

SUBMILLIMETRIC RECEIVERS : LOCAL OSCILLATORS AND MIXERS

J. J. JIMENEZ, P. PLAINCHAMP, A. COMERON and A. CLAIRON

Laboratoire Primaire du Temps et des Fréquences (LPTF)

Observatoire de Paris et Bureau National de Métrologie
61, avenue de l'Observatoire
75014 PARIS (France)

A B S T R A C T

With submillimetric (SUBMM) devices, lasers and mixers, the classical microwave techniques may be extended up to the SUBMM range.

The best choice for the local oscillator seems to be the optically pumped FIR laser because of the high number of active lines, output power and frequency stability. For the last one, values as low as $\sigma_y(\tau) = 2 \times 10^{-13} \tau^{-1/2}$ for $\tau \leq 20$ ms and a minimum measured value $\sigma_y(100 \text{ ms}) = 2 \times 10^{-12}$ have been obtained for the CH_3OH pumped laser ($70.5 \mu\text{m}$).

For a high IF bandwidth, high multiplication order and high frequency operation, the classical mixers used in microwaves (Schottky diodes, Josephson junctions and MIM diodes) may be extended to the SUBMM as well as to the IR spectrum. Some of them have sensitivities close to the quantum limit.

Since an analysis of the optical wave propagation in the atmosphere for inclement weather operation has shown the useful windows on the SUBMM range, a SUBMM receiver appears to be very promising to operate in the battlefield on fog, rain and snow as active imaging system.

1 - THE OPTICALLY PUMPED FIR LASER

a) Introduction.

Since the discovery in 1964 of the first molecular discharge laser, the H_2O lasing at 28, 78, 79 and $118 \mu\text{m}$ (Crocker, A. et al, 1964), others submillimetric (SUBMM) discharge lasers such as the HCN , H_2S , SO_2 and OCS were built within six years.

In 1970 Chang and Bridges obtained SUBMM laser action in CH_3F by optical pumping with a CO_2 laser and in the last years, more than 1 000 new lines have been reported in the $13 \mu\text{m} - 2 \text{ mm}$ range (Yamanaka, M., 1976) that produce laser activity in about 44 polar gases.

The generation of FIR radiation arises from rotational transitions in an excited vibrational state of a low pressure polar gas, and population inversion is achieved through selective pumping involving the near-resonant absorption of radiation from a strong infra-red pump laser such as CO_2 which has about 100 lines around $9.6 -$ and $10.4 \mu\text{m}$ (for the $^{12}\text{C}^{16}\text{O}_2$ molecule). The CO_2 laser is a suitable choice for optical pump because many molecules have strong vibrational-rotational absorption lines in the $9 - 10 \mu\text{m}$ region. One of the more important molecules is the methyl alcohol (CH_3OH), lasing in 70 lines between 37 and $1217 \mu\text{m}$ (Hodges, D. T., 1977). The number of FIR lines is being increased by extending the pump frequency range to the CO_2 sequence lines (Weiss, C. O. et al, 1977) which would be further extended to the complete $9 - 12 \mu\text{m}$ CO_2 region using rare isotopes (Freed, C. et al, 1974).

b) Resonator and coupling.

The more common FIR pumped laser uses a waveguide resonator constructed from hollow cylindrical dielectric or metallic tube, in order to reduce the diffraction losses (Marcatili, E. A. J. and R. A. Schmelzter, 1964 ; Abrams, R. L., 1972). Complete data on mode properties and propagation losses have been studied for different waveguides (Yamanaka, M., 1977). In general, dielectric waveguides are used for a linearly polarized mode while metallic waveguides are quasi-randomly polarized, but these are very compact and rugged for laser construction.

Injection of the CO_2 pump into the FIR cavity is normally obtained by focusing the radiation through a hole in one of the cavity end reflectors. The outcoupling of the FIR radiation is usually performed at the opposite end of the cavity.

Figure 1 shows the common resonator and coupling configurations (Yamanaka, M., 1977 ; Hodges, D. T., 1977) :

- (a) is a conventional Fabry-Perot resonator, with free space propagation between the two mirrors. For a long cavity ($2-3 \text{ m}$) the natural divergence of free space modes at FIR wavelengths results in conventional resonators with large transverse dimensions (about 100 mm) in order to support laser modes without excessive diffraction losses.
- (b) is the more classical waveguide structure, with low losses for hollow dielectric waveguide and mirrors external to the waveguide. In metallic waveguide, with broad wavelength coverage, the mirrors need to be very close to the waveguide ends, in order to reduce the propagation losses.

(d) uses parallel plate waveguide, useful for Stark effect tuning, modulation and phase-lock (Stein, S. R. et al, 1977 ; Stein, S. R. and Van de Stadt, 1977 ; Inguscio, M. et al, 1978). Linearly polarized output can be obtained using rectangular waveguides.

(c) and (e) show outcoupling systems other than the simple hole. In (c) the outcoupling mirror may be a metallic mesh (inductive grid or capacitive grid) or hybrid metal-mesh dielectric mirror (Danielewicz, E. J. et al, 1975) that couple the total mode out of the laser with a minimum angular divergence for the beam. Other mirror coupling, a variation of the conventional coupling hole, uses a high reflectivity dielectric coating for the CO₂ radiation and a metallic evaporated hole for the FIR outcoupling (Hodges, D. T. et al, 1976). Increasing the pumping efficiency, FIR output powers as high as 400 mW at 119 μm and 100 mW at 70 μm have been obtained (Hodges, D. T. et al, 1976). This system is useful up about 100 μm.

(e) is a special outcoupling developed for the 70 μm line of the CH₃OH (Plainchamp, P. to be published, 1978). A salt window (s. w in figure 1e) (KCl) at the Brewster angle for the CO₂ radiation reflects the 70 μm radiation with about 89 % reflectivity. An external concave gold mirror re-injects the CO₂ beam into the FIR cavity, increasing the pump efficiency. Such system is only useful around the 70 μm wavelength since the potassium-chloride has a high reflexion factor just around this wavelength.

c) Output power.

