SUB MM LASER LOCAL OSCILLATORS:

DESIGN CRITERIA AND RESULTS

Gerhard A. Koepf*
Phoenix Corporation

INTRODUCTION

The main thrust in cw submillimeter (smm) laser research in the past has been toward the discovery of laser lines and toward higher output power levels. Diagnostic experiments were limited to a very small number of gases. They were directed toward the pump absorption and pressure dependence regime [1,2,3]. Very little attention has been paid to the spectral features of the smm laser emission. It was only recently that gain profile and frequency stability measurements were performed [4,5,6]. The general experience was that these lasers are quite unstable sources and in the common design not generally suitable for local oscillator applications [5,7]. The reasons for this are that (1) power and frequency changes of the CO_2 pump laser translate into power and frequency changes of the smm output, (2) that reflections of pump radiation from the smm resonator cause severe instabilities of the pump laser and (3) that smm resonator instabilities are often very critical because of resonance effects at the pump frequency. In the following, new diagnostic results will be given of the spectral features and the power conversion efficiency. As a result of these experiments, several criteria are obtained for the design of frequency stable and efficient smm lasers for local oscillator applications. Finally, a new design is described and results on the power output and power and frequency stability will be given.

---

*This work was performed under Contract No. NAS5-26030 for the Instrument Electrooptics Branch, NASA, Goddard Space Flight Center.

SMM LASER DIAGNOSTICS

Spectral Features

The harmonic mixing technique has been used for heterodyne diagnostics of the smm laser output at a number of laser lines ranging from 170 μm to 1221 μm. This technique has been applied before to measure the absolute frequency of smm laser lines [8,9,10]. A GaAs Schottky Barrier diode in a quasioptical mount was used to generate very high harmonics of microwave frequencies and for down conversion of the smm laser frequency [11]. With this technique we obtained frequency multiplication factors up to 145. This made diagnostics of the 170 μm line of CH_3OH possible with a signal to noise ratio of over 30 dB. The spectral features of the laser gain were studied by tuning the laser resonator while displaying the beat frequency on a spectrum analyzer screen in a high persistence mode. Several basic physical effects could be isolated by a proper choice of the laser gas, the laser gas pressure, the pump intensity and the pump frequency.

Generally, at the low operating pressures of the laser gases, the pump radiation travelling back and forth in the resonator acts velocity selective on two groups of molecules [1]. When operated at extremely low pressure, also the smm laser transition is Doppler broadened. In the absence of substantial velocity cross relaxation and power broadening, the laser gain profile consists of two distinct spikes of Lorentian shape. The separation of the spikes is tunable by the pump frequency, and their width increases with increasing saturation of the pump and the smm transition. These effects could be verified for the first time at the 496 μm line of CH_3F. One example is given in Figure 1. The difference in amplitude of the spikes is due to differing pump rates in the two directions.

Another type of gain profile splitting is due to the Autler-Townes or dynamic Stark effect [12]. The strong pump field in the laser acting on the molecules lifts the M-degeneracy of the rotational levels. The laser transition splits up into $2\,(J+1)$ lines, where J is the rotational quantum number of the upper laser level. At normal operating pressures, these lines are collision broadened. The resulting shape of the gain profile depends on the type (P,Q,R) of the pump and laser transition on the magnitude of the pump field and the pump frequency [13]. This effect, which is well known in pulsed smm lasers, has recently been observed also in a CW amplifier and in the CH_3OH laser [4]. However, measurements of the line shape have not been reported so far. Our harmonic mixing technique revealed that dynamic Stark splitting is present at a large number of laser lines under regular operating conditions. We succeeded to isolate this effect best at the 1221 μm line of $C^{13}H_3F$ as shown in Figure 2. The observed line shape verifies the expected profile well: In this case, there are 5 pairs of M-sublevels. The largest splitting occurs for $M=0$ and the lowest for $M=5$. The highest amplitude goes with $M=1$. The symmetry of the two peaks indicates close to resonant pumping.

