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► To cite this version:

J.-M. Lourtioz, R. Adde, D. Bouchon, J. Pontnau. Design and performances of a CW CH₃OH waveguide laser. *Revue de Physique Appliquée*, 1979, 14 (2), pp.323-330. 10.1051/rphysap:01979001402032300 . jpa-00244601

HAL Id: jpa-00244601

<https://hal.science/jpa-00244601>

Submitted on 1 Jan 1979

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Classification
Physics Abstracts
42.60B

Design and performances of a CW CH₃OH waveguide laser (*)

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(Reçu le 31 octobre 1978, accepté le 27 novembre 1978)

Résumé. — On décrit la réalisation et les performances d'un laser continu à alcool de structure guide d'onde pompé optiquement. Il assure un fonctionnement stable dans le domaine des courtes longueurs d'onde submillimétriques avec un niveau de puissance de 10 à 100 mW. Des résultats significatifs présentés à 70 μm et 118 μm soulignent les lignes directrices essentielles au choix des paramètres du laser.

Abstract. — The design and performances of an efficient CW waveguide optically pumped CH₃OH laser are described for stable operation 10-100 mW level in the short submillimeter wavelength region. Significant results at 70 μm and 118 μm underline the more stringent guide-lines in the selection of the laser parameters.

1. Introduction. — A large number of CW (continuous wave) laser lines providing stable output at the mW level are now available between 40 μm and 1.2 mm due to the recent developments of the optically pumped far infrared lasers (later on labeled as FIR lasers). We describe here the design and performances of an efficient CH₃OH waveguide laser for stable operation at the 10-100 mW level in the short submillimeter wavelength region ($\lambda \lesssim 300 \mu\text{m}$). Such power levels are required in many FIR applications namely as local oscillator for heterodyne mixers, high order harmonic mixing for frequency synthesis from X band, material testing. In section 2 we analyze the selection of the CH₃OH FIR laser characteristics. The experimental set-up is described in section 3 and we report in section 4 some significant experiments which illustrate the discussion of section 2.

2. Discussion and selection of the FIR laser characteristics. — We analyze the FIR laser parameters in the framework of our goals, high power level (10-100 mW range whenever possible), emphasis on short FIR wavelengths range (40-300 μm) and ease of operation at different frequencies. Although discarding quantum effects, rate equation models of CW FIR lasers [1-8] describe fairly well a large part of the physical mechanisms involved. They allow to write the FIR output power in a closed form which we reproduce for the purpose of the discussion [2, 5, 8]

$$P_{\text{FIR}} = \frac{1}{2} I_{\text{SAT}} t S \left[\frac{2}{t} \times \frac{P_{\text{IR}}}{S} \times \eta_{\text{th}} \times F_{\text{abs}} \times \right. \\ \left. \times F_{\text{trans}} \times \frac{1}{I_{\text{SAT}}} - 1 \right] \quad (1)$$

where,

- P_{IR} is the pump power,
- t is the FIR transmission coefficient per pass,
- S is the FIR resonator cross-section,
- $\eta_{\text{th}} = \frac{1}{1 + g_2/g_3} \times \frac{v_{\text{IR}}}{v_{\text{FIR}}} \simeq \frac{1}{2} \frac{v_{\text{IR}}}{v_{\text{FIR}}}$ is the theoretical photonic conversion efficiency,
- I_{SAT} is the saturation intensity of the FIR transition,
- $F_{\text{abs}} = \frac{\alpha L}{\alpha L + \beta_{\text{IR}}} (\xi)$ is the fractional absorption of the pump power, α is the saturated absorption coefficient, L the FIR cavity length and β_{IR} the FIR cavity loss coefficient per pass of the pump. If coincidence of the pump with several absorption lines occurs, $Z (\leq 1)$ measures the fraction of the pump which goes into the useful transition.
- $F_{\text{trans}} = \frac{t(1 - A_e)}{t + a}$ is the fractional transmission loss of the FIR radiation, a is the FIR cavity loss per pass at the FIR wavelength (reflexion losses at the mirrors of the cavity + propagation losses in waveguide structures or diffraction losses in conventional Fabry-Perot resonators). A_e is the FIR excited state absorption coefficient [1].