The state of the art of millimetric and submillimetric wave sources (fig. 2) shows that the CW optically pumped FIR laser presents good performance between 42 μm and 1 222 μm (Fesenko, L. D. and S. F. Dyubko, 1976 ; Hodges, D. T. et al, 1976 ; Hodges, D. T. et al, 1977 ; Schubert, M. R. et al, 1977 ; Evenson, K. M. et al, 1977a ; Hodges, D. T., 1977a), where powers from 10 to 400 mW have been obtained using 20 - 40 W of CO₂ pump power. The stronger lines have been obtained at 70 μm (110 mW) (Evenson, K. M. et al, 1977a) and 119 μm (400 mW) (Hodges, D. T. et al, 1976) for the CH₃OH pumped laser. For the discharge FIR laser, the maximum reported output powers are at 337 μm (160 mW) (Belland, P. 1976) and at 190/195 μm (250 mW) (Veron, D. et al, 1978) for the HCN and DCN lasers respectively (fig. 2).

For $\lambda > 450 \mu\text{m}$ only the Backward-Wave Oscillator (BWO) has higher power than the lasers (Bonney, R. et al, 1977). But in the range $40 \mu\text{m} < \lambda < 400 \mu\text{m}$ the laser output powers are one to three orders higher than the best reported values of the CW BWO (Bonney, R. et al, 1977).

The values of other tubes and solid state sources (fig. 2) are from (Kaisel, S. F., 1977) and (Kuno, H. J. and T. T. Fong, 1978).

d) FM noise and stability.

One of the more important characteristics of a local oscillator is its FM intrinsic noise. A good frequency stability can be expected from such laser due to the absence of free electrons in the optical cavity (Weiss, C. O. and G. Kramer, 1975).

One method to define the oscillator FM noise is the measurement of its fractional frequency stability (Allan variance) versus the average measurement time (Rutman, J., 1978). Figure 3 shows the frequency stability of the IF signal (180 KHz) obtained beating two similar (2 m long) free running CH₃OH laser (70.5 μm, 4.25 THz) pumped by the same free running CO₂ laser (Plainchamp, P. to be published, 1978). The mixer is a metal-insulator-metal (MIM) diode. In curve C the measurement was realized through a wide-band post-detection amplifier (0.01 - 400 MHz). This curve is similar to previously published ones (Jimenez, J. J. and F. R. Petersen, 1977 ; Jimenez, J. J. et al, 1978), obtained using a 0.1 - 1 200 MHz amplifier and a 2 MHz beat note. The stability measurement is probably limited by the wide-band amplifier noise.

Curve D shows the frequency stability of the same beat note using a narrow-band amplifier (0 - 5 MHz) (Plainchamp, P. to be published, 1978). For $\tau \leq 20$ ms a nearly white frequency noise is obtained, $\sigma_y(\tau) = 2 \times 10^{-13} \tau^{-1/2}$, with a minimum value $\sigma_y(\tau) = 2 \times 10^{-12}$ for $20 \text{ ms} \leq \tau \leq 100 \text{ ms}$. For longer times ($\tau \geq 100 \text{ ms}$) the laser drift with a law $\sigma_y(\tau) \approx 1.5 \times 10^{-11} \tau$ mainly due to the FIR cavity drift and CO₂ drift.

The 22W CO₂ laser (used to pump both FIR lasers) frequency stability has been measured by comparing it with a high stability free-running low-power (2 W) CO₂ laser (Jimenez, J. J. et al, 1978). Its frequency stability (fig. 4, curves A and B) is about the same order of magnitude than the high stability laser, in despite of its high output power. Curve A is obtained under conditions where the CO₂ laser is not coupled to the FIR laser, and curve B when the CO₂ is pumping the FIR laser : a slight degradation due to the back-coupling effect (optical feedback from the FIR cavity) appears only for $\tau \geq 30$ ms, in good agreement with (Godone, A. et al, 1978).

The CH₃OH (70 μm) stability values are about three orders of magnitude better than the obtained with free running SUBMM lasers, such as the HCN laser (337 μm, $\sigma_y(\tau) \approx 10^{-9}$ for $10^{-4} \leq \tau < 20$ s) (Wells, J. S., 1973) and far enough from the equivalent values obtained with free running millimetric tubes or solid state oscillators (typical values are $\sigma_y(\tau) = 10^{-7} - 10^{-8}$ for $\tau = 1$ s). The CH₃OH (70 μm) free running laser stability is only similar to that of the best stabilized FIR laser, the phase-locked HCN laser (Wells, J. S., 1973) and may be compared, in the short term ($\tau \leq 0.1$ s) with other well stabilized lasers such as the CO₂ (CO₂ stabilized) (Freed, C. 1976).

e) Long term frequency stabilization.

Until now, no classical stabilization techniques, used for other lasers have been applied to ameliorate the long term stability of the FIR laser. Instead, electronic tuning techniques have been developed for FIR lasers which make it possible both, to frequency modulate the laser at very high rate, and to phase-lock it to a reference oscillator (Stein, S. R. et al, 1977 ; Stein, S. R. and H. Van de Stadt, 1977 ; Inguscio, M. et al, 1978). Tuning is achieved by applying an electric field (Stark effect) across the laser medium (fig. 1d). This method avoid the introduction of lossy materials inside the cavity and provides high speed frequency tuning, limited only by the life time of photons inside the cavity.

Stark modulation has been applied to the CH₃F (496 μm) laser as well as to the CH₃OH laser (119 - and 70 - μm). Frequency shifts versus field strength are about 5 KHz/(V/cm) for the CH₃F (Stein, S.R. et al, 1977) ; 29 KHz/(V/cm) for the 119 μm

line of CH_3OH (Inguscio, M. and F. Strumia, private communication, 1978) and 45 KHz/(V/cm) for the 70 μm line of CH_3OH (Inguscio, M. and F. Strumia, private communication, 1978) and we expect the best tuning range for the 70 μm line.

Using Stark effect, a bandwidth tunability of many MHz has been obtained until now in the CH_3F (496 μm) (Strumia, private communication, 1978) but higher values may be expected. Up to date, the BWO bandwidth tunability (20 %) is much better (Bonney, R. et al, 1977).

f) The optically pumped FIR laser as local oscillator.

Because of its useful output power, high number of emission lines, high free running frequency stability and possibility of tunability, the optically pumped FIR laser could be the best choice for local oscillator (L. O.) in the SUBMM region. The 70.5 μm line of the CH_3OH laser will be used in frequency synthesis as a SUBMM frequency secondary standard for further frequency multiplication to measure to parts in 10^{12} the frequency of the helium-neon methane-stabilized laser (3.39 μm) in a very accurate laser frequency synthesis chain (Jimenez, J. J., 1978b).