A less well known spectral feature of smm lasers is their tendency to relaxation oscillations. Such oscillations can readily be observed with fast detectors on many lines in the time domain when the pump laser operates in a chopped mode. Generally these oscillations are of a damped kind; however, they also may occur in a continuous mode, especially when the pump laser is not well stabilized. The frequency of these oscillations is typically a few MHz. At low pressures it increases approximately with the square root of the pressure and the pump rate. At high pressure and high pump rate it approaches a fixed value. We have verified this behavior with observations in the time and frequency domain [14]. Our harmonic mixing technique allowed a clear discrimination against transverse mode beats by the existence of symmetrical frequency components and by the fact that the observed width of the gain profile is less than the oscillation frequencies.

Pump Absorption

Our concept of controlled pump beam propagation described below allows to measure the pump power reflected from the smm laser resonator. With the laser evacuated, we measured reflection of 40-50% of the pump power depending on the pump frequency. A part of these losses (about 15% per pass) are due to the tight dimension of the injection hole and the unfavorable mode of the pump laser. We also observed 5% losses per pass through the Brewster window and a total of 10-20% reflection losses at the resonator mirrors. As the laser gas pressure is decreased the reflected pump power decreases. The absorption coefficient, the transition from saturated to unsaturated absorption and the transition from Doppler broadening to homogeneous broadening is specific to each gas. Therefore, the particular dependence of the returned power versus pressure plotted in Figure 3 is not relevant. However, it shows how much or how little pump power is actually absorbed at a number of representative laser gases, when operated at their optimum pressure and at optimum pump detuning.

DESIGN CRITERIA

These diagnostic experiments provide new inputs into the question of how to improve the stability and efficiency of optically pumped smm laser local oscillators. Generally, a single mode operation on a low loss mode with high mode quality is required. This points the way to rather large diameter dielectric waveguides. The Doppler contribution and the dynamic Stark splitting should be avoided; variations of the pump frequency and pump intensity cause complicated changes of the gain profile shape. This leads to changes in the smm oscillation frequency by the cavity pulling effect. In smm lasers cavity pulling is very pronounced because the line Q and the resonator Q are of the same order of magnitude. Of the line splittings the dynamic Stark splitting by the pump field is observed more likely. Most laser lines operate well beyond the Doppler broadened regime. Therefore, low pump intensities are desirable as they are obtained by using larger waveguide diameters.

A high degree of frequency and power stability of the pump laser is a prerequisite for smm laser local oscillator applications. However, even the best known stabilization schemes are insufficient if pump power feedback from the smm resonator to the pump laser is given. CO_2 lasers are also quite sensitive to cavity pulling.

A further cause of instabilities are resonances of the pump frequency inside the smm resonator. In the common mode of optically pumping, the pump beam is reflected back and forth in the resonator in an uncontrolled way. Standing waves are built up that are highly sensitive to changes in resonator length. Such changes are translated to the smm field. As a consequence, the smm laser sensitivity to thermal and acoustical effects is greatly increased.

The criteria for high conversion efficiency of the pump power into smm radiation follow from our Figure 3. The pump power actually absorbed in the laser gas at the optimum pressure is generally only a fraction of the power provided by pump laser. This explains the rather small conversion efficiencies reported throughout the literature. The highest reported values (20-30%) are given for difluoromethane. This is a gas with an exceptionally high absorption at its operating pressure [15,16]. It is estimated that most of the power is absorbed in this gas after one round trip, such that losses into the waveguide walls and reflections are of no importance. However, if we use the power actually absorbed in the gases as given in Figure 3 as a reference, we obtain conversion efficiencies of over 25% of the theoretical values also for other gases that are rather weak absorbers. The laser design therefore should avoid a high degree of pump saturation and provide a long interaction length of the pump beam with the laser gas besides minimizing losses in the waveguide walls. The design criteria as discussed in this section are summarized in Table I.

- Stabilize pump laser in power and frequency
- Avoid feedback of pump radiation
- Minimize resonances of pump field
- Minimize cavity pulling effects due to gain profile splitting
- Control pressure and temperature
- Provide single mode operation
- Provide efficient pumping

Table I. Criteria for smm laser local oscillator design.