The expression of equation (1) approaches the

(*) This work was supported in part by the Groupement de Recherches Coordonnées du C.N.R.S. n° 11 (Greco Micro-ondes).

(**) Associé au C.N.R.S.

Fig. 1. — Influence of the descriptive parameters on the FIR power efficiency. The double arrows and the darker frames underline the main interactions.

standard expression for a saturated homogeneously broadened transition :

$$P_{\text{FIR}} = \frac{1}{2} I_{\text{SAT}} \times t \times \left[\frac{G_0 L}{t + a} - 1 \right] \quad (1\text{bis})$$

where the FIR gain G_0 is given by :

$$G_0 = \frac{2}{L} \times \frac{P_{\text{IR}}}{S} \frac{t + a}{t} \times \eta_{\text{th}} \times F_{\text{abs}} \times F_{\text{trans}} \times \frac{1}{I_{\text{SAT}}} \quad (1\text{ter})$$

In the favorable case of strong FIR emission lines which exhibit high gain at the optimum pressure p_{opt} , equations (1) and (1bis) reduce to :

$$P_{\text{FIR}} \simeq P_{\text{IR}} \times \eta_{\text{th}} \times (F_{\text{abs}} \times F_{\text{trans}})_{p_{\text{opt}}} \quad (2)$$

The diagram of figure 1 illustrates the influence of the descriptive parameters of the ensemble constituted by the FIR laser and its optical pump (left column) upon all fundamental FIR physical processes (dynamical molecular processes as well as the FIR cavity finesse at the pump and FIR wavelengths). The consequences on the different parameters entering in the FIR output power formula are represented in the right column of figure 1. It must be emphasized here that the complete picture of the phenomena involved in CW FIR optically pumped lasers is more complex than is shown in figure 1 as many parameters interact with each other in an intricate way. However we have restricted our representation to the main interactions both for clarity of the figure and in order to simplify the discussion.

2.1 FIR GAS PARAMETERS. — Emission lines in FIR lasers mainly arise from pure rotational transitions within a low-lying excited vibrational manifold of a polar molecule. Strong dipole moments of both the IR absorption and the FIR emission transitions and a close frequency coincidence of the pump with the absorption line center are required to achieve efficient optical pumping. Owing to the versatility of the CO₂ laser some 44 molecules have been tried [9, 10]. However, the drastic influence of the molecular relaxation mechanisms (fast rotational relaxation and vibration relaxation *bottleneck* [4]) upon the achievable population inversion strongly limits the number of good molecules exhibiting CW FIR power performances. We have selected the CH₃OH molecule in the present study since it provides many FIR emission lines, in particular in the range of short FIR wavelengths with powerful lines at 118 μm , 70 μm , 40 μm . The high efficiency of these emission lines may be attributed in part to the good coincidence between the CO₂ pump and the CH₃OH absorption (the line centers are respectively distant of $\simeq 35$ MHz and $\simeq 25$ MHz for the 70 μm and 118 μm transitions allowing almost exact tuning of the CO₂ laser).

The FIR gas pressure p is a parameter of fundamental importance in the FIR laser operation. For each FIR laser line, there is a definite and low range of operating pressure (see section 4.2). The optimum pressure $p_{\text{opt}} \left(\frac{dP_{\text{FIR}}}{dp} \right)_{p_{\text{opt}}} = 0$ in equation (1) is determined mainly by the pump laser power P_{IR} and the three physical pressure-dependent parameters I_{SAT} , A_e and α . The parameters I_{SAT} and A_e dictate the low value of p_{opt} ($\lesssim 100$ mtorr) :

— The saturation intensity of the FIR transition I_{SAT} is proportional to the square of the rotational relaxation rate γ_R [1, 6] ($\gamma_R \sim 10^8 \text{ s}^{-1} \text{ torr}^{-1}$), which gives $I_{\text{SAT}} \sim p^2$.

