SUBMILLIMETER LOCAL OSCILLATORS FOR HETERODYNE SPECTROSCOPY*

Edward J. Danielewicz, Jr.
Electronics Research Laboratory
The Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009

SUMMARY

The far infrared or submillimeter portion of the electromagnetic spectrum, which spans the range of wavelengths between roughly 50 μm and 1.0 mm, is experiencing a tremendous growth in activity due to rapidly emerging source technologies. This paper reviews the major technological innovations in continuous wave (CW) submillimeter sources which are specifically suitable for application as local oscillators in heterodyne systems. A description of the various sources is given which underscores the general principles and operating features for each type of device. Particular emphasis is placed on CW optically pumped lasers, which have had a dramatic impact as widely available sources of narrow linewidth coherent radiation. The state-of-the-art is summarized for these lasers and performance data are presented for a compact and reliable local oscillator package recently developed at the Aerospace Corporation and for several different designs from other laboratories. Optically pumped lasers are then compared and contrasted with other competing sources such as backward wave oscillators, IMPATT diodes, and Josephson junctions. By comparing their advantages and limitations for use as local oscillators, the potential applications of these different sources are projected. The prospects for increased tunability, reliability and scalability are briefly considered, and several novel techniques for generating partially tunable radiation using Schottky diode mixers or CW Raman lasers are highlighted.

I. INTRODUCTION

The submillimeter wave (SMMW) portion of the electromagnetic spectrum between the infrared and millimeter regions corresponding to wavelengths between 50 μm and 1.0 mm is experiencing tremendous growth due to rapidly developing source technologies. In spite of absorption by atmospheric water vapor in the SMMW region, there is an enormous wealth of information to be somehow obtained within this large segment of the spectrum that covers nearly two decades in frequency. This potential provides strong motivation for attempts to exploit the recent progress in source availability.

---

*This work supported by the Division of Magnetic Fusion of the U. S. Department of Energy

Many practical applications of SMMW technology in areas such as high-resolution astronomy [1], plasma diagnostics [2], remote sensing of upper atmosphere constituents [3], molecular spectroscopy [4], imaging and non-destructive testing [5], and all-weather radar and communication [6] will require the advantages of high spectral resolution and sensitivity provided by heterodyne systems. Coherent sources are essential as local oscillators in any heterodyne system, and several excellent general review articles on SMMW sources are available [7], [8]. The aim of this paper is to review the present state-of-the-art of the most promising continuous wave (CW) SMMW sources suitable for local oscillator applications. Strictly speaking this paper should only assess the relevant properties of SMMW sources. However, it is useful to preface the detailed description of the various sources with some general remarks about SMMW heterodyne receivers.

In contrast to other spectral regions, the performance of a SMMW heterodyne receiver is so intimately coupled to the performance of both the local oscillator and the mixing element that an understanding of these receivers requires some discussion of the complete "front end". There are two possibilities for a heterodyne receiver: one chooses either a tunable oscillator and a narrow band detector or a fixed frequency oscillator and a broad band detector. Both approaches have been successfully demonstrated in the SMMW range. A very important consideration in both cases is the minimum local oscillator power for which maximum sensitivity can be obtained from the mixer. This requirement is a strong function of the selected mixer element.

The most widely used mixer element at microwave and millimeter wave frequencies is the Schottky diode. It is a room temperature, wide bandwidth device having high sensitivity and good mechanical stability. A basic property of a Schottky diode is that substantial local oscillator power is needed to minimize its conversion loss. On the order of a few milliwatts is typically required at lower frequencies near $\lambda \approx 1$ mm, and this increases to tens of milliwatts as one goes toward higher frequencies. Such SMMW power has been difficult and expensive to obtain in the past, and this was the primary limitation in the development of SMMW technology. However, recent innovations in SMMW sources, particularly the optically pumped lasers, have provided the necessary local oscillator power needed for efficient Schottky diode receivers. If one can accommodate cryogenic mixers such as photoconductors or Josephson junctions, the requirements on local oscillator power are significantly relaxed at the expense of the added complications with helium cooled operation. In addition, the photoconductors have fundamental bandwidth limitations of ≤ 100 MHz. Besides the threshold requirements on output power, there are a number of other criteria listed in Table I which also must be considered when comparing the choices for a local oscillator. In the next section these criteria will be used to compare the competing sources in an attempt to evaluate the potential of each type for local oscillator applications.

II. CW SUBMILLIMETER SOURCES

SMMW source development is being pursued from both of the bounding spectral regions. From the low frequency side efforts are underway to extend millimeter wave technology toward higher frequencies. Others are trying to transfer optical or laser techniques from the high frequency end, so that one often finds a blend of these two technologies in the SMMW transition region. The overlapping and intermingling of technologies are reflected in Table II which lists the possible CW sources to be considered.

Heading the list are the optically pumped lasers, which have had a revolutionizing impact on SMMW technology since their inception in 1970 [9]. Particular emphasis will be placed on describing the latest developments in these rapidly maturing sources.

Backward wave oscillators are a considerably older vacuum tube technology which has enjoyed renewed interest in the SMMW region because of their highly desirable tunability.

Josephson junctions are more esoteric devices which offer the potential of acting simultaneously as both the mixing element and the local oscillator. LO power can be derived from the internal Josephson oscillation in the junction itself, with the frequency of this internal oscillation proportional to the voltage bias across the device. In principle, a readily tunable receiver is then possible. The main source of difficulty with the internal LO mode of operation is the broad linewidth on the order of 1 GHz, which is characteristic of such Josephson oscillations. Promising results have been reported at short MMW frequencies [10], however, so this type of system cannot be ruled out for wide bandwidth heterodyne systems in the future. Unless arrays of junctions can be developed, Josephson devices do not appear to be the best prospect for tunable coherent SMMW sources with milliwatt level output powers. However, Josephson devices will continue to be of importance as heterodyne mixers in conjunction with external LO sources because they are highly nonlinear, extremely fast, and have very low LO power requirements on the order of 1-10 μW in the SMMW region [11].

IMPATT diodes are solid state sources which have been operated into the SMMW region, and combined with harmonic generators offer some hope of achieving compact solid state local oscillators in the near future. Progress in these two areas will also be covered in the following sections.

Electric discharge lasers can provide large amounts of power up to about 300 mW, but only at a very few fixed frequencies at short SMMW wavelengths. This limits their utility in heterodyne applications [12].

Gyrotrons are receiving considerable attention lately as sources of exceedingly high power and efficiency [13]. CW output power on the order of 1.5 kW has been reported at a wavelength of 0.9 mm [14], but the main emphasis is on achieving high power and these are large devices at present. Gyrotron oscillators have poor temporal coherence and it appears that these devices cannot be scaled down in size and power for LO applications without significant loss in efficiency.

In the following sections, advantages and limitations will be discussed in more detail for a few selected sources which have been most successfully utilized in practical heterodyne applications.

III. BACKWARD WAVE OSCILLATORS

The operating features of a backward wave oscillator (BWO) or carcinotron can be very briefly described in a highly simplified manner with the help of the cross-sectional diagram given in Fig. 1. An electron beam is emitted from a cathode (1) and is focused through an interaction region (4) by a magnetic field $\vec{B}$ (3) and is collected at the collector (6). The electron beam moving in a vacuum interacts with a periodic structure (4) which supports the generated electromagnetic wave. The interaction is phase-matched for the wave in the reverse direction to the electron beam (hence the name backward wave oscillator) and is coupled out through the output port (5). The BWO is essentially a voltage tunable oscillator whose tuning characteristics are strongly dependent on the characteristics of the periodic slow wave structure. The advantages and limitations are summarized in Table III for these devices.

The primary advantage of the BWO is the continuous electrical frequency tuning which can be done rapidly without mechanical adjustments. The typical tuning range for a wideband BWO is about 20% of the center frequency. Thomson CSF, Paris, offers the highest frequency commercially available carcinotrons (up to 400 GHz) and they are presently developing tubes which would have output powers > 10mW in the 400-600 GHz range [15]. Frequencies of up to 1,300 GHz have been reported for laboratory models [16], but above 300 GHz the efficiency of operation falls off rapidly. Table IV shows that at $\lambda = 0.4$ mm the efficiency has fallen to less than 2×10^{-3}%, compared with 11% for a tube designed for $\lambda = 4.0$ mm. Unless there is a considerable advance in the technology of cathode emitters, there seems to be little hope of pushing the efficient performance to higher frequencies.

State-of-the-art in performance for SMMW BWO's is illustrated in Fig. 2 which shows the operating characteristics of an extended bandwidth BWO intended for use as a local oscillator in a heterodyne receiver [17]. Continuous spectral coverage from 320-390 GHz with greater than 10 mW output power is achieved at rather low power consumption. One obvious technical weakness of the BWO is the strong variation in the output power as the frequency is changed (Fig. 2) due to the unintended resonances in the guiding structure and the output couplers.

A relatively high sensitivity of the output frequency to the beam voltage of 10-30 MHz/V for these tubes would seem to preclude their use in heterodyne systems when a stable frequency is necessary. However, recent studies [18] designed to evaluate the potential of using BWO's as local oscillators for heterodyne spectroscopy have shown that they can be readily phase-locked to an external stable reference source of lower frequency. Linewidths as narrow as 750 kHz at 40 db below the peak value at 244 GHz were achieved. These same studies measured the noise properties in the 230-380 GHz range of three different tubes. Noise temperatures were in the 1000-3000°K range at an IF frequency of 1.4 GHz, which corresponds to a signal to noise ratio approximately equal to 120 db/MHz. This resulted in the conclusion that the BWO has all of the required qualities of a tunable oscillator for wavelengths near $\lambda \approx 1$ mm and several successful heterodyne experiments have already been performed [19], [20], [21].

A fine example of a practical application of a BWO in a SMMW heterodyne receiver is the recent observation of the carbon monoxide molecule in interstellar clouds by Erickson [22], who was able to achieve system noise temperatures as low as 3400°K (SSB) at 345 GHz. The requirements for high voltages and magnetic fields make carcinotrons relatively large and heavy (10-30 kg), but this situation may be improved with the development of new advanced magnetic materials.