2 – THE MIXER

With an appropriate choice of the nonlinear device and a source of coherent radiation, it will be possible to built low noise SUBMM receivers in a large frequency domain.

Two methods may be considered :

- 1) a detector with a high quantum efficiency ($\eta \approx 1$) but with a small bandwidth (about 100 MHz) combined with a tunable or fixed L. O., and
- 2) a detector with a low quantum efficiency ($\eta \ll 1$) but with a large bandwidth ($\gg 1$ GHz) combined with a L. O. of different fixed frequencies, such as the FIR pumped laser.

The classical optical detectors (Keyes, R. J., 1977) may be classified in two groups that differ by the physical mechanism involved in the detection process :

- a) the thermal detectors, where the heating of the incident radiation causes a change in some electrical properties of the detector, and
- b) the quantum (or photon) detectors, where there is a direct interaction between the incident photons and the carriers of the detector material.

The thermal detectors respond theoretically equally to all wavelength, but practical limitations of available blackening material often modify this assumption. The more important thermal detectors are the thermocouple, the bolometer, the pneumatic (Golay detector) and the calorimeter. The time constant of a thermal detector is usually between a few milliseconds and a few seconds.

The quantum detectors have shorter time constants, inferior or equal to a few microseconds, but its response varies with the wavelength. The more important quantum detectors are the photoelectric (or photoemissive), the photoconductive (intrinsic, extrinsic or free carrier) and the photovoltaic (p-n junction) detector. The photoconductive (extrinsic and hot electrons) detectors seem to be very promising mixers in the 100 – 2000 μm region, but the higher IF bandwidths obtained are inferior to 200 MHz, and in general, only a few MHz (Mc Coll, M., 1977).

The faster detectors used in the optical region are devices that extend the classical function of the microwave mixer through the SUBMM region as well as to the IR spectrum, to wavelengths as short as 1.52 μm (Evenson, K. M. et al, 1977b). The more used are the point contact diodes (metal-semiconductor, metal-insulator-metal (MIM), superconductor-insulator-superconductor (Josephson junction, J. J.) and the Schottky barrier diodes. Some of them (MIM and Schottky barrier diodes) have been built in planar structure. (For a review of SUBMM and IR mixers, see Pyée, M. and J. Auvray, 1975 ; Knight, D. J. E. and P. T. Woods, 1976 ; Mc Coll, M. 1977 ; Jimenez, J. J., 1978a).

The main parameters to choose a heterodyne mixer are its sensitivity (or noise temperature), bandwidth and operating temperature. Only the JJ and the photoconductive mixers work at liquid helium temperatures. The Schottky barrier diode has been some times cooled in order to improve its noise temperature (Kerr, A.R., 1975).

Table 1 summarizes the main parameters of the highest frequency nonlinear devices, used as detectors (wavelength limit) and as mixers (heterodyne detectors) in the FIR and the IR*.

In the SUBMM range, the more used are the Si-metal (PC), Ga-As-metal (PC and planar Schottky barrier) and the Josephson junction (PC). All them have a cutoff frequency in the few THz range and high multiplication orders (Table 1), the higher ones (401 and 825) corresponding to the JJ. Moreover, this device and the Schottky barrier diode, have the lowest noise as heterodyne receivers.

The Ge-metal (PC) and the In As-metal (hot carrier diode) (PC) have permitted to detect the 10 μm radiation. A mixing between two CO_2 lasers has been obtained with the last one, giving a 50 GHz beat note (Aukerman, L. W. and J. W. Erler, 1977).

The Metal-Insulator-Metal (MIM) (PC) diode, first used in MIT (Hocker L. O., et al, 1978) is the main device in the complete IR range. It is realized from a whisker (tungsten wire, 10 to 25 μm diameter) electrochemically sharpened to a tip radius of 50 – 100nm,

* For a complete reference of the values reported on table 1 and figure 4, see (Jimenez, J. J., 1978a and Mc Coll, M. 1977).

in contact with a polished base (nickel). A natural oxide layer, 1 – 2 nm width, is between the two metals. The straight portion of the whisker from the tip to a right angle bend serves as antenna (Matarrese, L. M. and K. M. Evenson, 1970) to concentrate the focused laser field at the tip. The same type of optical coupling is used for the others PC diodes, and antenna gains of 6 – 12 dB have been obtained in the SUBMM range using some special reflector (Krautle, M. et al, 1978 ; Fetterman, H. R. et al, 1978).

The highest frequency ever mixed, 197 THz (1.52 μm) (Evenson, K. M. et al, 1977b) has been obtained with the MIM point contact diode.

Typical IF bandwidth for the PC devices are in the 1 – 100 GHz range, with sensitivities (minimum detectable powers*) comparable and even better than the values obtained with photoconductive devices. Figure 4 shows the MDP (and noise temperature) for several mixers or receivers (filled-in data points) in the millimetric, submillimetric and infrared range. Among them, the J J and the Schottky diodes seem to be the more useful devices in the MM and SUBMM range, with MDP values about one order of magnitude higher than the quantum limit for the J J, and about two to three orders higher than the quantum limit for the Schottky diodes, in the 500 μm – 10 mm range.

The planar structure diodes, Schottky barrier and MIM (Jimenez, J J , 1978a) seem also very interesting in the SUBMM range.

Table 1 . Summary of performance characteristics of the common optical frequency detectors and mixers devices. Although some of the data has been obtained by private communications, most has been reported in the literature (Jimenez, 1978a). For a given detector, values reported in the table are not necessarily from the same experiment.