— The FIR excited state absorption $A_e \sim p^n$ ($1 \leq n \leq 2$) has the following origin. The population inversion among the active FIR rotational levels is achieved only for two opposite velocity classes of molecules since the FIR gas absorption transition is Doppler-broadened. The fast rotational relaxation when compared to vibrational relaxation ($\gamma_R > \gamma_V$, where $\gamma_V \simeq \gamma_{V\text{Diff}} \sim 10^3 \text{ s}^{-1} \text{ torr cm}^2$) leads to fast thermalization in the excited vibrational manifold. Therefore the molecules in the active FIR levels having velocities different from the pumped molecules give rise to strong reabsorption.

The direct consequence of the low value of p_{opt} is the low IR saturation intensity I_0 ($\sim p^2$ for the collision dominated regime [11]). It results in a relatively strong saturation of the IR absorption

$$(I_{\text{IR}}/I_0 \simeq 5-10 \rightarrow \alpha \sim P_{\text{IR}}^{-1/2})$$

and a modest value of the IR saturated absorption coefficient per pass at the optimum pressure $(\alpha L)_{p_{\text{opt}}}$ when compared to the coefficient β_{IR} related to the other loss mechanisms of the pump. Increasing the pump power and then the FIR gain G_{FIR}^0

$$(G_{\text{FIR}}^0 \sim \alpha P_{\text{IR}} \sim P_{\text{IR}}^{1/2}, \text{ see equation (1)})$$

allows a small increase of p_{opt} (see sect. 4.2 and ref. [1, 5, 12]) which approximately compensates the increase of the saturation effects (I_{IR}/I_0) so that $(\alpha L)_{\text{opt}}$ remains nearly independent of P_{IR} . Therefore the optimization of the FIR power efficiency is strongly correlated with the optimization of the pump absorption efficiency f_{abs} .

Direct actions on the gas are buffer gas addition which may help the vibrational relaxation [13] and control of the gas temperature which may improve the Boltzmann occupation factor of the lower level of the IR absorption transition [14].

2.2 FIR CAVITY. — We have used a waveguide structure. This narrow bore configuration has been the first decisive progress towards FIR laser with high power efficiency [15] since it favors the diffusion processes which generally govern the vibrational relaxation. Besides, waveguide cavities present several

advantages over the Fabry-Perot cavities such as compactness and ease of alignment. Although metal waveguide cavities may be constructed with smaller cross-sections due to their lower FIR loss propagation [16, 17, 18], they suffer from higher diffraction losses at the mirrors and we have used mainly dielectric waveguides. Moreover the latter ones facilitate low order mode operation and selection of the FIR emission lines which may be simultaneously excited by the pump in complex molecules such as CH_3OH .

The choice of the waveguide geometry (cross-section S , length L) together with the coupling structures is a trade off as illustrated in figure 1. It is important to reach the maximum absorption in the gas (αL)_{opt} with a long absorption path and a high optimum pressure favored by a rapid vibrational relaxation. However low IR and FIR losses and optimum FIR transmission must be realized simultaneously. Efficient output couplers must have the following properties : optimum IR reflection coefficient to operate with a collimated pump beam, low FIR absorption losses and low adjustable coupling coefficient (5-10 %). Hybrid couplers meeting this requirements have been realized at wavelengths larger than 100 μm [19, 20, 21]. At wavelengths smaller than 100 μm technological problems arise from the FIR absorption of the IR reflecting coating and the increasing difficulty to match the etalon conditions of the hybrid coupler substrate, thus we have used the conventional output hole mirror in the present experiments. With these simple hole couplers the dominant IR losses inside the FIR cavity are the losses at the output mirror if the injected IR beam is collimated. However, there are propagation losses in the waveguide walls if the IR beam is uncollimated, consequently the two injection methods have comparable efficiencies. Using in our experiments an IR uncollimated beam we have found that the choice of the waveguide diameter is not critical in the 20-30 mm range for a length of 2 m and throughout the 70 μm -300 μm wavelength region. Although a decrease of the cross-section was accompanied by the expected increase of the optimum FIR gas pressure, the simultaneous increase of the propagation IR losses made the FIR output power quite independent of the cross-section. Besides in this waveguide diameter range the FIR losses are kept small for the low order modes and the excitation of high order modes is limited [18].