The BWO performance at long SMMW wavelengths is satisfactory, but there are, however, basic fundamental limitations to extending the efficient operation of BWO's to higher frequencies. Serious fabrication difficulties arise, because extremely high precision of machining and alignment is demanded for SMMW operation. The slow wave structure has to be machined to tolerances within 1μm and the dimensions of the structure are on the order of a fraction of a free space wavelength. As the size of the device decreases, a difficulty arises in avoiding serious heat dissipation due to unwanted interception of the electron beam by the structure. Along with these problems are additional circuit losses which increase at least as the square root of the frequency due to the decrease in the skin depth and even more rapidly increasing losses caused by surface machining imperfections. All of these loss mechanisms contribute to the rapid power falloff with increasing frequency, and impose severe requirements on the electron beam quality, particularly with respect to the high values of beam current density and magnetic focusing field required. To offset the increasing losses, the beam current must be increased to densities of 10-20 A/cm^2, which can only be obtained at cathode temperatures exceeding the values usually recommended for long life. Lifetimes of 1000-2000 hours are typical for tubes operating near 300 GHz and decrease at higher frequencies. These rather short lifetimes, the high cost of approximately $80,000 for the tube and its stabilized high voltage power supply, and the limited availability of these devices, especially for frequencies above abut 400 GHz, diminish the prospect of near term widespread application of the BWO as a local oscillator for the SMMW region.

A very promising alternative electron beam oscillator design, the ledatron [23], offers the possibility of overcoming or reducing the deficiencies of the BWO. Oscillation at $\lambda \approx 1$ mm has been observed with a peak power of about 300 mW and a tuning range of 40%, but these tubes are still in an early stage of development and more work is needed to establish the potential for efficient SMMW operation.

IV. IMPATT DIODE OSCILLATORS

Over the past several years, significant progress in increasing output power and efficiency has been achieved with silicon IMPATT diode oscillators operating at frequencies up to about 300 GHz [24]. These results clearly place IMPATT diodes as the premier solid state device for the generation of millimeter wave power. Therefore, their potential for extension into the SMMW region must be examined.

The operating principle of IMPATT (impact avalanche and transit time) diodes is based on the injection of carriers, generated in a reverse-biased p-n junction by avalanche breakdown, into an intrinsic drift region. The electric 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 voltage is applied, a phase delay occurs between the current and the voltage waveforms due to the transit time effect. This results in a frequency dependent negative resistance that can be used to give oscillation when the crystal is incorporated in a microwave circuit as in Fig. 3. Variation of the external circuit impedance allows the frequency of oscillation to be tuned over a broad range since the negative conductance covers a wide frequency bandwidth of 10-20%. Bias current tuning is the most effective way of producing broadband swept frequency generation, and high frequency modulation rates (≥100 MHz) can be achieved. Mechanical tuning is necessary for optimum performance at a specific frequency and this is achieved by varying the position of the movable short in the oscillator circuit.

A comparison of the properties of IMPATT devices is given in Table V. Besides tunability, there are many other attractive features of such a solid-state generator like compact size and ruggedness, low power consumption, and reliable operation with long lifetimes. These advantages would make IMPATT devices highly desirable as local oscillators in the SMMW region if the high efficiency operation can be extended to higher frequencies.

Unfortunately, there are some fundamental limitations which have hindered the scaling of IMPATT's to higher frequencies. The current state-of-the-art is shown in Figure 4 where the steep falloff in output power with frequency above the demarcation point at about 100 GHz can be clearly seen. The output power is ultimately limited by the realizable circuit impedance which causes the mismatch between the device and the circuit to become increasely difficult to overcome at higher frequencies. The power falloff is mainly due to the adverse effects of the diode package and mounting parasitics. Limitations other than transit time effects have also been considered. There are problems with diffusion aided spreading and buildup of the injected current, and with the frequency response of the avalanche process itself [25].

As one attempts to extend IMPATT operation to higher frequencies, the diode dimensions must be reduced to reduce the parasitic capacitance effects. Unfortunately, thermal problems associated with dissipation of the power increase as the size of the device decreases. Since the parameters of the junction are strongly dependent on temperature, the minimization of thermal resistance in device packaging plays an important role in performance [26]. The physical dimensions of the device also become inconveniently small and severe demands are placed on processing and fabrication techniques. Recent improvements in output power from the MMW devices are primarily due to diamond heat-sinking and improved packaging techniques. Commerically available CW IMPATT oscillators can now produce single device outputs of 700 mW at 94 GHz, 100 mW at 140 GHz, and 25 mW at 220 GHz. Recently, liquid nitrogen cooled Si IMPATT's have produced output powers of 2.2 mW and 4.5 mW at frequencies of 412 and 295 GHz respectively with a tuning range of 10% [27]. With such output powers these devices are on the verge of being useful as LO sources and hopefully developments in this area will continue.

Another serious problem with IMPATT oscillators is the very high noise level, which is attributable to the random way in which the avalanche grows from a few initial ionizing events. The noise exceeds that of a klystron or Gunn diode MMW oscillator and for this reason they are difficult to use as LO's in low noise receivers. Recent results have shown that they can be phase-locked at harmonic frequencies through injection-locking with a fundamental mode reference source of high frequency stability and low noise [28]. But as yet it is difficult to assess the extent to which this technique will be effective in the SMMW region.

The catastrophic fall in efficiency as the frequency approaches the SMMW region is reasonably well understood and it is unlikely that efficient operation will be extended beyond 400 GHz with conventional techniques. Perhaps a quasioptical approach to diode packaging may be the only way to extend the frequency coverage further into the SMMW range. There is no doubt about IMPATT utility at the long wavelength end of the SMMW spectrum, and, as shown in the following section, harmonic generators can provide useful extension of the frequency coverage.

In addition to avalanching, electron tunneling can occur in a sufficiently thin p-n junction and this leads to a tunnel transit time or TUNNETT mode of oscillation [25]. Since tunneling is a very fast process (10^{-16} sec), the idea of using a tunnel transit time mode offers promise of enabling one to extend the frequency limit well beyond 300 GHz, assuming the appropriate quasioptical circuit can be devised. Further experimental work on TUNNETT's should enhance their value for SMMW systems.

V. HARMONIC GENERATORS

The long-standing method of harmonic generation in nonlinear junctions pumped by tunable sources offers the possibility of extending the range of tunable MMW oscillators into the SMMW region. The formidable problems of pushing existing MMW sources to higher frequencies, combined with recent advances in the fabrication of Schottky diodes have caused renewed interest in these harmonic generation techniques.

A harmonic generator is simply a frequency converter in which power is generated at a higher frequency by exploiting a nonlinearity in the current-voltage characteristic. For example, the current through a Schottky diode will contain harmonics of the frequency of the driving field, and this harmonic power can be radiated into free space or into a waveguide in which the diode is mounted [29]. In principle harmonic power can be generated in proportion to $1/n^2$ at the nth harmonic of the applied field, but the useful range of frequencies is limited by junction capacitance and impedance matching to the external circuit [30]. Higher frequencies require special fabrication techniques that produce extremely small area contacts with diameters of 0.1-2.0 μm and very low values of junction capacitance [31]. These small contact areas create a limit on the amount of generated harmonic power, however, since they restrict the allowable fundamental pump power to about 100 mW. Above this power level the diode will usually burn out or suffer electrical breakdown.

The most successful device of this type has been a crossed waveguide harmonic generator (Figure 5), and conversion efficiencies of 2% giving 2 mW of output power at 228 GHz have been obtained [29]. The maximum second harmonic output was 3.5 mW at 226 GHz for the saturation limit of 200 mW of input power from the source klystron, and a frequency tunability of about 5% was retained. In the 200-300 GHz region more recent results have achieved second harmonic conversion efficiencies as high as 6-8% yielding 4 mW at 270 GHz, and 2-3 mW was produced at 305 GHz with ~1% conversion efficiency in a tripling mode [32]. This represents sufficient LO power for good conversion efficiency in a Schottky diode mixer at these frequencies, and has allowed system noise temperatures of 3100°K (SSB) to be reached at 270 GHz [32].

Further into the SMMW region, output powers of about 0.1 mW have been obtained at 447 GHz [30] which are thus far insufficient as sources of LO power for Schottky diode mixers. However, these power levels will suffice for He cooled InSb or Josephson mixers, and several heterodyne receivers have been realized for such applications as measuring the first SMMW molecular line in an astronomical source [33], and for airborne observation of atmospheric ozone in the 440-530 GHz region [34]. In molecular spectroscopy, more SMMW experiments have been performed using this technique than with any other [35]. Above about 500 GHz, however, harmonic generation has not proved a useful source of LO power even for the very sensitive cryogenic detectors.

Some improvement can be anticipated as new fabrication techniques are introduced, since these sources are as yet relatively undeveloped. If more power can be generated in the future, the favorable features of these devices will bring them into much more widespread use.

VI. OPTICALLY PUMPED MOLECULAR LASERS

All of the sources previously discussed are characterized by a drastic falloff in output power with increasing frequency. Transit time effects, unrealizable mechanical tolerances, and impedance matching problems severely limit their high frequency response. To circumvent these limitations a fresh approach was needed. The departure from attempts to extend conventional technology to higher frequencies was pioneered in 1970 by Chang and Bridges, who introduced the optically pumped molecular (OPM) laser [36]. The optical pumping technique has now succeeded in generating a rich spectrum of laser lines from $\lambda \approx 40$ to 2000μm, thereby bridging the gap in source availability up to the infrared. A comparison of OPM lasers with other CW SMMW sources (Fig. 6) shows that for frequencies greater than 600 GHz they are clearly the dominant source technology [37]. A brief outline of the operating features of these lasers is worthwhile, since they have had such a dramatic impact on the SMMW region. Detailed descriptions are available in several excellent review articles [37], [38].