DETECTOR	Detection	Harmonic generator and mixer (heterodyne)				
	Wavelength limit (μm)	Frequency limit ν_1 (b) (ν_2) (c) (THz)	Multi- plication order	Time response (e) ($\tau=1/\nu_1$ (fs)	MDP ^(a) at frequency ν	
					MDP (WHz^{-1})	ν (THz)
1. Point contact						
1.1. Metal-Semiconductor (MS)						
Si (PC) (e)	84	{ 3.56 (1.58)	4 23	280	*	*
Ge (PC)	10.6	*	*	*	*	*
Ga As (PC)	337	0.89	9	1120	2×10^{-14}	0.89
Ga As (SB) (f)	{ 5 (g) 10.6 (g) 42	{ 4.25 2.52	1 (h) 33	235	{ 5×10^{-17} 1 to 2×10^{-19}	2.52 0.76 to 0.32
In As (PC)	10.6	28.3	1 (h)	35	10^{-8}	28.3
1.2 Metal-Insulator-Metal (MIM) (PC)						
	{ 0.5 (g, i) 1.52 (j)	{ 197 (88) (10)	1 (k) 3 (l) 15	5	{ 10^{-13} $10^{-15} - 10^{-16}$	28.3 0.89
1.3. Superconductor-Insulator-Superconductor Josephson Junction (PC)						
	{ 9.5 (g) 70.5	{ 4.25 (3.8) (0.89)	43 401 825	235	{ 10^{-17} 6×10^{-20} 3×10^{-21}	0.89 0.45 0.32
2. Planar structure						
2.1 Metal-Semiconductor (MS) Ga As (SB)						
	337	0.76	82	1316	*	*
2.2 Metal-Insulator-Metal (MIM)						
	{ 0.45-0.6 (g) 3.39 10.6	0.89	13	1120	*	*

(a) MDP : Minimum detectable power, represents the sensitivity of a mixer (coherent or heterodyne detector) or a receiver, in a normalized bandwidth $B = 1$ Hz. It is expressed in units of W.Hz^{-1} . $\text{MDP} = kTB_{\text{IF}}$, where k is the Boltzman's constant, T the mixer (or receiver) noise temperature and B_{IF} the IF bandwidth. The quantum limit is $h\nu = kT$.

(b) ν_1 is the highest frequency obtained with the device.

(d) $1 \text{ fs} = 10^{-15} \text{ s}$.

(c) (ν_2) (many values may be reported) is the highest frequency obtained for the highest multiplication order (next column).

(*) no available data

* See definition in table 1.

- | | |
|--|--|
| (e) PC = point contact | (i) positive rectified voltage |
| (f) SB = Schottky barrier | (j) negative rectified voltage |
| (g) rectification may be thermal | (k) three frequencies mixing without harmonic generation |
| (h) two frequencies mixing without harmonic generation | (l) three frequencies mixing with harmonic generation |

In order to choose the best mixer, we require some display of the difference frequency between the signal and the known reference frequency of the L. O., radiating in the same spectral region. There are two main possibilities :

- a) the simplest technique would be to heterodyne the signal with an harmonic of an electronically measurable L. O. frequency, directly generated in the nonlinear device. Such devices should be capable of high-order harmonic generation and need to have high cutoff frequencies. The metal-semiconductor PC, Schottky barrier diode and J J seem to be the best choice up to a few THz.
- b) we may mix the signal with a spectrally adjacent known L. O. in a wideband device. If necessary this difference is down-converted to a frequency within the response band of the device by mixing it with other radiation (usually microwaves). In this case the PC and Schottky barrier diodes may be the best choice, specially if the difference between signal and L. O. is large.

Optical frequency mixing is a new subject, but commercial development of SUBMM devices is limited to photodiodes and Schottky diodes. Other devices (JJ, MIM and in general PC diodes) are very delicate and need to be used in special laboratories. For frequencies higher than a few THz, the MIM diode is up to day the best choice.

3 – FIR WAVE PROPAGATION

Two cases need to be considered : a) the optical beam propagation at the top of the earth's atmosphere, and b) the optical beam propagation at the earth atmosphere. The first case apply to the space research, specially interstellar astronomical observations ; the second case concern the earth communications, civil or military.

The molecular line astronomy can be used as a diagnostic tool for the study of the physical conditions, such as mass, density and temperature of the interstellar gas. Rotational transitions of many molecules (H_2O , HCN, OCS, NH_3 , HCOOH, CH_3OH , etc. . .) occur in the MM and SUBMM regions. In these cases, the receiver is over the top of the earth's atmosphere and its attenuation is not important.

In the second case, although the atmosphere is quite transparent in the visible and near infrared, attenuation is high into the SUBMM region. This is due to absorption of the radiation by the atmospheric constituents, the greatest problem arising from the water vapor.

Operation in inclement weather (rain, fog or snow), as it is founded in Europe, favors the near and intermediate IR regions (1 – 25 μm) and the SUBMM region (beyond 300 μm) (Kruse, P. W. and V. Garber, 1976 ; Hartman, R. L. and P. W. Kruse, 1976). In fact, the inclement weather is characterized by a distribution of particule size : at wavelength much smaller than the particle diameter the scattering of radiation is relatively independant of wavelength. In fog conditions, the more useful windows are at 337, 750, 850 and 1 300 μm (Kruse, P. W. and V. Garber, 1976), where FIR lasers are available. Experiments at 850 μm have showed the advantages of a such receiver compared with a 3 mm receiver (Hartman, R. L. and P. W. Kruse, 1976). In these conditions, a SUBMM receiver appears to be very promising to operate in the battlefield on inclement weather as active imaging system.

However, greater receiver sensitivity and/or power output of the laser sources, and more experimental studies on SUBMM propagation are needed in this wavelength region.

R E F E R E N C E S

- ABRAMS, R. L. (1972) "Coupling losses in hollow waveguide laser resonators" IEEE J. Quant. Electr., QE-8, 11, pp. 838-843.
- AUKERMAN, L. W. and J. W. ERLER, (1977) "Infrared hot carrier diode mixers", Optics Lett., 1, 5, pp. 178-180.
- BELLAND, P., (1976) "Lois d'échelle pour la conception optimale des lasers HCN (337 μm) continus utilisant l'effet de guide d'onde." Thesis, University of Paris, January, 259 pages.
- BONNEFOY, R. , G. KANTOROWICZ and P. PALLUEL, (1977) "Broadbanding of a submillimetre π -wave Backward - wave oscillator" Proc. 7th European Microwave Conf., Copenhagen Denmark, Sept. pp.
- CHANG, T. Y. and T. J. BRIDGES (1970) "Laser action at 452, 496 and 541 μm in optically pumped CH_3F ". Optics Comm. 1, 9 pp. 423-426.
- CROCKER, A. ; H. A. GEBBIE, M. F. KIMMITT and L. E. S. MATIAS. (1964) "Stimulated emission in the far-infrared". Nature, 201, pp. 250-251