LASER LOCAL OSCILLATOR DESCRIPTION

The new concept of controlled pump beam propagation has been introduced a while ago [17]. A four-fold degenerate resonator configuration is chosen with two mirrors of 6m radius of curvature separated at 1.76m. The pump beam is injected through a hole that is displaced halfway between the center and the rim of the mirror. As it is shown schematically in Figure 4, the pump beam makes four roundtrips through the resonator. It diverges to a maximum diameter and converges to a beam waist before leaving the resonator through the injection hole. The total interaction length with the laser gas is 14m. No resonances and no losses into the waveguide walls occur. The outgoing beam is at an angle of about 1/2 degree. It separates from the ingoing beam after a distance and can be reflected to an absorber or to a power meter. Feedback into the pump laser and pump resonances are completely eliminated.

The smm laser head consists of a stainless steel tube that supports the 3.8mm ID glass waveguide, with flanges at each end for attachment of the mirror and window assemblies. The mode coupling losses introduced by the use of curved mirrors are minimal [18]. At wavelength below 150-200 µm, the resonator becomes Gaussian. One of the laser end assemblies is separated from the flange by vacuum bellows. It includes a large diameter differential drive centered at the axis for length tuning. The mirror assemblies are joined together by three invar rods. The thermal expansion of the rods is compensated by high expansion aluminum sleeves.

For the CO_2 laser we chose active stabilization by locking it to the resonance frequency of a temperature controlled, mechanically and thermally stable etalon. The scheme is shown in Figure 5. The pump beam passes through a ZnSe disc which is rotated close to Brewsters angle so that about 100 mW are split-off. One part of this beam serves to monitor the pump power level, the other part is matched to the confocal etalon with a lens. In addition to the tunable DC voltage, a 41 Hz dither voltage is applied to the piezoelectric translator in the etalon which modulates the transmission band. The power modulation of the transmitted beam is phase detected, and a high voltage is derived for length control of the CO_2 laser resonator. When the feedback loop is closed, the etalon DC voltage can be used to tune the pump laser frequency for maximum smm laser output power. This stabilization scheme provides a pump beam which is essentially free of modulation.

Description of Laser Performance

The output power of the smm laser and the pump laser were recorded simultaneously over extended periods. The smm laser was operated in a sealed-off mode. Due to residual leaks in the vacuum system, pressure increases of 1-2 mTorr per hour were observed. A warm-up period of one hour was allowed before making measurements. The temperature of both end assemblies, the steel tube and the invar rods were monitored with thermocouples. The readings never exceeded 2-3°C above room temperature. As a consequence, the resonator requires no re-adjustment after the warm-up period.

From the recordings a drop by 4% and by 1.5% follows for the putput power of the smm laser and the pump laser, respectively, over a period of two hours (see Figure 6). During this time the PZT voltage that controls the CO_2 laser frequency is driven through its entire range of 1000 V by the active loop circuit. It was observed that the CO_2 laser always drifts toward lower frequencies, even after several hours of operation. Relocking of the control loop at the other end of the PZT voltage range occurs automatically, sometimes within as little as 10 seconds. The somewhat larger drop of the smm power seems to be caused by pollution of the laser gas. After several hours of operation, the original power level could usually be obtained only with a freshly filled laser tube.

These results can be considered typical for lines that are pumped with the CO_2 laser operating not too far off its line center. This was confirmed by additional although less extensive measurements at a number of other lines ranging from 70 µm to 1.22mm. For detunings of more than 40 MHz from the line center the locking of the loop is less reliable because of mode competition. The spectral range of the CO_2 laser is about 90 MHz. The output power levels at a number of characteristic lines as indicated on the scale of a Scientec power meter are given in Table II.

WAVELENGTH	LASER-GAS	READING
118 µm	CH_3OH	62.0 mW
170 µm	CH_3OH	39.0 mW
206 µm	CD_3F	25.0 mW
247 µm	CD_3F	15.0 mW
394 µm	HCOOH	38.0 mW
433 µm	HCOOH	32.0 mW
447 µm	CH_3I	32.0 mW
496 µm	$CH_3F - SF_6$	15.0 mW
513 µm	HCOOH	17.0 mW
570 µm	CH_3OH	3.5 mW
747 µm	CH_3Br	3.0 mW
1221 µm	$C\,^{13}H_3F$	2.5 mW

Table II. Laser output power readings from Scientec power meter.