The basic operation of an OPM laser is illustrated in Figure 7. Transitions between specific rotational energy levels within the ground and first excited vibrational states of a polar molecular gas are utilized in both the absorption and emission processes. The pumping is achieved through an accidental near coincidence between a rotational-vibrational absorption line of the molecule and a suitable pump laser line. The intense and efficient CO_2 laser emission lines in the infrared near $\lambda = 10$μm are almost exclusively used for this purpose. The pump photons selectively excite a particular rotational level in the excited vibrational state and produce population inversion between the unoccupied adjacent rotational states. In typical molecules like CH_3F and CH_3OH possessing a permanent dipole moment, the large rotational transition matrix elements lead to high gain, and laser emission can be achieved with a suitable optical cavity. The molecular kinetics are also very important for efficient CW operation of an OPM laser. In the steady state, vibrational relaxation through diffusion or V-T/R processes must be sufficiently fast to prevent destruction of the inversion by rotationally thermalizing collisions. Operating pressures are typically limited to the 100 mtorr region by the relatively slow rate of vibrational relaxation in diffusion dominated systems, such as CH_3F, and this adversely affects the rate of energy extraction by limiting the pump absorption. However, non-diffusion limited operation using molecules such as CH_2F_2 with very fast V-T/R relaxation rates has recently overcome this limitation, leading to increased CW power and operating efficiencies as high as 32% of the theoretical limit [39], [40].

The physical components which make up an actual OPM laser system are displayed in Figure 8. The setup consists of a grating tuned CW CO_2 laser with a single line output power in the range of 10-50 W. The pump radiation is normally injected into the SMMW resonator by focusing through a hole in one of the cavity end reflectors. The more common resonators and output coupling schemes have been well reviewed [41], [42], but in general the best beam mode quality, linear polarization, and output powers have been obtained from hollow dielectric waveguide resonators [43]. The combination dielectric-metallic rectangular waveguide is another configuration [44] which has proven to be very useful for Stark tuning [45], high speed modulation [46], and phase-locking of the laser output [47]. Output coupling can be accomplished with a simple hole in the cavity end reflector, but for practical applications where output beam quality is important some type of hybrid output coupler either metal mesh-dielectric [48] or dielectric-hole coupler [43] is necessary.

The properties of OPM lasers are summarized in Table VI. A prime advantage of the OPM laser as a local oscillator is its inherently narrow linewidth, since molecular transitions in these low pressure gases yield gain linewidths of $<$ 10 MHz. OPM lasers are easily constructed and relatively inexpensive. Commercial systems complete with power supplies and associated electronics are available for under $40K from a number of suppliers, so that these sources are widely available to researchers. Another important advantage of these lasers is their versatility. A large number of emission lines (>1000) are available, so that there is almost complete coverage of the entire SMMW range with an average spacing on the order of a fraction of a wavenumber [49]. A single laser can also be made to operate over the entire SMMW on a variety of wavelengths by tuning the CO_2 pump. Molecules like CH_3OH [50] and CH_2F_2 [51] each have more than 50 laser lines spread throughout this region. For other wavelengths, it is often a relatively simple procedure to change the laser gas. These lasers operate sealed-off because there is no discharge to destroy the lasing molecules. This allows very high frequency stability, about three orders of magnitude better than for free running electric discharge SMMW lasers [52]. Phase-locking to a low frequency reference standard has also been demonstrated [53].

The major disadvantage of OPM lasers is their lack of tunability. Stark tuning offers the potential for increased range, but only up to about 100 MHz [54]. Recent advances in Schottky diode mixer technology have practically eliminated this problem, however since IF bandwidths as large as 20 GHz can be now obtained [55]. In conjunction with the available laser lines, this increased bandwidth will allow a heterodyne spectrometer to be built which provides almost complete coverage of the SMMW region [56]. Several novel techniques have also been recently demonstrated for increasing the tuning of OPM lasers and they will be described in the following section. Another limitation of OPM lasers is their inherent inefficiency. The optical pumping process at best cannot achieve power conversion exceeding about one-half of the Manly-Rowe limit [37]. Only a handful of lines actually operate with CW conversion efficiencies within an order of magnitude of this limit, but the proliferation of new source molecules such as CH_2F_2 has greatly added to the number of such strong SMMW laser lines. Relatively low efficiency imposes larger size and higher power requirements on the CO_2 pump laser system, and the need for two laser resonators increases the complexity of the overall system. Amplitude instability caused by coupling between the two laser cavities has been a problem in the past, but recent design improvements have now essentially eliminated this problem. None of the limitations for OPM laser sources have proved insurmountable, and compact and well engineered systems have been built in several laboratories.

One such OPM laser system was constructed at the Aerospace Corporation for use in a transportable heterodyne receiver suitable for diagnostic experiments on large Tokamak plasma machines [57]. Several unique design features have been incorporated into this new self-contained OPM laser package. Because of the stringent requirements for reliable operation in hostile environments and remote field sites, this new design is much more complex than the laser normally used in the laboratory. For compactness and mobility, both the CO_2 pump laser and the FIR laser cavities were built into a single Invar frame with overall dimensions of 2.0 m x 0.4 m x 0.4 m. Figure 9 shows a view of the complete package with the CO_2 pump laser mounted above the SMMW waveguide resonator. The low temperature coefficient of expansion of Invar helps to ensure the long term temporal stability of the laser power and frequency. In addition, a temperature controller circulates constant temperature coolant throughout the structural components of the frame. Provisions have also been made for remote-tuning of the CO_2 and SMMW lasers for operation from remote control areas. The highest possible CW output power is required, as well as a small angular divergence for the output beam. To achieve these goals, the SMMW laser is equipped with a state-of-the-art hybrid output coupling mirror.

Preliminary performance measurements have been obtained with two prototype systems operating in our laboratory. Using CH_2F_2 as the lasing medium, true CW output power of typically 45 mW is obtained at a wavelength of 214.7 μm with long term amplitude stability of ±3% (Figure 10). It must be emphasized that this excellent amplitude stability has been achieved without actively stabilizing the CO_2 pump laser, and conceivably it can be improved with such a stabilization system. Another important feature of the package is that it can be operated in a sealed-off mode with a single fill of CH_2F_2 gas for extended periods of up to 2 weeks. This is very desirable for increased reliability and ease of day to day operation. A vapor trap has also been constructed that can be used to recapture and recycle the CH_2F_2 gas for a number of cycles, since the chemical reactivity of this molecule is quite low.

The noise spectrum and frequency stability of this SMMW laser package are critical performance characteristics. These parameters were measured by heterodyning two of these lasers together. The outputs from both lasers were mixed in a 0.25μm Schottky diode mixer fabricated in house and optimized for the high laser frequency [58]. The IF signal produced by offsetting one laser 3.9 MHz from the other in Figure 11 confirms single mode operation from both lasers, since only a single beat note is present on either side of the receiver center frequency. The free-running frequency stability of the beat signal in Figure 12 was better than 20 kHz, as measured from the half-width of the signal for a two minute exposure. This excellent level of performance is well within the requirements for local oscillator applications in Tokamak diagnostic experiments, and plans to utilize this system for such measurements are now underway.

Another noteworthy design has been developed at the NASA Goddard Space Flight Center, where CO_2 pump laser radiation is injected off-axis into a novel four-fold degenerate Gaussian resonator within the SMMW waveguide [59]. This has the advantages of improved stability, through elimination of feedback effects and greater efficiency associated with better utilization of the pump power. The technique may prove especially useful for many of the more weakly absorbing gases other than CH_2F_2. Excellent amplitude and frequency stability has been obtained with this system, which is described in detail elsewhere in these proceedings [60].

A SMMW heterodyne receiver system has also been constructed at the Max Planck Institute for Radio Astronomy for the observation of interstellar molecules [61]. Figure 13 shows results for heterodyne mixer conversion loss indicating that values as low as 11.6 dB have been achieved at 761 GHz. This translates to a system noise temperature of only 3,670°K (DSB) [62]. From Figure 13 one can see that the conversion loss for this Schottky diode is not yet saturated up to the maximum available laser LO power of 10 mW. This establishes a lower limit on the amount of LO power necessary for efficient performance at these high frequencies, and implies that with increased LO power it will be possible to achieve still lower system noise temperatures.

OPM laser technology is now rapidly maturing, and several well-engineered systems have been designed and constructed for various purposes. Present levels of performance are sufficient for local oscillator applications in practical heterodyne systems well into the SMMW region. Novel techniques described in the following section for extending the tuning range of OPM lasers will contribute significantly to their utility, and the accelerating rate of advance in OPM laser technology should lead to additional practical applications during the next 1-3 years.

VII. NOVEL OPTICALLY PUMPED LASER TUNING TECHNIQUES

The techniques of sideband generation and CW stimulated Raman emission have recently been extended into the SMMW region. These advances show promise of eliminating the serious tuning problems now associated with OPM lasers.

The principle of generating tunable sidebands is illustrated in Figure 14. A quasi-optical Schottky diode mixer is fed coaxially with tunable microwave radiation and simulataneously irradiated with the output of an OPM laser. Tunable sidebands are generated at the SMMW frequency by nonlinear mixing in the Schottky diode and radiated by the long wire antenna of the corner cube mixer. Output powers of 10^{-7} W continuously tunable from 2.5 to 18 GHz have been obtained in this way from the first SMMW experiments [63]. Initial laboratory experiments have used this tunable SMMW source in an infrared-submillimeter double resonance study of an excited vibrational state in CH_3F [64]. A Schottky diode heterodyne receiver easily detected the sideband radiation with signal to noise ratios of 40 dB, and since the time response is fast the kinetics of energy transfer processes could also be investigated. Thus, the introduction of these tunable sources combined with the sensitive heterodyne detectors has opened up the possibility for new types of high resolution SMMW spectroscopic studies.

The technique of CW stimulated Raman scattering in a three level molecular system is schematically illustrated in Fig. 15. An intense pump laser with frequency ν_p is nearly resonant with an infrared transition of frequency ν_{31} with an offset $\Delta\nu_p = \nu_p - \nu_{31}$. Using the nonlinear properties of the molecular gas itself, a signal is generated by the stimulated Raman effect near the rotational frequency ν_{32}. In contrast to the two step resonant absorption and re-emission process of a normal OPM laser, the CW Raman laser is a simultaneous two-photon process, and changing of the pump offset will tune the SMMW frequency by the same amount. The tuning in the Raman case is larger, since in the normal laser the change in the emission frequency is reduced by the ratio of the SMMW frequency to the pump frequency due to the Doppler effect. Experiments have been conducted with NH_3 ** and HCOOH [65] and interpreted as the first observations of stimulated SMMW Raman lasing using a CW pump laser. These results demonstrated that Raman effects can be observed at the power levels typical in a CW OPM laser, and that dramatic increases in tuning range can be achieved. A frequency tuning of 50 MHz, which is roughly the tuning range of the CO_2 pump laser, was observed using NH_3 at 67μm. This corresponds to about an order of magnitude increase in tunability. Raman emission has the additional advantage that the power scaling behavior will also be different from normal OPM lasers, and could eventually lead to higher achievable output powers. Although very promising, this technique is still in the preliminary stages of development and more work will be needed to fully assess its true potential.

