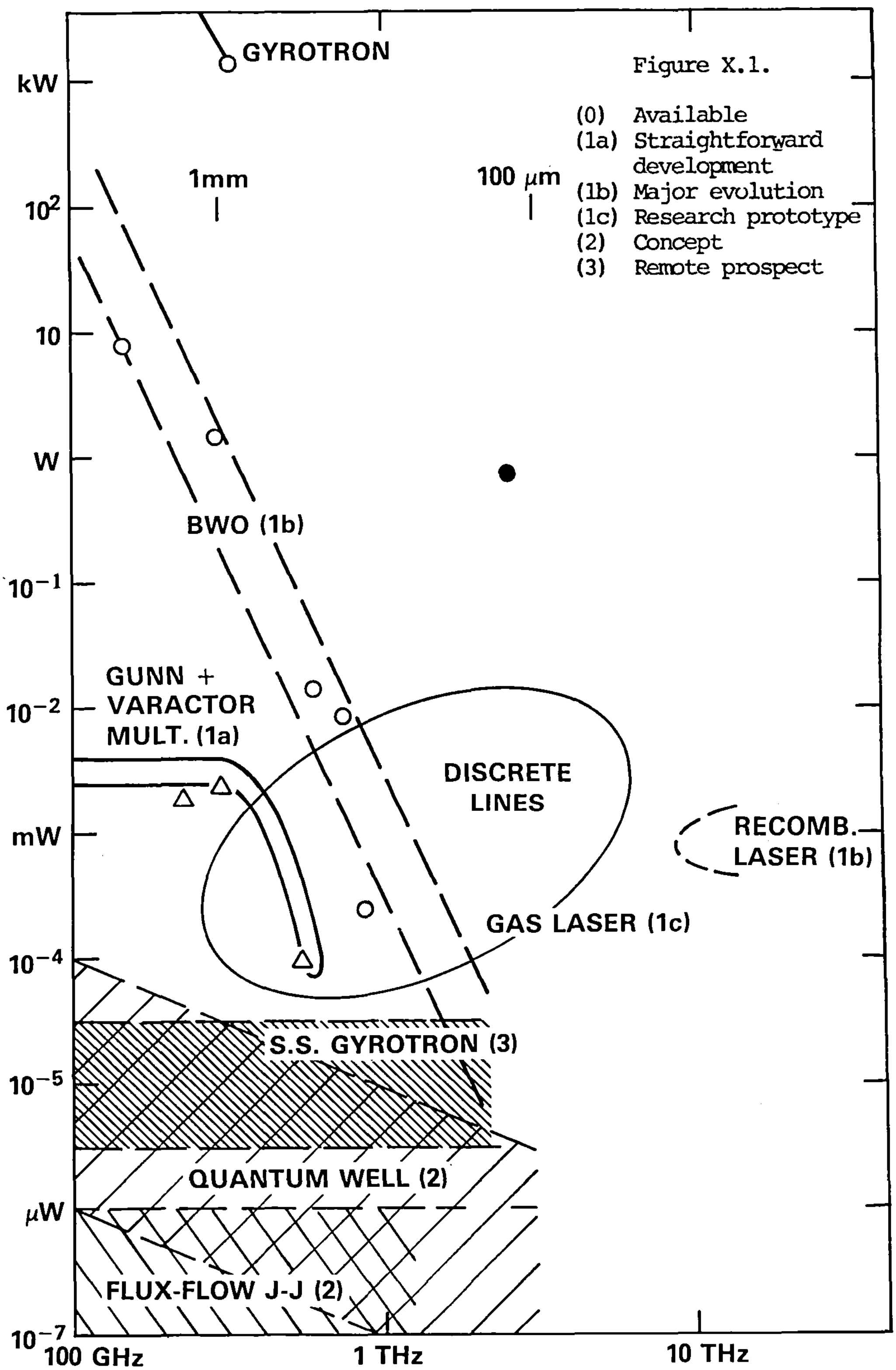
3. Questionable prospects without significant materials development:

   - The solid-state gyrotron has been advanced as a potential source of SMMW radiation and studies, currently underway, are addressing the feasibility of an experimental demonstration.

These and the issue of lifetime at high frequencies (large heat dissipation per surface area of structure) will have to be addressed in future development.

Two other candidate solid-state devices, the real-space transfer device, and the quantum well tunneling device rely on the emerging heterostructure growth technology and, if high frequency oscillation can be achieved in either, will be limited in output power by achievable current densities. The scaling behavior with varied area and/or stacked junctions is just beginning to be investigated by researchers and is far from being understood. The development of imbedding circuits to allow oscillation into the SMMW region is a major current challenge for both devices. The low power requirements, compactness, and potential ruggedness of solid-state devices along with a tunability limited by the design of the imbedding circuits make these technologies enticing prospects, expecially for SIS mixers with lower LO power requirements than Schottky diode mixers. They would present modest cryogenic requirements ($<$ 1W load at $\sim$100°K).

The other candidate solid-state devices, the flux-flow Josephson device and the solid-state gyrotron are in stages of development too premature for definitive evaluation. Either might yet prove the wild card of low-power SMMW local oscillator sources for driving SIS mixers. Either would require cryogenic operation, though heat dissipation requirements would be modest.


GYROTRON
kW
Figure X.1.
(0) Available
(1a) Straightforward development
(1b) Major evolution
(1c) Research prototype
(2) Concept
(3) Remote prospect
1mm
100 μm
10²
10
W
BWO (1b)
10⁻¹
GUNN + VARACTOR MULT. (1a)
10⁻²
DISCRETE LINES
mW
RECOMB. LASER (1b)
GAS LASER (1c)
10⁻⁴
S.S. GYROTRON (3)
10⁻⁵
QUANTUM WELL (2)
μW
FLUX-FLOW J-J (2)
10⁻⁷
100 GHz
1 THz
10 THz

C. Specialized Development

It should be borne in mind that the ensemble of SMMW LO technologies to which the LDR falls heir is inadequate to the requirements posed by the mission. Several SMMW sources, such as the free-electron gyrotron, are totally inappropriate to the specialized requirements of low power, high stability and narrow linewidth called for in any spectroscopic application, and, especially, to the stringent physical requirements of a spaceborne application. While one cannot say that a given emerging technology will have "no" other applications, it is safe to assume that, in the medium-term, astronomical requirements will drive the goals of several such technologies and must foster their development.

D. Epilogue

This survey of existing and emergent technologies suggests that, while the ultimate goal of a fully integrated submillimeter receiver will remain a challenge facing scientists and technologists into the next century, there are several clear avenues which can currently be pursued to enable the high resolution mission of the LDR in the medium-term. It is clear, further, that, in the case of local oscillator sources, in particular, several technological approaches bear parallel development since no single technology can be expected to meet the full range of requirements of the desired instrumentation.

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16. Abstract

Existing and prospective submillimeter local oscillator technologies are surveyed and compared with respect to criteria of suitability for application in spaceborne submillimeter heterodyne receivers as those proposed for the Large Deployable Reflector (LDR). Solid-state and plasma devices are considered in terms of fundamental limitations.

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