The laser output was also investigated with a wave analyzer. It was found that the dither frequency of 41 Hz produces a 0.4% modulation, while the 60 and 120 Hz components from the CO_2 discharge are below 0.3%.

With respect to matching of the laser beam to the antenna pattern of a mixer, the mode pattern of the laser beam is of importance [19]. The laser was found to operate alternately on a strong and a very weak transverse mode when the resonator length was changed. The cross section of the strong mode was recorded in the focus of a lens by a pyroelectric detector with an aperture of 1mm. This revealed an almost perfect Gaussian intensity pattern, which is surprising to some degree in view of the toroidal excitation volume of the pump beam, the hybrid hole coupler and the large number of relatively low loss modes in a waveguide resonator. The linear polarization of the mode was ensured by a polarizer.

The frequency stability of the laser was investigated by mixing the laser beam with harmonics of a very stable microwave oscillator in a Schottky diode. As compared to other similar efforts [20], a very simple approach of generating a stable reference in the smm region was chosen. The output of a stable synthesizer operating in the X-band was amplified and applied to the diode coaxially through a bandpass filter. Due to the strong nonlinearity of the diode very large multiplication factors can be obtained. By using the 62nd harmonic, and tuning the synthesizer through a 50 MHz wide band centered at 12.25 GHz, beat signals ranging from 10 MHz to 2.5 GHz were obtained. After a second down conversion into the 150 MHz band, a frequency counter with printer and a spectrum analyzer were used to monitor the long term frequency stability of the laser line at 761 GHz of formic acid.

The short term fluctuations of the beat signal as displayed on the spectrum analyzer were typically 5-10 kHz wide, in close agreement with other measurements performed at this line [5]. In this reference, heavy pump power feedback is mentioned to have affected the stability measurements for time intervals above 0.1 second. In our laser no such effects could be observed. For long term frequency measurements, the printer was set to take samples at different time intervals. The observed frequency changes varied in rate and direction. Over a one second and a one minute time interval mean drifts of 740 Hz and 14 kHz were obtained. The Allan variance for these intervals was calculated to be $7.8\ 10^{-10}$ and $1.2\ 10^{-8}$, respectively. The lowest and highest frequencies recorded over one locking period of the CO_2 laser (two hours) were about 0.5 MHz apart.

The frequency drifts are mainly attributed to drifts of the CO_2 pump laser. Aside from the active stabilization, there are several mechanisms that can cause frequency drifts. The stability of the etalon is limited to 1.5 MHz per day. The active loop electronics are not perfectly linear and are also subject to thermal drifts. In addition, small changes in the orientation of the CO_2 laser beam were observed to shift the transmission band of the etalon. Such directional changes of the pump beam can occur as a consequence of the tuning of the CO_2 laser by the PZT mounted grating.

CONCLUSIONS

A smm laser with an amplitude and frequency stability suitable for application as a local oscillator in a high resolution heterodyne radiometer/spectrometer has been described. The mode pattern is very close to a Gaussian profile so that efficient coupling to a quasioptical mixer is possible. The laser provides sufficient output power at a large number of lines to drive the mixer into the low conversion loss regime. Radiometric integration times of several minutes with a spectral resolution of 1 MHz will be possible. With present state-of-the-art Schottky mixers and low noise preamplifiers a radiometric temperature resolution of a few ^{o}K can be expected over a spectral range from 500 to 900 GHz.

REFERENCES

[1] Hodges, D. T.; Tucker, J. R.; and Hartwick, T. S.: Basic Physical Mechanisms Determining the Performance of the CH_3F Laser. Infrared Physics, vol. 16, 1976, pp. 175-182.

[2] Weiss, C. O.: Pump Saturation in Molecular Far-Infrared Lasers. IEEE J. Quantum Electron, vol. QE-12, 1976, pp. 580-584.