- DANIELEWICZ, E. J. ; T. K. PLANT and T. A. DETEMPLE (1975) "Hybrid output mirror for optically pumped far infrared lasers". Opt. comm., 13, pp. 366-369.
- EVENSON, K. M., D. A. JENNINGS, F. R. PETERSEN, J. A. MUCHA, J. J. JIMENEZ, R. M. CHARLTON and C. J. HOWARD (1977a), "Optically pumped FIR lasers : frequency and power measurement and laser magnetic resonance spectroscopy" IEEE Jour. Quant. Electr., QE-13, 6, pp. 442-444
- EVENSON, K. M., D. A. JENNINGS, F. R. PETERSEN and J. S. WELLS (1977 b)"Laser frequency measurements : a review, limitations, extension to 197 THz (1.5 μm);" Laser Spectroscopy III, editor J. L. Hall and J. L. Carlsten, Springer-Verlag, Berlin, pp. 56-68.
- FESENKO, L. D. and S. F. DYUBKO (1976) "Optimization of the parameters of optically pumped submillimetric lasers" Sov. Jour. Quant. Electr., 6, 7, pp. 839-843.
- FETTERMAN, H. R. ; P. E. TANNENWALD, B. J. CLIFTON, C. D. PARKER, W. D. FITZGERALD and N. R. ERICKSON, (1978) "Far IR heterodyne radiometric measurements with quasi-optical Schottky diode mixers". To be published IEEE Trans. Microwave Theory and Techniques.
- FREED, C. ; A. H. M. ROSS and R. G. O'DONNELL, (1974) "Determination of laser line frequencies and vibrational-rotational constants of the $^{12}\text{C}^{18}\text{O}_2$, $^{13}\text{C}^{16}\text{O}_2$ and $^{13}\text{C}^{18}\text{O}_2$ isotopes from measurements of CW beat frequencies with fast HgCdTe photo-diodes and microwave frequency counters". Jour. Molecular Spectroscopy, 49, pp. 439-453.
- FREED, C and R. G. O'DONNELL, (1976) "Advances in CO_2 laser stabilization using the 4.3 μm fluorescence technique". 2nd Frequency Standards and Metrology Symposium, Copper Mountains, Co, USA, 5-7 July.
- GODONE, A. C. O. WEISS and G. KRAMER, (1978) "FM-noise measurements on an optically pumped FIR laser". IEEE Jour. Quant. Electr., QE-14, 5, pp. 339-342.
- HARTMAN; R. L. and P. W. KRUSE, (1976) "Submillimeter system for imaging through inclement weather". Proc. 2nd International Conf. and Winter School on Submillimeter waves and their applications, San Juan, Puerto Rico, 6-11 December, pp. 229-230.
- HOCKER, L. O., D. R. SOKOLOFF, V. DANEU, A. SZOKE and A. JAVAN, (1968) "Frequency mixing in the infrared and far-infrared using a metal-to-metal point contact diode". Appl. Phys. Lett., 12, 12, pp. 401-402.
- HODGES, D. T. ; F. B. FOOTE and R. D. REEL, (1976) "Efficient high-power operation of the CW far-infrared waveguide laser" Appl. Phys. Lett., 29, 10, pp. 662-664.
- HODGES, D. T. ; F. B. FOOTE and R. D. REEL, (1977) "High-power operation and scaling behavior of CW optically pumped FIR waveguide lasers" IEEE Jour. Quant. Electr., QE-13, 6, pp. 491-494.
- HODGES, D. T. , (1977) "CW (continuous wave) optically pumped FIR (far infrared) lasers". Proc. of the Soc. Photo-optical Instrumentation Engrs.(SPIE), Vol 105, Far infrared/Submillimeter wave. Technology/Applications, pp. 6-10.
- INGUSCIO, M. ; P. MINGUZZI, F. STRUMIA and M. TONELLI, (1978) "The Stark effect as a means for frequency tuning optically pumped FIR lasers". Proc. 3rd International Conf. on Submillimetre Waves and their applications, University of Surrey, Guildford, U.K., 29 March-1 April, pp. 144-145.
- KAISEL, S. F., (1977) "Microwave tube technology review", Microwave Jour. 20, 7, pp. 23-42.
- KERR, A. R. (1975) "Low-noise room-temperature and cryogenic mixers for 80 -120 GHz" IEEE Trans. Microw. Theory Techn. MTT-23, 10, pp. 781-787.
- KEYES; R. J. (1977) "Optical and Infrared Detectors" 7 review papers. Edited by R. J. Keyes, Springer-Verlag, Berlin 304 pages.
- KNIGH, D. J. E. and P. T. WOODS, (1976) "Application of nonlinear devices to optical frequency measurements" Jour. Phys. E., 9, pp. 898-916.
- KRAUTLE, H., ; E. SAUTER and G. V. SCHULTZ, (1978) "Properties of a submillimeter mixer in a open structure configuration." To be published. Also, 1977, "Antenna characteristics of whisker diodes used as submillimeter receivers" Infrared Phys. 17, 6, pp. 477-483.
- KRUSE, P. W. and V. GARBER, (1976) "Technology for battlefield target recognition in inclement weather" Proc. IRIS (23).
- KUNO, H. J. and T. T. FONG, (1978). "Solid-state millimeter-wave sources". EASCON Conf., Washington, D. C.
- JIMENEZ, J. J. and F. R. PETERSEN, (1977) "Recent progress in laser frequency synthesis" Infrared Physics, 17, 6, pp. 541-546.
- JIMENEZ, J. J. ; F. R. PETERSEN, P. PLAINCHAMP, C. SALLOT and X. DRAGO, (1978). "Mesure des fréquences optiques au LPTF" Bull. d'Information BNM (France), 9, 31, pp. 19-27.
- JIMENEZ, J. J., (1978a), "Synthèse et mesure des fréquences optiques" Revue Phys. Appl. (France). To be published.
- JIMENEZ, J. J., (1978b), "Microwave to visible frequency synthesis" URSI Open Symposium on Time and Frequency, Session OS1/1.2, Helsinki, Finland, 1-4 August.