VIII. CONCLUSION

This review has summarized the state-of-the-art performance of CW SMMW sources. Each source type was introduced with a brief description of its basic operating features. The advantages and limitation of the various devices were then compared in an attempt to assess their potential for application as local oscillators in low noise heterodyne receivers.

**Unpublished article by G. D. Willenberg, U. Huebner, and J. Heppner entitled "Far Infrared CW Raman Lasing in NH_3."

The assessment of the current situation leads to the following conclusions. The combination of a sealed-off, high power OPM laser and a room-temperature Schottky diode mixer is an extremely attractive package for heterodyne systems. Present levels of performance are sufficient for many practical applications. As a consequence of the new compact and reliable laser packages, immediate applications to scientific problems and feasibility studies can be expected. The near term outlook is that OPM lasers will be implemented, simply because of their availability, throughout the SMMW range. For frequencies above 500 GHz, they are the sole alternative. In the long wavelength portion of the SMMW spectrum, backward-wave oscillators have demonstrated satisfactory performance in heterodyne systems. However, high cost, limited availability, and a reputation of short lifetime have prevented widespread applications. In spite of these limitations, backward-wave oscillators are currently the only sources of widely tunable coherent SMMW radiation. At present, solid state sources such as the IMPATT diode have not yet reached a stage of development to be useful in the SMMW region. The long range prospects are good that further efforts will lead to compact tunable solid state SMMW sources. In the near future, harmonic generators will extend the useful range of both the BWO and IMPATT devices to higher frequencies, but probably not much beyond 600 GHz.

A solid foundation now exists for continued development of SMMW sources, but SMMW technology is still in its infancy and significant work remains. As in the past, progress will depend on the synergistic relationship between practical applications and viable sources. The necessity to exploit the unique properties of SMMW radiation in important applications will accelerate the advancement of SMMW sources. Improved source performance, in turn, will multiply the number of potential applications. This cycle can be expected to continue, and significant results can be anticipated from SMMW heterodyne systems in the near future.

The assistance of my colleagues, D. T. Hodges and J. R. Tucker, in critically reviewing the manuscript is gratefully acknowledged.

REFERENCES

[1] C. B. Cosmovici, M. Inguscio, F. Strafella, and F. Strumia," On the Possibility of Submillimetric Interstellar Lines Detection by Means of Laser Heterodyne Techniques," Astrophysics and Space Sciences, 60, 475 (1979).

[2] N. C. Luhmann Jr., "Instrumentation and Techniques for Plasma Diagnostics: An Overview," in Infrared and Millimeter Waves, Vol. 2, K. J. Button, ed, Academic Press: New York (1980).

[3] H. M. Pickett, and T. L. Boyd, "A 163 Micron Laser Heterodyne Radiometer for OH: Progress Report," in Heterodyne Systems and Technology, NASA CP-2138, 1980. (Paper 21 of this compilation.)

[4] A. F. Krupnov, and A. V. Burenin, "New Methods in Submillimeter Microwave Spectroscopy," in Molecular Spectroscopy: Modern Research, Vol. II, K. N. Rao, ed., Academic Press: New York (1976).

[5] D. T. Hodges, F. B. Foote, E. E. Reber, and R. L. Schellenbaum, "Near Millimeter Wave Radiometric Imaging," Fourth International Conference on Infrared and Millimeter Waves and Their Applications, Miami, Florida, Dec. 10 - 15, (1979).

[6] H. R. Fetterman, and H. R. Schlossberg, "Submillimeter-Wave Optically-Pumped Molecular Lasers," Microwave J., 17, 35-39 (1974).

[7] D. H. Martin, and K. Mizuno, "The Generation of Coherent Submillimeter Waves," Adv. in Phys., 25, 211 - 246 (1976).

[8] B. D. Guenther, and R. T. Carruth, "Millimeter and Submillimeter Wave Sources for Radar Applications," U.S. Army Missile Research and Development Command, Technical Report H-78-6 (1978).

[9] T. Y. Chang, "Optically Pumped Submillimeter Wave Sources," IEEE Trans. Microwave Theory Tech., MTT-22, 983 - 988 (1974).

[10] B. T. Ulrich, "Josephson Effect Heterodyne Receivers," Inf. Phys., 17, 467 - 474 (1977).

[11] T. G. Blaney, "Radiation Detection at Submillimeter Wavelengths," J. Phys. E: Sci. Instrum., 11, 856 - 881 (1978).

[12] B. F. J. Zuidberg, and A. Dymanus, "Submillimeter Heterodyne Detection with a Laser Local Oscillator," Appl. Phys., 16, 375 - 379 (1978).

[13] J. L. Hirshfield, "Gyrotrons," in Infrared and Millimeter Waves, Vol 1, K. J. Button, ed., Academic Press: New York (1979).

[14] A. A. Andronov, V. A. Flyagin, A. V. Gaponov, A. L. Gol'Denberg, M. I. Petelin, V. G. Usov, and V. K. Yulpatov, "The Gyrotron: High-Power Source of Millimeter and Submillimeter Waves," Inf. Phys., 18, 385 - 393 (1978).

[15] G. Kantorowicz and P. Palluel, "Backward Wave Oscillators," in Infrared and Millimeter Waves, Vol. 1, K. J. Button, ed., Academic Press: New York (1979).

[16] M. B. Golant, Z. T. Elekceenko, Z. S. Korotkova, L. A. Lunkind, L. A. Negerev, O. P. Petrova, T. B. Rebrova, and V. S. Savelena, "Wide Range Oscillators for the Submillimeter Wavelengths," Prib. Tekh. EksP., 3, 231 - 237 (1969).

[17] B. Epsztein, "Recent Progress and Future Performances of Millimeter-Wave BWO's," Proceedings of AGARD Conference on Millimeter and Submillimeter Wave Propagation and Circuits, Munich, Germany, Sept. 4-8, (1978).

[18] Th. de Graauw, M. Anderegg, B. Fitton, R. Bonnefoy, and J. J. Gustincic, "Properties of O-Type Carcinotron Oscillators for Submm Heterodyne Spectroscopy," Third International Conference on Submillimeter Waves, Guildford, U. K., March 29 - April 1, (1978).

[19] S. Lidholm, and Th. de Graauw "A Heterodyne Receiver for Submillimeter-Wave Astronomy," Fourth International Conference on Infrared and Millimeter Waves, Miami, Florida, Dec. 10-15, (1979).

[20] A. H. F. Van Vliet, Th. de Graauw, and H. J. Schotzau, "Sub-mm Heterodyne Detection Using Carcinotron Local Oscillators and InSb Bolometer Mixers, Third International Conference on Submillimeter Waves and Their Applications," Guildford, U. K., March 29 - April 1, (1978).

[21] A. H. F. Van Vliet, and Th. de Graauw "A Heterodyne Receiver for Submillimeter Wave Astronomy", Fourth International Conference on Infrared and Millimeter Waves and Their Applications, Miami, Florida, Dec. 10-15, (1979).

[22] N. Erickson, "A 346 GHz Heterodyne Receiver and Its Use in Observations of Carbon Monoxide in Interstellar Clouds," Ph. D. Thesis, University of California, Berkeley, CA., August (1979).

[23] K. Mizuno, and S. Ono, "The Ledatron," in Infrared and Millimeter Waves, Vol. 1, K. J. Button, ed., Academic Press: New York (1979).

[24] H. J. Kuno, "IMPATT Devices for Generation of Millimeter Waves," in Infrared and Millimeter Waves, Vol. 1, K. J. Button, ed., Academic Press: New York (1979).

[25] M. E. Elta and G. I. Haddad, "High-Frequency Limitations of IMPATT, MITTAT, and TUNNETT Mode Devices," IEEE Trans. Microwave Theory Tech., MTT-27, 442 - 449 (1979).

[26] T. A. Midford and R. L. Bernick "Millimeter-Wave CW IMPATT Diodes and Oscillators," IEEE Trans. Microwave Theory Tech., MTT-27, 483 - 492 (1979).

[27] T. Ishibashi, M. Ino, T. Makimura, and M. Ohmori, Electron. Lett., 13, 299 - 300 (1977).

[28] K. Mizuno, M. Ohmori, K. Miyazawa, M. Morimoto, S. Kodaira, and S. Ono, "Frequency Stabilization of IMPATT Diodes in the Submillimeter Wave Region," Inf. Phys., 18, 401 - 403 (1978).

[29] N. J. Cronin, D. H. Martin, G. A. Ediss, and G. T. Wrixon, "Generation of Millimeter and Submillimeter Waves by Frequency Multiplication," Inf. Phys., 18, 731 - 734 (1978).

[30] T. Takada, and M. Ohmori, "Frequency Triplers and Quadruplers with GaAs Schottky-Barrier Diodes at 450 and 600 GHz", IEEE Microwave Theory Tech., MTT-27, 519 - 523 (1979).

[31] M. McColl, "Review of Submillimeter Mixers," S.P.I.E. Seminar on Far Infrared/Submillimeter Wave Tech. and Appl., Vol. 105, 24 - 34 (1977).

[32] N. R. Erickson, "A 200 - 300 GHz Heterodyne Receiver," The IEEE/MTT-S International Microwave Symposium, Washington, D. C., May 26 - 30, (1980).

[33] T. G. Phillips, P. J. Huggins, G. Neugebauer, and M. W. Werner, "Detection of Submillimeter (870 μm) CO Emission from the Orion Molecular Cloud," Astrophys. J., 217, L161 - L164 (1977).