[3] Henningsen, J. O. and Jensen, H. G.: The Optically Pumped Far-Infrared Laser: Rate Equations and Diagnostic Experiments. IEEE J. QE, vol. QE-11, 1975, pp. 248-252.

[4] Heppner, J.; Hubner, V.; and Weiss, C. O.: Saturated and Small Signal Gain in CW Laser-Pumped FIR Laser Gases. IV Int. Conference on Infrared and MM Waves and their Applications, Dec. 10-15, 1979, Conference Digest, pp. 161-162.

[5] Godone, A.; Weiss, C. O.; and Kramer, G.: FM-Noise Measurements on an Optically Pumped FIR Laser. IEEE J. of Quantum Electron, vol. QE-14, 1978, pp. 339-342.

[6] Plainchamp, P. M.: Frequency Instability Measurements of the CH_3OH Optically Pumped Laser at 70.5 and 118 μm. IEEE J. of Quantum Electron, vol. QE-15, 1979, pp. 860-864.

[7] Button, K.: Is there a Future for Submillimeter Lasers? Panel Discussion, Laser 78 Conference, Orlando, LF, Dec. 1978, Conference Digest, pp. 833-836.

[8] Radford, H. E.; Petersen, F. R.; Jennings, D. A.; and Mucha, J. A.: Heterodyne Measurements of smm Laser Spectrometer Frequencies. IEEE J. Quantum Electron, QE-13, 1977, pp. 92-94.

[9] Kramer, G. and Weiss, C. O.: Frequencies of some Optically Pumped Submillimeter Laser Lines. Appl. Phys. 10, 1976, pp. 187-188.

[10] Dyubko, S. F. and Fesenko, L. D.: Frequencies of Optically Pumped Submillimeter Lasers. 3rd Int. Conference on Sub MM Waves and their Applications, 28 March - 1 April 1978, Conference Digest, pp. 70-73.

[11] Fetterman, H. R.; Clifton, B. J.; Tannenwald, P. E.; and Parker, C. D.: Submillimeter Detection and Mixing Using Schottky Diodes. Appl. Phys. Lett., 24, 1976, pp. 70-72.

[12] Autler, S. H. and Townes, C. H.: Stark Effect in Rapidly Varying Fields. Phys. rev., 100, Oct. 15, 1955, pp. 703-722.

REFERENCES (continued)

[13] Skribanovitz, N.; Kelly, M. J.; and Feld, M. S.: New Laser Technique for the Identification of Molecular Transitions. Phys. rev. A, vol. 6, 1977, pp. 2302-2311.

[14] Lawandy, N. M. and Koepf, G. A.: Relaxation Oscillations in Optically Pumped Molecular Lasers. IEEE J. of Quantum Electronics. vol. QE-16, 1980.

[15] Danielewicz, E. J. and Weiss, C. O.: New Efficient CW Far-Infrared Optically Pumped CH_2F_2 Laser. IEEE J. of Quantum Electronics, vol. QE-14, 1978, pp. 705-708.

[16] Danielewicz, E. J. et al.: High Performance at new FIR Wavelengths from Optically Pumped CH_2F_2. Optics Letters, 4, 1979, pp. 280-282.

[17] Koepf, G. A. and McAvoy , N.: Design Criteria for Optically Pumped FIR Laser Cavities. IEEE JQE, vol. QE-13, 1977, pp. 418-421.

[18] Degnan, J. J. and Hall, D. R.: Finite Aperture Waveguide - Laser Resonators. IEEE J. of Quantum Electron, vol. QE-9, 1973, pp. 901-910.

[19] Fetterman, H. R.; Tannenwald, P. E.; Clifton, B. J.; Parker, C. D.; Fitzgerald, W. D.; and Erickson, N. R.: Far IR Heterodyne Radiometric Measurements with Quasi-Optical Schottky Diode Mixers. Applied Physics Letter, 33, 1978, p. 151.

[20] Godone, A.; DeMarchi, A.; and Bava, E.: An Improved Multiplier Chain for Precise Frequency Measurements up to 20 THz. 33rd Annual Frequency Control Symposium, Atlantic City, May-June 1979.