- MARCATILI, E. A. J. and R. A. SCHMELTZER, (1964) "Hollow metallic and dielectric waveguides for long distance optical transmission and lasers" *Bell. System Tech. Jour.* 43, pp. 1783-1809.
- MATARRESE, L.M. and K. M. EVENSON, (1970) "Improved coupling to infrared whisker diode by use of antenna theory" *Appl. Phys. Lett.*, 17, 1, pp. 8-10.
- Mc COLL, M.(1977) "Review of submillimeter wave mixers" *Proc. Soc. Photo-Optical Instruments Engrs (SPIE)*, Vol. 105, Far Infrared/ Submillimeter wave. Technology/ Applications, pp. 24-34.
- PLAINCHAMP, P. (1978) "Frequency instability measurements of the CH₃OH (70.5 μm) optically pumped laser" To be published.
- PYEE, M. and J. AUVRAY, (1975) "Generation et comparaison des fréquences dans le domaine submillimétrique et infrarouge" *Bull. Information BNM (France)*, 6, 19, pp. 11-22.
- RUTMAN, J., (1978) "Characterisation of phase and frequency instabilities in precision frequency sources : fifteen years of progress" *Proc. IEEE*, 66, 9 , pp.
- SCHUBERT, M. R. ; M. DURSCHLAG and T. A. De TEMPLE, (1977) "Diffraction limited CW optically pumped lasers" *IEEE Jour. Quant. Electr.*, QE-13, 6, pp. 455-459.
- STEIN, S. R. ; A. S. RISLEY, H. Van de STADT and F. STRUMIA, (1977) "High speed frequency modulation of far infrared lasers using the Stark effect" *Applied Optics*, 16, 7, pp. 1893-1896.
- STEIN, S. R. and H. Van de STADT, (1977) "Electronic tuning and phase-lock technique for optically pumped far infrared lasers" *Proc. 31st Annual Symp. Frequency Control*, editor Electronic Industries Assoc., Washington, D. C., pp. 601-604.
- VERON, D., P. BELLAND and M. J. BECCARIA, (1978), "Continuous 250 mW gas discharge DCN laser at 190/195 μm" *Proc. 3rd International Conf. on Submillimetre Waves and their applications*, University of Surrey, Guildford (U. K.), 29 March-1 April, pp. 182-183.
- WEISS, C. O. and G. KRAMER, (1975), "Optically pumped far-infrared laser for infrared frequency measurements" *Proc. 5th International Conf. on Atomic Masses and Fundamental Constants*, Paris (France), June. Edited by J. H. Sanders and A. W. Wapstra, Plenum Press, New-York, 1976, pp. 383-389.
- WEISS, C. O. ; M. GRINDA and K. SIEMSEN, (1977), "FIR laser lines of CH₃OH pumped by CO₂ laser sequency lines" *IEEE Jour. Quant. Electr.*, QE-13, 11, p. 892.
- WELLS, J. S. , (1973) "A stabilized HCN laser for infrared frequency synthesis" *IEEE Trans. Instrum. Meas.*, IM-22, 2, pp. 113-118.
- YAMANAKA, M. (1976) "Optically pumped gas lasers. A wavelength table of laser lines" *Rev. Laser Engr (Japan)* 3, 1976, pp.57-98.
- YAMANAKA, M. (1977) "Optically pumped waveguide lasers" *Jour. Opt. Soc. Am.*, 67, 7, pp. 952-958.

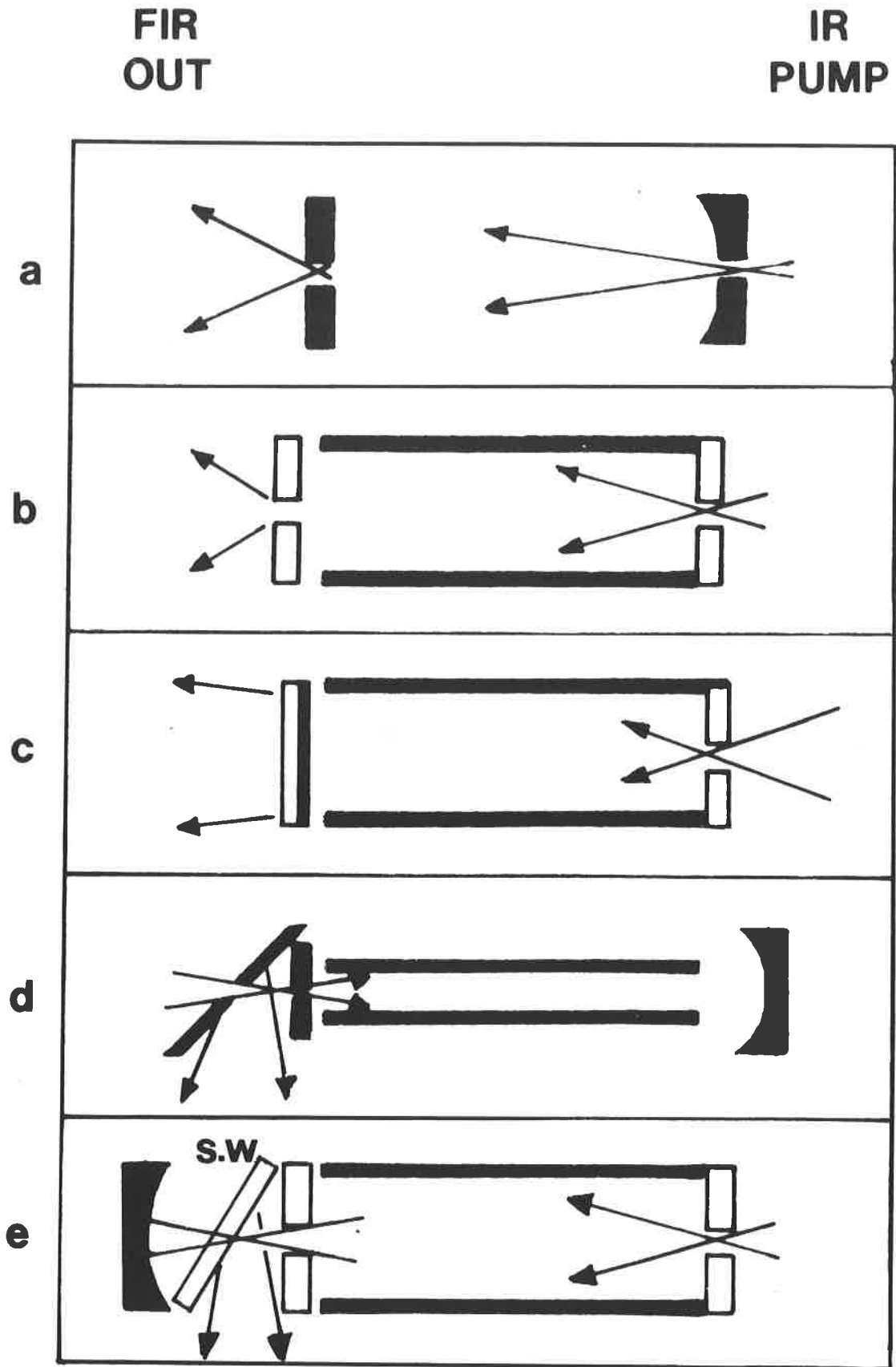


Fig.1 Power vs. wavelength and frequency for various resonator and coupling configurations