[34] A. H. F. Van Vliet, Th. de Graauw, S. Lidholm and H. V. d. Stadt," An InSb Mixer Receiver Operating Between 440 and 530 GHz," Fourth International Conference on Infrared and Millimeter Waves, and Their Applications, Miami, Florida, Dec. 10-15, (1979).

[35] F. C. Delucia, "Millimeter-and Submillimeter-Wave Spectroscopy," in Molecular Spectroscopy: Modern Researh, Vol. II, K. N. Rao, ed., Academic Press: New York (1976).

[36] T. Y. Chang and T. J. Bridges, "Laser Action at 452, 496, and 541 μm in Optically Pumped CH_3F", Opt. Commun., 1, 423 - 426, (1970).

[37] D. T. Hodges, "A Review of Advances in Optically Pumped Far-Infrared Lasers," Inf. Phys., 18, 375 - 384 (1978)

[38] T. Y Chang, "Optical Pumping in Gases," in Topics in Appl. Phy., 16, Y. T. Shen, ed., Berlin: Springer Verlag (1977).

[39] T. A. Galantowicz, E. J. Danielewicz, F. B. Foote, and D. T. Hodges, "Characteristics of Non-Diffusion Limited Optically Pumped CW Lasers - Experimental Results for CH_2F_2," in Proceedings of the International Conf. on Lasers '78, V. J. Corcoran, ed., STS Press: McLean, VA. (1979).

[40] E. J. Danielewicz, T. A. Galantowicz, F. B. Foote, R. D. Reel and D. T. Hodges," High Performance at New FIR Wavelengths from Optically Pumped CH_2F_2," Opt. Lett., 4, 280 - 282 (1979).

[41] M. Yamanaka, "Optically Pumped Waveguide Lasers," J. Opt. Soc. Amer., 67, 7, 952 - 958 (1977).

[42] F. Kneubühl and E. Affolter," Infrared and Submillimeter-Wave Waveguides," in Infrared and Millimeter Waves, Vol. 1, K. J. Button, ed., Academic Press: New York (1979).

[43] D. T. Hodges, F. B. Foote, and R. D. Reel, "High-Power Operation and Scaling Behavior of CW Optically Pumped FIR Waveguide Lasers," IEEE J. Quantum Electron., QE-13, 491 - 494 (1977).

[44] M. S. Tobin, and R. E. Jensen, "Far IR Laser with Metal-Dielectric Waveguide To Observe the Stark Effect," Appl. Opt., 15, 2023-2024 (1976).

[45] M. Inguscio, P. Minguzzi, A. Moretti, F. Strumia, and M. Tonelli," Stark Effect on CH_3OH and CH_3F FIR Lasers: Large Frequency Tuning and Resolved Structures," Appl. Phys., 18, 261 (1979).

[46] S. R. Stein, A. S. Risley, H. Van de Stadt, and F. Strumia, "High Speed Frequency Modulation of Far Infrared Lasers Using the Stark Effect, " Appl. Opt., 16, 1893 - 1896 (1977).

[47] S. R. Stein, and H. Van de Stadt, "Electronic Tuning and Phase-Lock Technique for Optically Pumped Far-Infrared Lasers," Freq. Contr., 31 601 (1977).

[48] M. R. Schubert, M. Durschlag and T. A. De Temple, "Diffraction Limited CW Optically-Pumped Lasers," IEEE J. Quantun Electron., QE-13, 455 - 459 (1977).

[49] M. Yamanaka, "Optically Pumped Gas Lasers. A Wavelength Table of Laser Lines," Rev. Laser Eng. (Japan), 3, 57-98 (1976); M. Rosenbluh, R. J. Temkin, and K. J. Button, "Submillimeter Laser Wavelength Tables," Appl. Opt., 15, 2635 - 2644 (1976); J. J. Gallagher, M. D.

Blue, B. Bean, and S. Perkowitz, "Tabulation of Optically Pumped Far Infrared Laser Lines and Applications to Atmospheric Transmission," Inf. Phys., 17, 43 - 55 (1977).

[50] F. R. Peterson, K. M. Evenson, D. A. Jennings, and A. Scalabrin, "New Frequency Measurements and Laser Lines of Optically Pumped CH_3OH," IEEE J. Quantum Electron., QE-16, 319 - 323 (1980).

[51] A. Scalabrin, and K. M. Evenson, "Additional CW FIR Laser Lines From Optically Pumped CH_2F_2," Opt. Lett., 4, 277 - 279 (1979).

[52] J. J. Jimenez, P. Plainchamp, A. Comeron, and A. Clairon," Submillimeter Receivers: Local Oscillators and Mixers," Proceedings of AGARD Conference on Millimeter and Submillimeter Wave Propagation and Circuits, Munich, Germany, Sept. 4 - 8 (1978).

[53] C. O. Weiss, E. Bava, A. De Marchi, and A. Godone, "Injection Locking of an Optically Pumped FIR Laser," IEEE J. Quantum Electron., QE-16, 498-499, (1980).

[54] M. Inguscio, P. Minguzzi, A. Moretti, F. Strumia, and M. Tonelli, "Stark Effect on CH_3OH and CH_3F FIR Lasers: Large Frequency Tuning Resolved Structures," Appl. Phys., 18, 261 - 270 (1979).

[55] P. E. Tannenwald, "Far Infrared Heterodyne Detectors," in Heterodyne Systems and Technology, NASA CP-2138, 1980. (Paper 28 of this compilation.)

[56] N. McAvoy and V. G. Kunde, "Detection of Atmospheric Constituents Using Submillimeter Wave (SMMW) Heterodyne Radiometry," S.P.I.E. Seminar on Far Infrared/Submillimeter Wave Tech. and Appl., Vol. 105, 112 - 116 (1977).

[57] E. J. Danielewicz, E. L. Fletcher, A. R. Calloway, and D. T. Hodges, "New CW FIR Laser Sources for Plasma Diagnostics Applications," in Proc. Japan-USA Workshop on Far Infrared Diagnostics, Cambridge, Mass., Jan. 28 - 31 (1980).

[58] M. McColl, D. T. Hodges, A. B. Chase, and W. A. Garber," Detection and Mixing at Submillimeter Wavelengths Using Schottky Diodes with Low Junction Capacitance," Third International Conference on Submillimeter Waves, Guildford, U. K., March 29 - April 1 (1978).

[59] G. A. Koepf, and N. McAvoy, "Design Criteria for FIR Waveguide Laser Cavities," IEEE J. Quantum Electron., QE-13, 418 - 421 (1977).

[60] G. A. Koepf, "Sub mm Laser Local Oscillators: Design Criteria and Results," in Heterodyne Systems and Technology, NASA CP-2138, 1980. (Paper 38 of this compilation.)

[61] H. P. Röser, and G. V. Schultz, "Development of an Optically Pumped Molecular Laser," Inf. Phys., 17, 531 - 536 (1977).

[62] G. V. Schultz, E. Sauter, H. P. Röser, and W. Reinert, "Experiments for Sensitivity Enhancement of a Heterodyne Detection System at Submm Wavelengths," Fourth International Conference on Infrared and Millimeter Waves and Their Applications, Miami, Florida, Dec. 10 - 15 (1979).

[63] H. R. Fetterman, P. E. Tannenwald, B. J. Clifton, C. D Parker, W. D. Fitzgerald, and N. R. Erickson, "Far-IR Heterodyne Radiometric Measurements with Quasioptical Schottky Diode Mixers," Appl. Phys. Lett., 33, 151 - 154 (1978).

[64] W. A. M. Blumberg, H. R. Fetterman, D. D. Peck, and P. F. Goldsmith, "Submillimeter Double Resonance Study of CH_3F Using Reradiation from Schottky Barrier Diodes," Appl. Phys. Lett., 35, 582 - 585 (1979).

[65] H. P. Röser, "The Development of an Optically Pumped Submm Laser as a Local Oscillator in a Heterodyne System," Ph. D. Thesis, University of Bonn, W. Germany (1979).

TABLE I.- CRITERIA FOR COMPARISON OF CW SMMW LOCAL OSCILLATORS

- OUTPUT POWER
- FREQUENCY RANGE
- EFFICIENCY
- TUNING BANDWIDTH
- FREQUENCY STABILITY
- LINEWIDTH
- LIFETIME
- NOISE
- SIZE
- COST AND AVAILABILITY

TABLE II.- SUMMARY OF CW SMMW SOURCES

- OPTICALLY PUMPED LASERS
- BACKWARD WAVE OSCILLATORS
- JOSEPHSON JUNCTION OSCILLATORS
- IMPATT DIODES
- HARMONIC GENERATORS
- SIDEBAND GENERATORS
- ELECTRIC DISCHARGE LASERS
- GYROTRONS

TABLE III.- PROPERTIES OF BACKWARD WAVE OSCILLATORS

- ADVANTAGES
  - CONTINUOUSLY TUNABLE ELECTRICALLY
  - WIDE RANGE OF TUNABILITY
  - NARROW LINE WIDTH
  - EASILY PHASE OR FREQUENCY LOCKED
  - LOW NOISE CHARACTERISTICS
  - COMPACT
- LIMITATIONS
  - FABRICATION PROBLEMS
  - RELATIVELY HIGH COST
  - UNAVAILABILITY
  - RAPID POWER FALLOFF WITH FREQUENCY
  - REDUCED LIFETIME AT HIGH FREQUENCIES

TABLE IV.- CHARACTERISTICS 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}

TABLE V.- PROPERTIES OF IMPATT DIODES

- **ADVANTAGES**
  - COMPACT SIZE AND RUGGEDNESS
  - POTENTIAL LONG LIFE AND RELIABILITY
  - WIDELY TUNABLE
  - MODEST DC POWER REQUIREMENTS
  - POTENTIAL HIGH EFFICIENCY
- **LIMITATIONS**
  - HIGH NOISE LEVELS
  - WIDE LINEWIDTH
  - RAPID POWER FALLOFF AT HIGH FREQUENCIES
  - UNAVAILABILITY