2.3 PUMP LASER BEAM. — The pump beam is characterized by its power P_{IR} , frequency offset from the FIR gas absorption line center $\delta\nu_{\text{IR}}$, and mode profile together with the injection optics. For a sufficiently high value of the pump power, P_{FIR} is proportional to P_{IR} . This is shown by equation (2) and has been verified experimentally (see sect. 4.3 and ref. [19]). Therefore it may seem obvious to associate a powerful CO_2 laser to the FIR resonator. However the amplitude and frequency stability requirements imply single

mode operation which becomes difficult to achieve with large gain CO_2 lasers. We have designed in the laboratory a CO_2 laser providing $\simeq 30$ W output power on the strong lines and single mode operation has been obtained partly due to the small bore of the CO_2 discharge tube (8-10 mm) but mainly to the high transmission coefficient ($\gtrsim 30\%$) of the ZnSe output coupling mirror. The cavity length ($\simeq 1.60$ m) is a compromise between output power (20-30 watts) and tuning range (60-80 MHz). As far as the CO_2 laser transverse mode presents a gaussian or doughnut shape, we have not found that this has much influence on the FIR output power. This result comes probably from the use of an IR uncollimated beam.

We now turn to the aspect of *on* or *off* resonance of the IR pumping within the absorption line. For a large majority of FIR molecules the frequency offset $\delta\nu_{\text{IR}}$ has a value $\neq 0$. The FIR gain $G_{\text{FIR}}(\nu)$ exhibits two peaks corresponding to the emissions of the two separate classes of molecules with opposite velocities excited inside the FIR cavity (the two classes collapse into the *zero velocity class* of molecules when $\delta\nu_{\text{IR}}=0$). The separation of the two peaks increases with the frequency of the FIR emission line

$$\delta\nu_{\text{FIR}} \simeq \delta\nu_{\text{IR}} \times (\nu_{\text{FIR}}/\nu_{\text{IR}})$$

and their amplitudes decrease strongly with increasing $\delta\nu_{\text{IR}}$ since the number of excited molecules is approximately proportional to the Doppler factor contained in the absorption coefficient

$$\alpha(\delta\nu_{\text{IR}}) = \alpha(0) \exp(-\delta\nu_{\text{IR}}^2/4 \delta\nu_{\text{Doppler}}^2)$$

(see also experimental results in section 4.4). On the other hand P_{IR} is nearly constant (20 %) throughout the tuning curve of the CO_2 laser. Consequently the FIR power is optimum when the CO_2 laser is tuned to match as closely as possible the FIR gas absorption transition (i.e. $\delta\nu_{\text{IR}}$ minimum). Furthermore the frequency instabilities of the CO_2 laser are equivalent to variations of $\delta\nu_{\text{IR}}$ and create changes in the FIR gain lineshape and amplitude. They are the main sources of the FIR output power fluctuations and their effect becomes very important at short FIR wavelengths. Therefore the design of an efficient and stable FIR laser implies the stabilization of the CO_2 laser frequency.

3. Technical description. — The experimental set-up shown in figure 2 consists of a 1.60 m grating tuned CO_2 laser and an 1.80 m long oversized FIR pyrex waveguide resonator. The single CO_2 laser discharge is 1.20 m long and is operated at a 20 torr gas mixture ($\text{CO}_2\text{-N}_2\text{-He}$: 1-1,5-3) with 12-13 kV and 28 mA supplied by a regulated constant current power supply. This single discharge structure has many advantages (simplicity, compactness, regulation of the discharge current) but requires Brewster windows for electric

Fig. 2. — Schematic of the stabilized optically pumped FIR laser.