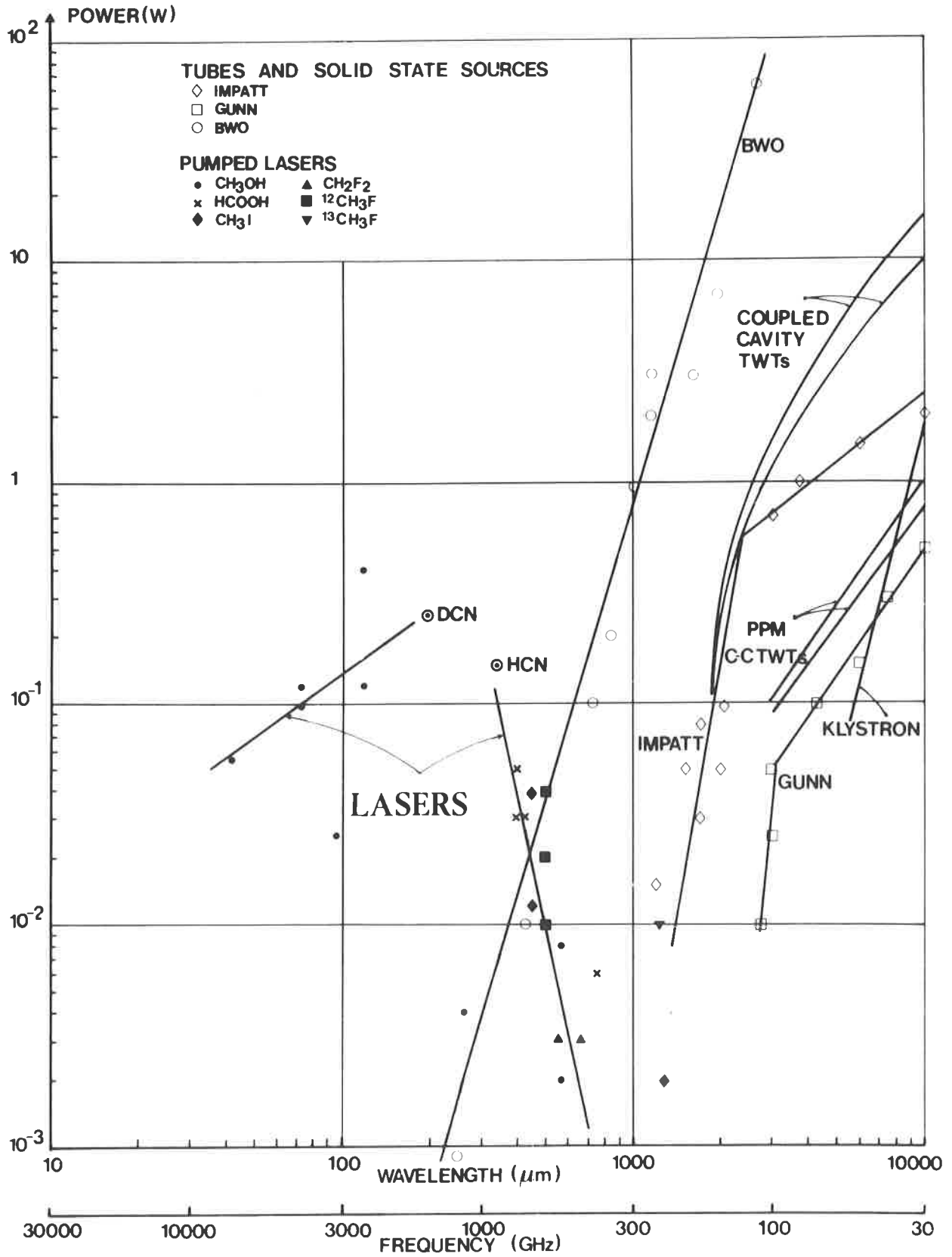


Fig.2 Millimetric and submillimetric wave sources

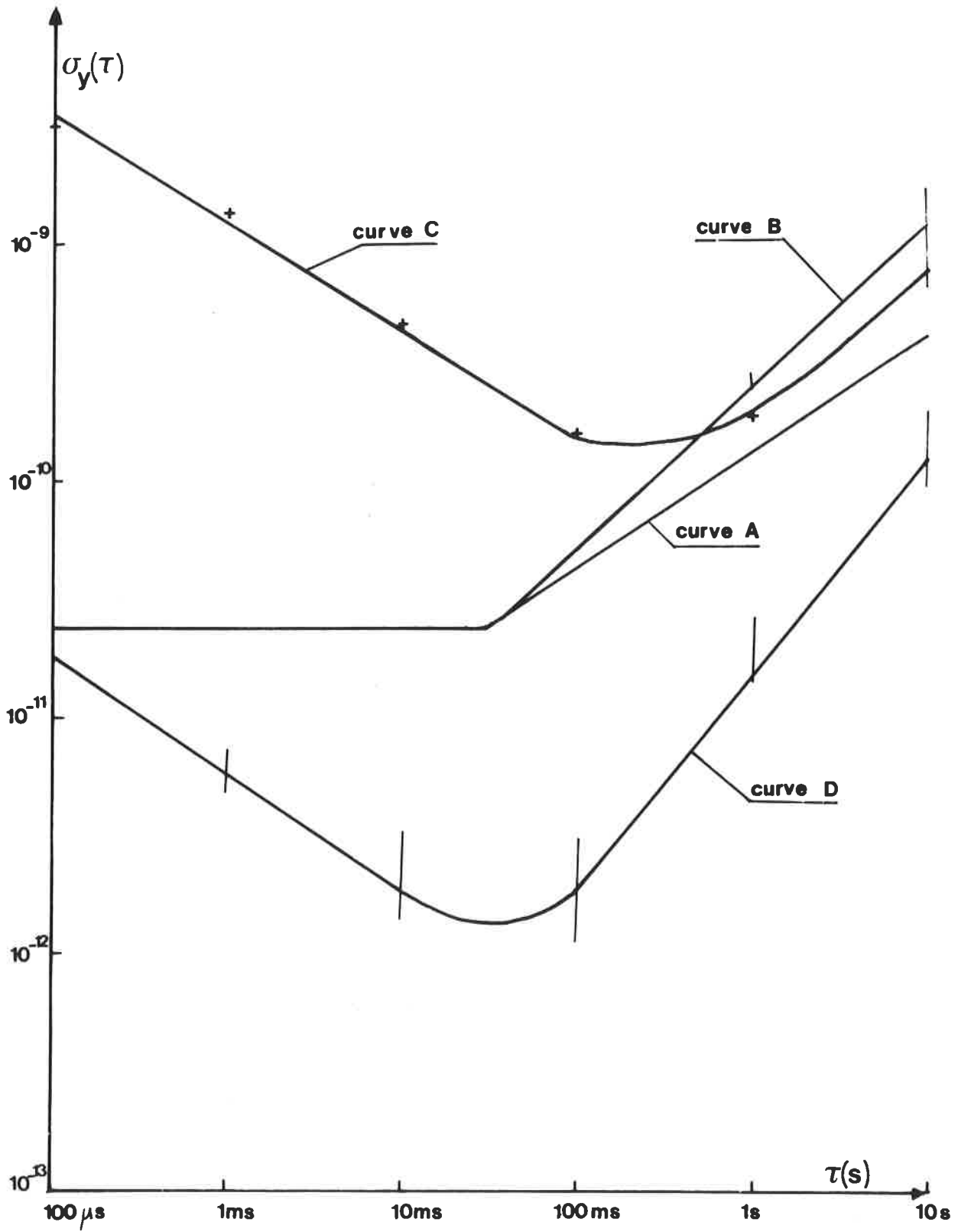