TABLE VI.- PROPERTIES OF OPTICALLY PUMPED MOLECULAR LASERS

- **ADVANTAGES**
  - INHERENTLY NARROW LINEWIDTH
  - EASILY CONSTRUCTED AND WIDELY AVAILABLE
  - RELATIVELY INEXPENSIVE
  - WIDE SPECTRAL RANGE
  - HIGH FREQUENCY STABILITY
  - PHASE-LOCKED OPERATION DEMONSTRATED
  - VERSATILITY
- **LIMITATIONS**
  - LACK OF TUNABILITY
  - INEFFICIENT
  - HIGH POWER REQUIREMENTS
  - INSTABILITIES
  - INCREASED COMPLEXITY
  - RELATIVELY LARGE SIZE

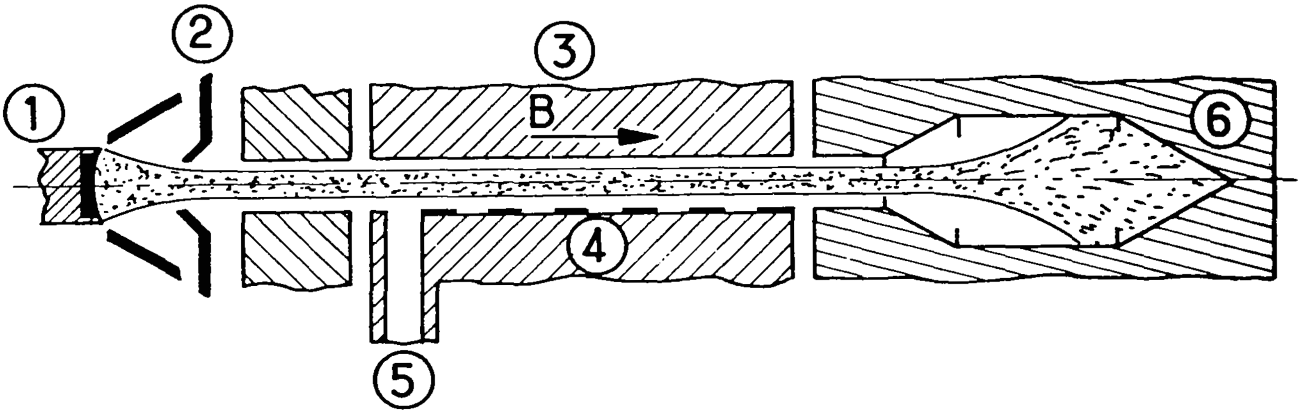

Figure 1.- Cross-sectional diagram of a backward wave oscillator (after Ref. 15).

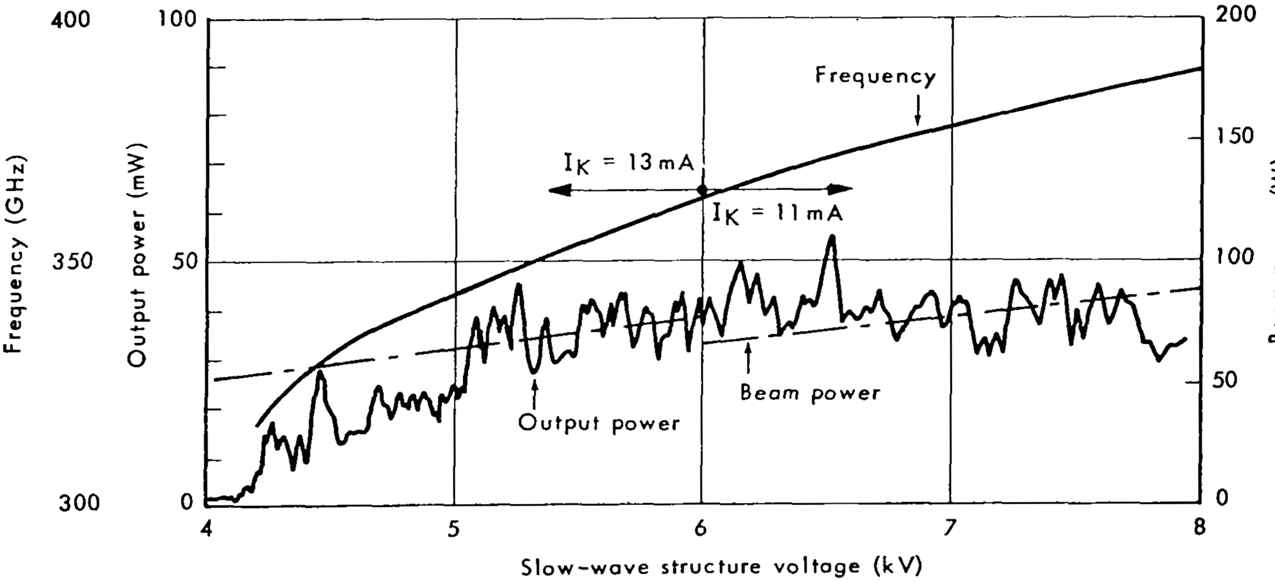

Figure 2.- Performance characteristics of a wide bandwidth medium power carcinotron (after Ref. 17).

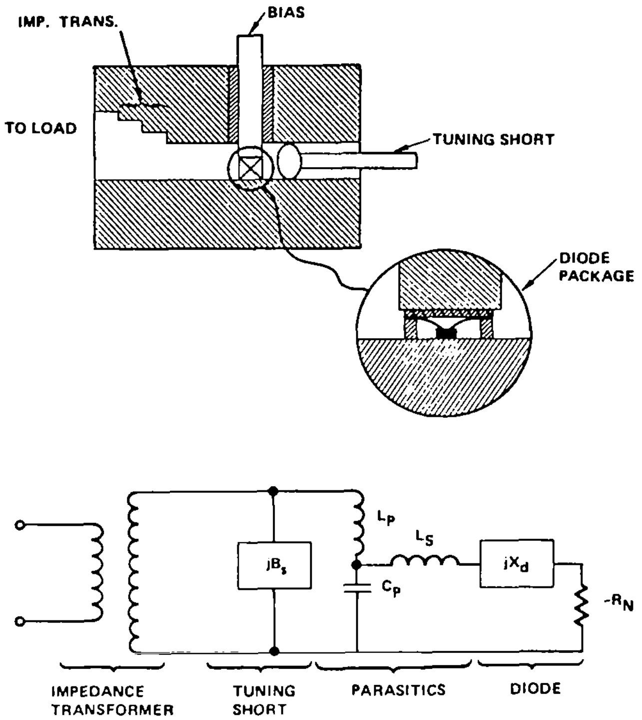

Figure 3.- Cross-sectional diagram and equivalent circuit of an IMPATT oscillator (after Ref. 24).

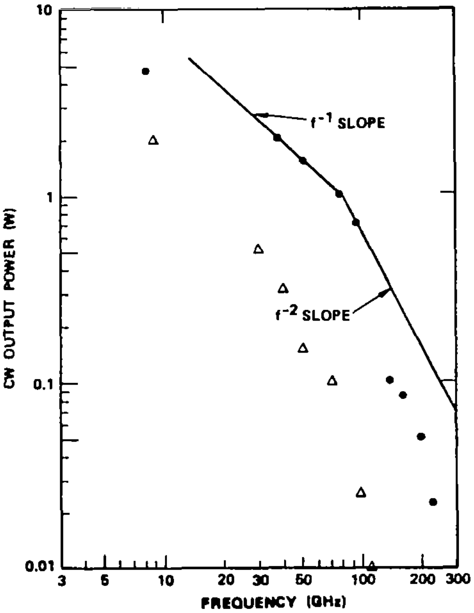

Figure 4.- State-of-the-art performance of IMPATT diodes (after Ref. 24).

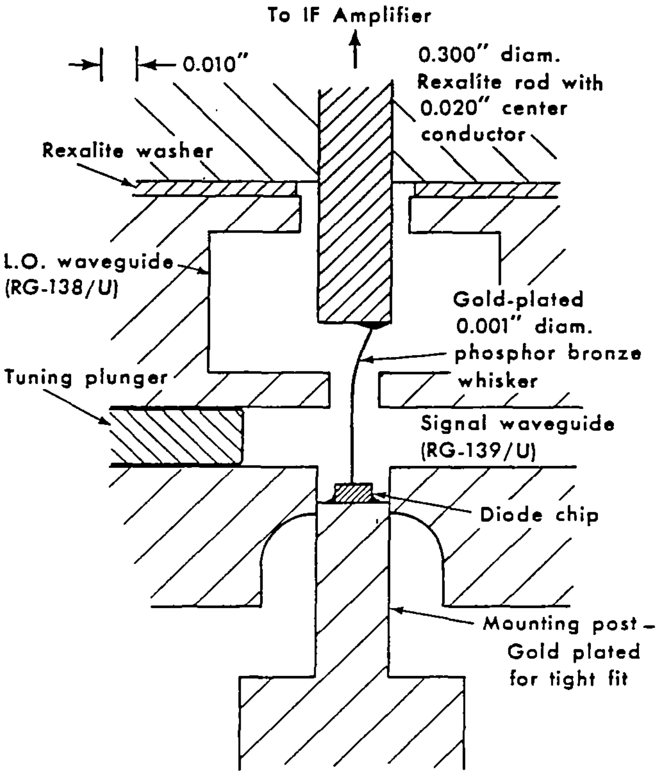

Figure 5.- Cross-sectional diagram of a crossed-waveguide mounted Schottky diode harmonic generator (after Ref. 22). 1" = 2.54 cm.

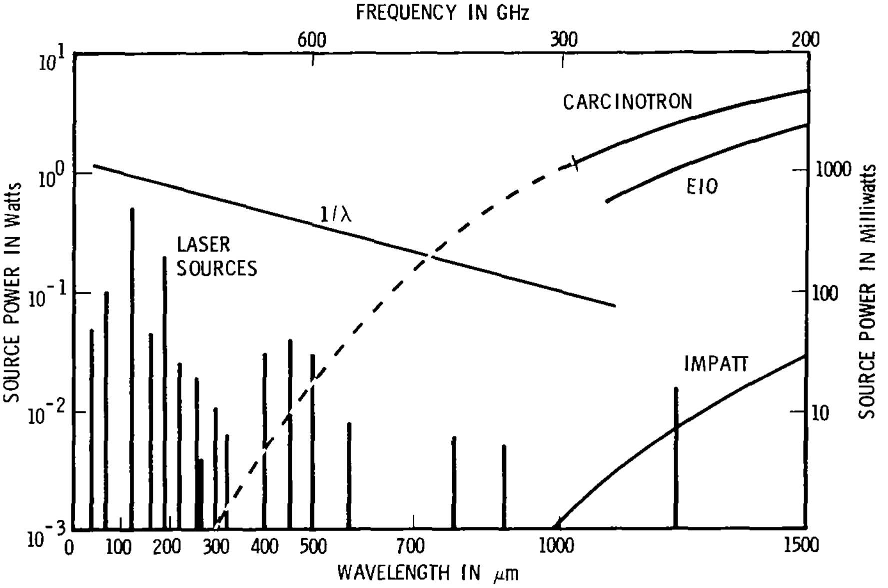

Figure 6.- Comparison of CW SMMW source technology (after Ref. 37).