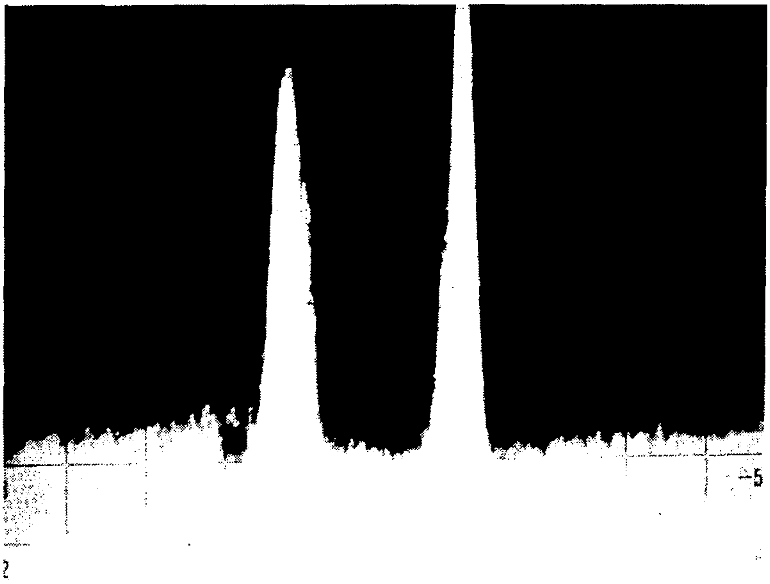

Figure 1.- Gain profile splitting due to velocity selective pumping: CH_3F pumped with 9P20 line at 3m Torr pressure; center frequency 604 GHz, 1 MHz/div.

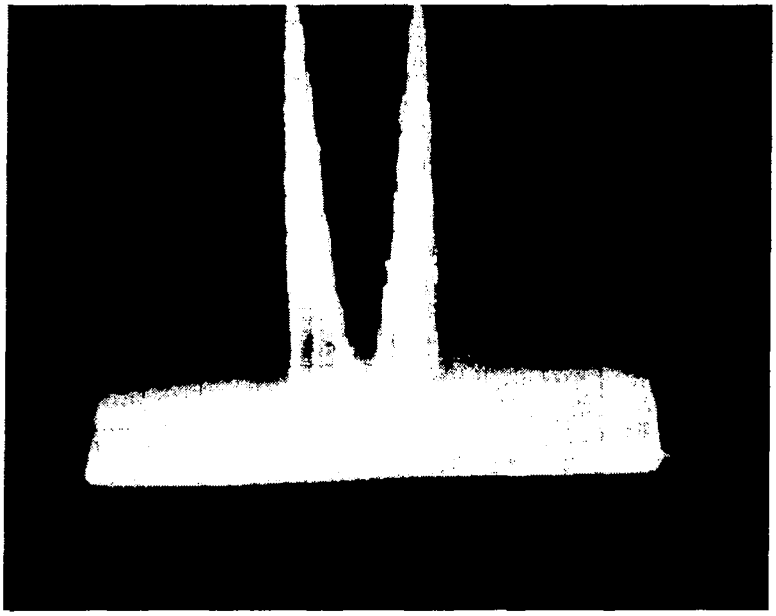

Figure 2.- Gain profile splitting due to dynamic Stark effect: $C^{13}H_3F$ pumped by 9P32 line at 36m Torr pressure; center frequency 245 GHz, 1 MHz/div.