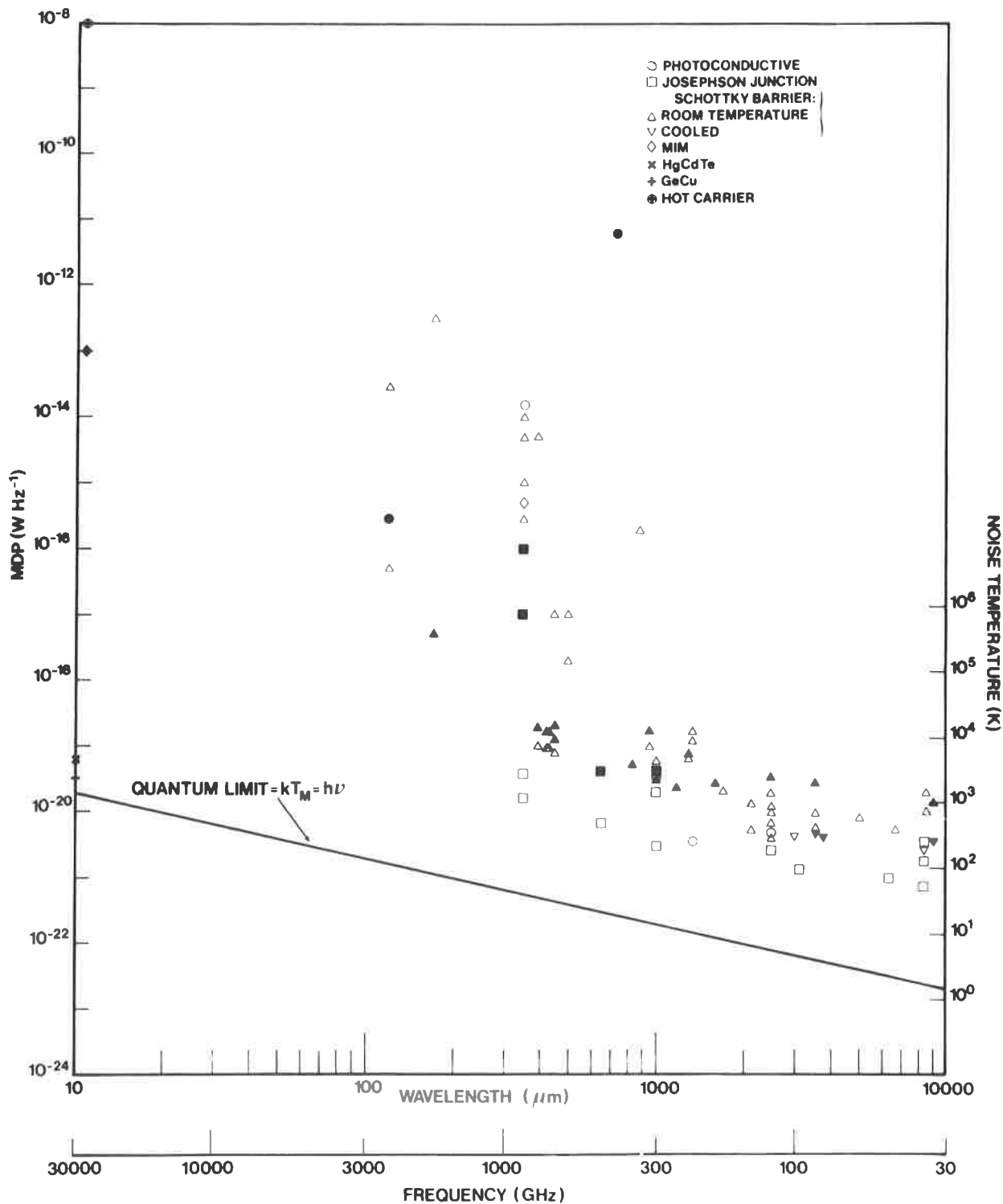


Fig.3 Frequency stability of the IF signal



Filled-in data points refer to receivers

Fig.4 MDP for several mixers or receivers