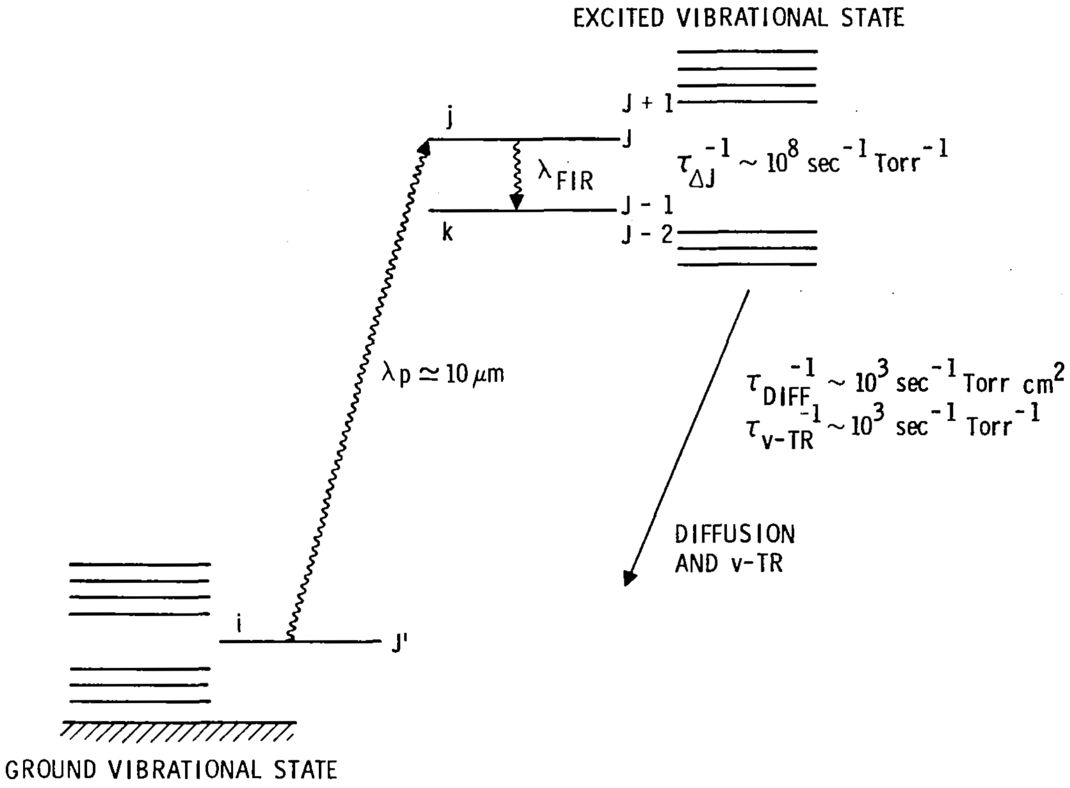

Figure 7.- Energy level diagram for an optically pumped laser.

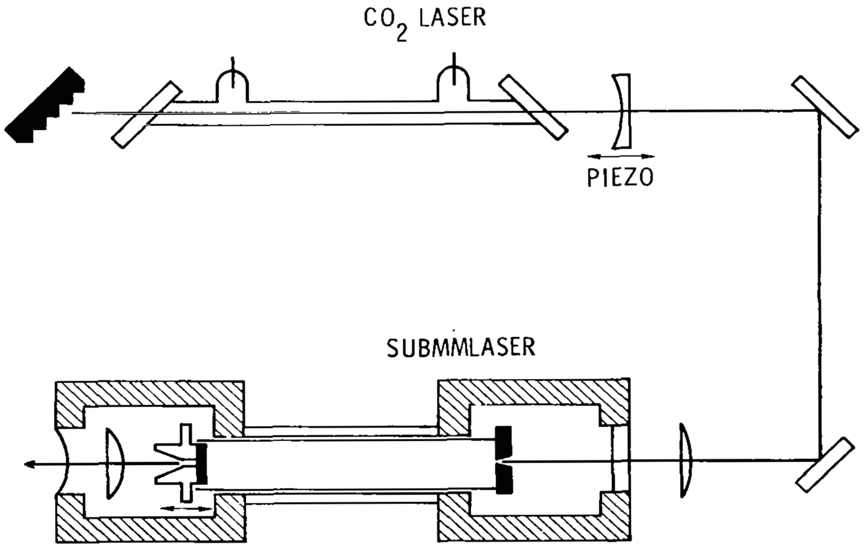

Figure 8.- Schematic of an OPM laser system.

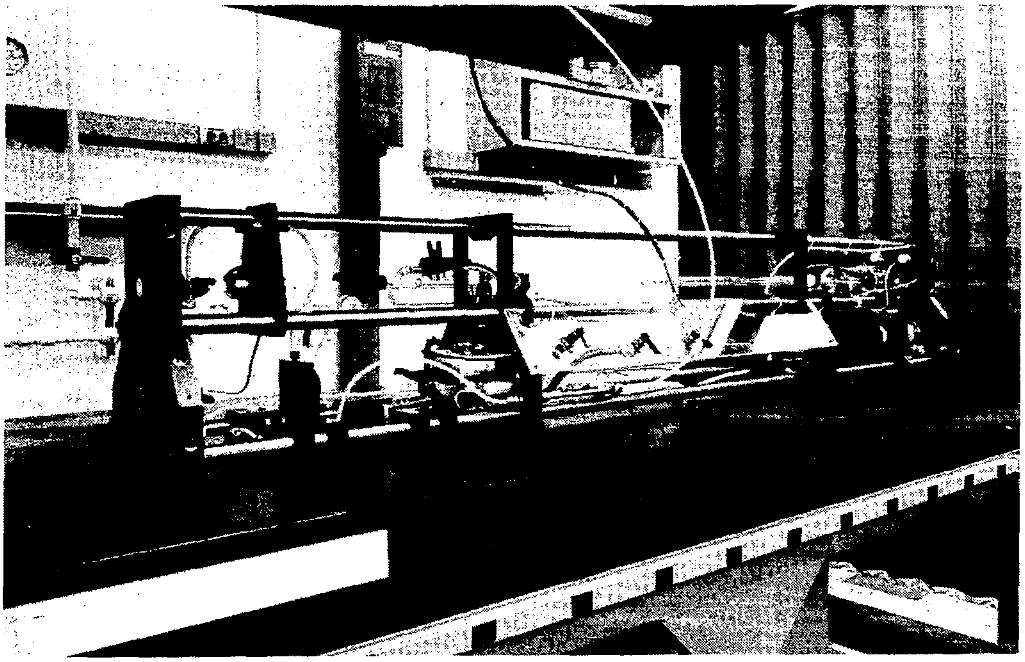

Figure 9.- Picture of Aerospace SMMW laser package.

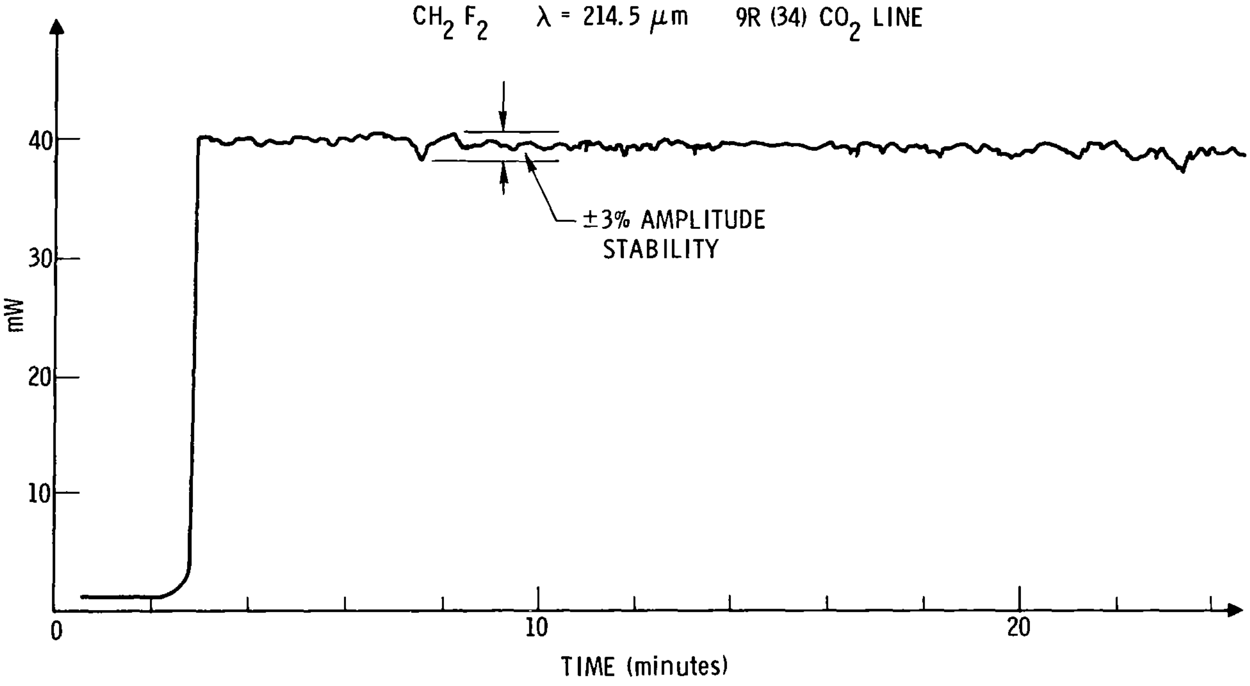

Figure 10.- Amplitude stability of OPM laser.