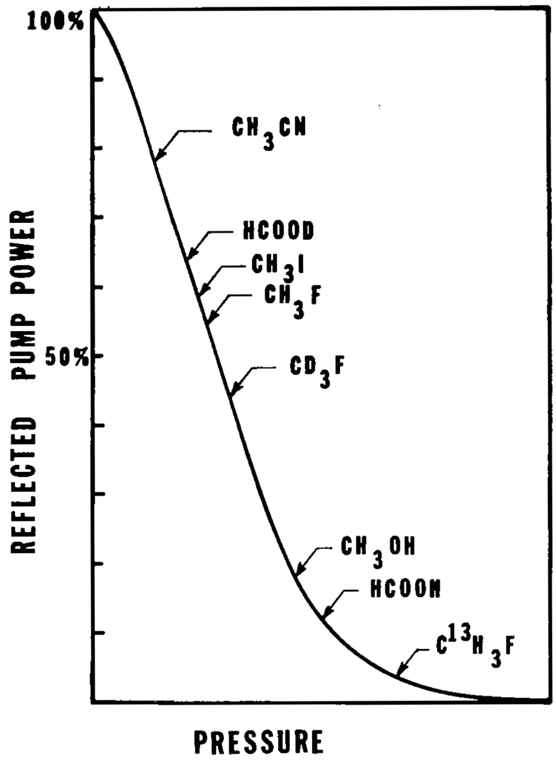

Figure 3.- Measurement of pump power reflected from resonator for representative laser gases at their respective optimum operating pressures. The pressure scale is uncalibrated.

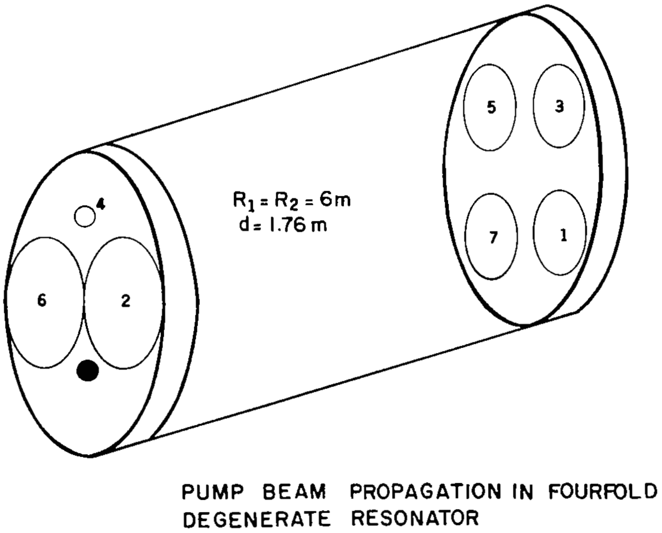

Figure 4.- Schematic of four fold degenerate resonator and pump beam footprints.

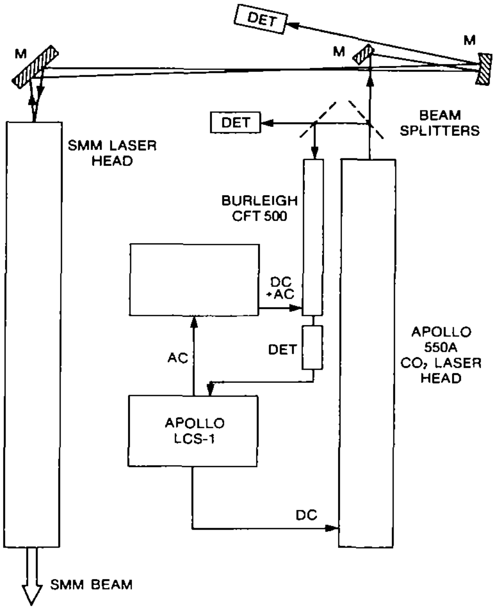

Figure 5.- CO_2 laser stabilization and pump beam propagation.

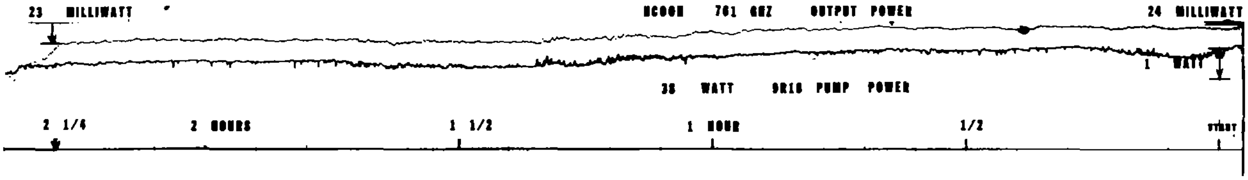

Figure 6.- Long term power stability. Upper trace: 761 GHz line of HCOOH, lower trace 9R18 pump power. Both baselines are heavily offset.