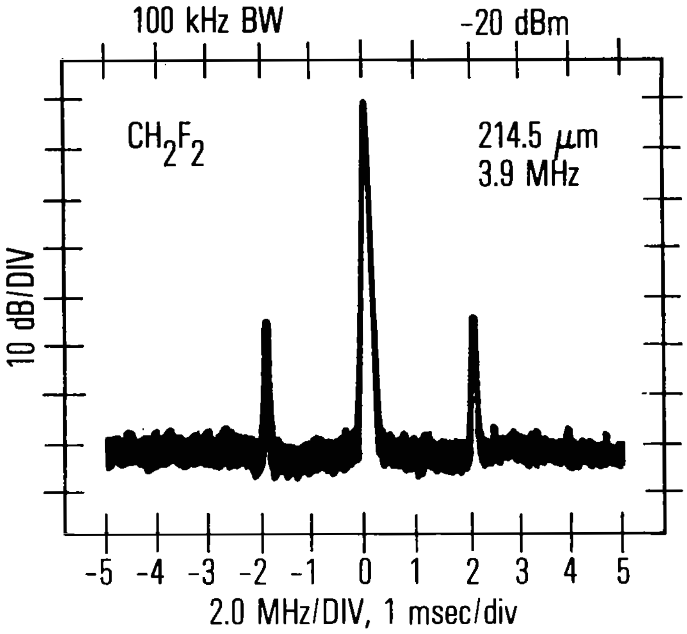

Figure 11.- Heterodyne mixing of two OPM lasers.

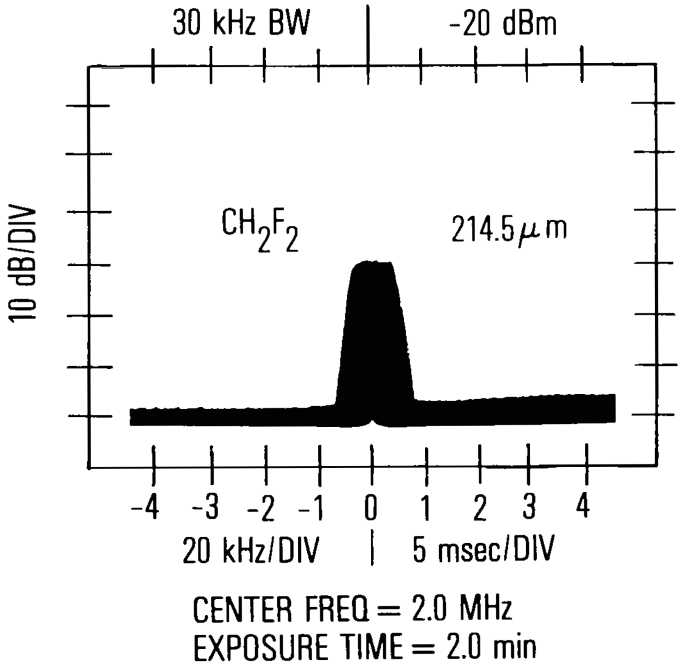

Figure 12.- Frequency jitter of heterodyne beat signal.

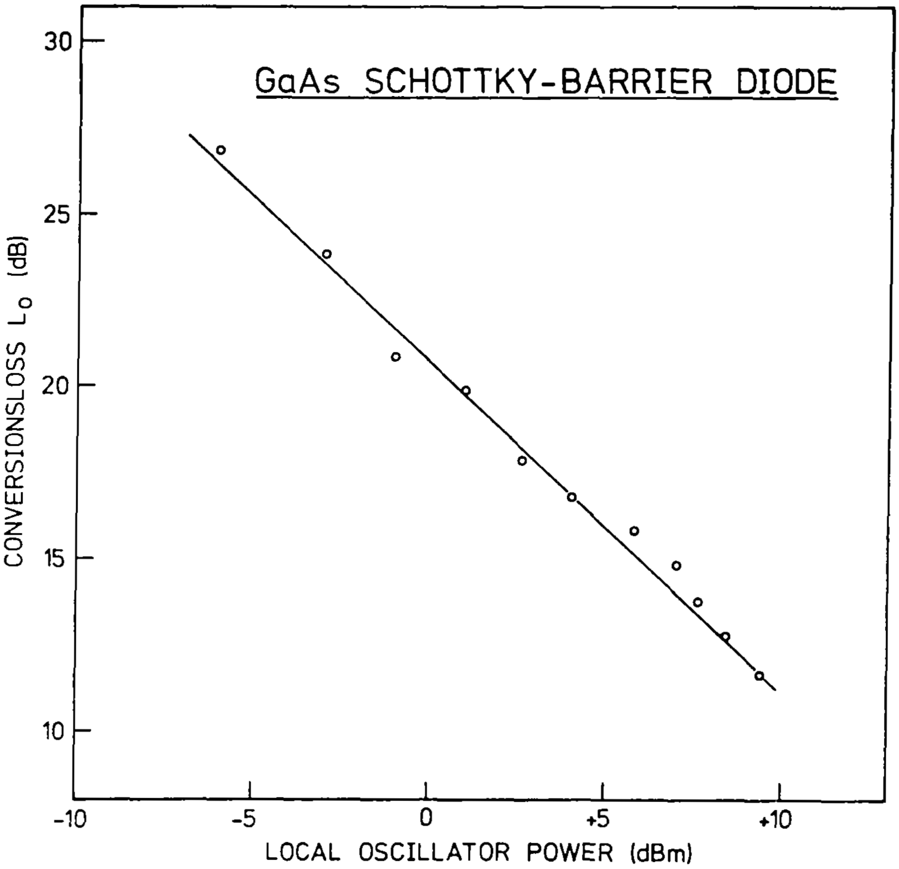

Figure 13.- Schottky diode mixer performance at 761 GHz (after Ref. 62).

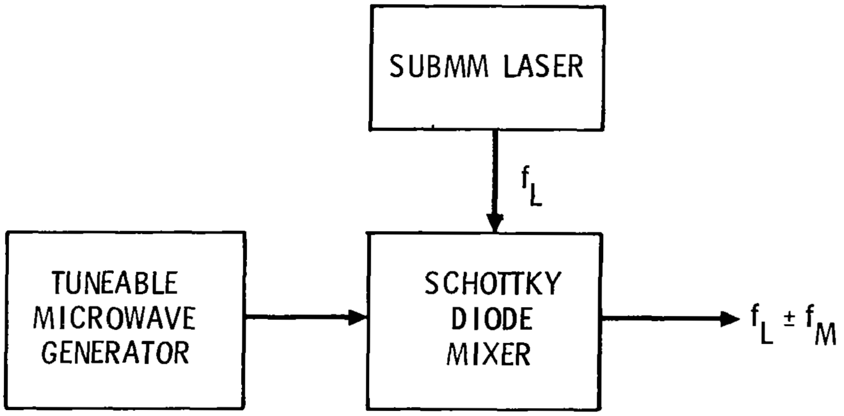

Figure 14.- Schematic diagram of a Schottky diode tuneable sideband generator.

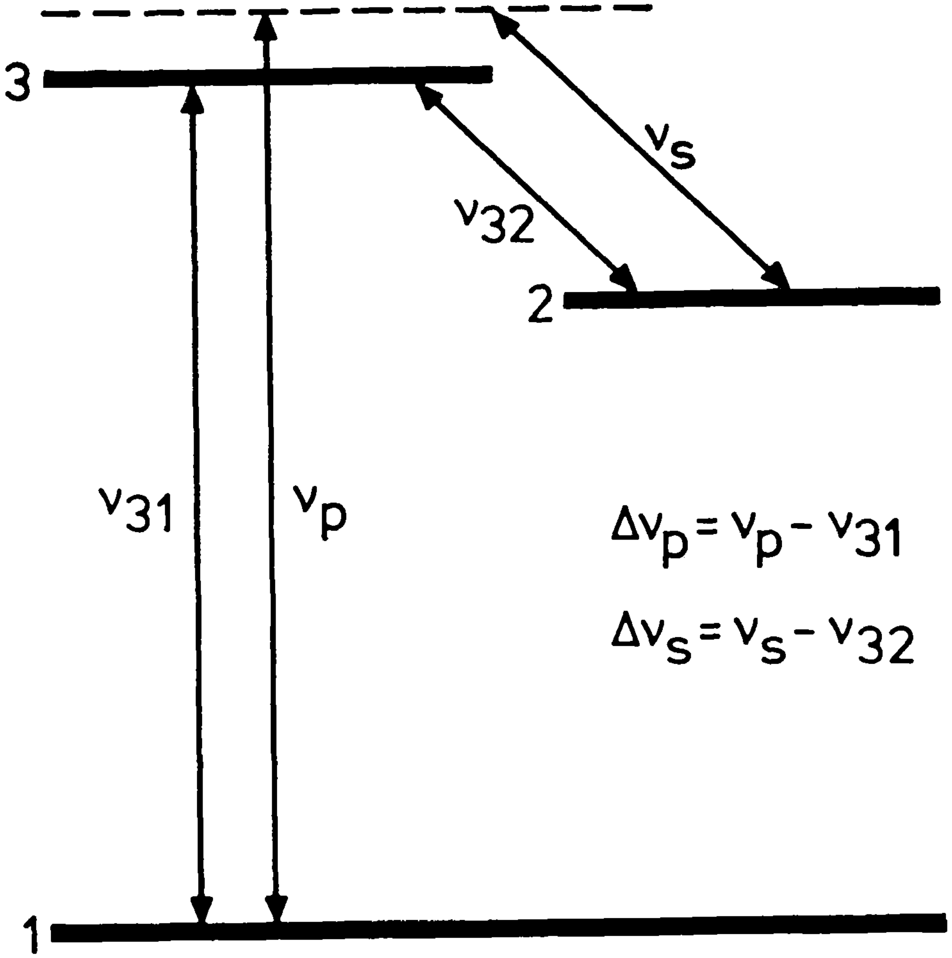

Figure 15.- Energy level diagram illustrating resonantly enhanced Raman scattering in a three-level system.