insulation. We found that deposits were formed at the inner surface of the windows in running conditions and their periodic cleaning was necessary to maintain the CO₂ laser operation on the low order efficient modes. Both the Brewster windows and the output mirror are made of zinc selenide. The output mirror is mounted on a piezoceramic translator (PZT) which allows fine frequency tuning over a ≈ 80 MHz range and stabilization of the CO₂ laser frequency. The 10 m radius of curvature of this mirror gives a slightly divergent output beam which is injected with a $f/300$ mm ZnSe lens into the FIR resonator and enters through a ZnSe Brewster window. The small fraction of the pump beam which is reflected at the entrance window ($< 1\%$) allows an easy control of the injected pump power.

The FIR waveguide laser is composed of a standard Pyrex tube 1.70 m long and of two gold-coated flat mirrors placed at a distance nearly a few millimeters from the waveguide no as to minimize the FIR losses. The nearly 2 mm hole input mirror is mounted on a translator and serves essentially to enter the pump beam, since most of the FIR is extracted at the opposite end of the cavity through a 4-5 mm hole. A monocrystalline Z-cut (1 mm thick) quartz window absorbs the 10 μ m radiation and prevents damaging of the thin teflon vacuum window. Meanwhile our laser input design takes advantage of the FIR beam (≈ 15 -20 % of the total FIR power) propagating back through the input mirror for monitoring. This beam expands rapidly due to the small size 2 mm hole and is extracted with a 45° off axis mirror having the same 2 mm diameter hole and 5-10 cm distant from the input mirror.

In free running conditions the instabilities of the FIR output amplitude reflect essentially the frequency instabilities of the CO₂ laser since the FIR cavity length variations must be relatively large to have an effect. Short term fluctuations are related to the fre-

quency jitter of the CO₂ laser induced by its coupling to an external cavity while the slow drift of the FIR results from the thermal expansion of the CO₂ cavity due to heating effects of the optical elements (mirror, grating, Brewster window). Consequently a good amplitude stability of the FIR is obtained with a good frequency stabilization of the CO₂. The stabilization system which is used is quite simple and has been described earlier [22]. The CO₂ laser is *frequency locked* by maximizing the FIR amplitude, i.e., the power level of the FIR beam coupled out at the input mirror in our case (see Fig. 2). This method allows to utilize the whole power of the main output beam.

4. Experimental results. — 4.1 LASER PERFORMANCES. — The CO₂ laser provides nearly 30 W on the strongest lines and 20 W on the weaker ones in single low order mode operation. Discharge tubes with 8 mm and 10 mm ID have been tried and the transverse profile of the output beam was respectively gaussian or doughnut shaped with an average cross-section of 6 mm to 8 mm, but no change has been found in its power level. The FIR power is measured with a calibrated Moll thermopile of 1 cm² detective area and a sensitivity of 0.15 mV/mW. On the 70 μ m and 118 μ m CH₃OH test lines respective powers of 40 mW and 70 mW are currently available outside the output FIR windows.

These FIR powers are obtained respectively with 18 and 17 W CO₂ power injected inside the waveguide cavity. The corresponding ratio η/η_{th} of the experimental optical pumping efficiency over the theoretical one are 4 % and 10 %. The typical FIR amplitude stability represented figure 3 is about 5-6 % over 30 min. Figure 3 also shows that periodic corrections of the FIR cavity tuning allow 10 % stability over 3-5 hours.

Fig. 3. — Amplitude stability of the 70 mW FIR laser at 118 μ m. The time constant of detector and trace recorder is ≤ 1 s. (The dashed line corresponds to a readjustment of the FIR cavity tuning.)

4.2 FIR GAS PRESSURE DEPENDENCE OF P_{FIR} . — We have represented in figure 4 the experimental set-up in the case where the FIR gas pressure is monitored

Fig. 4. — Schematic diagram of the experimental arrangement for studying the pressure dependence of P_{FIR} .

continuously. The CO_2 laser frequency is stabilized on the maximum power of a reference FIR laser. Discrete values of the IR power could be selected with an attenuator based on methyl alcohol. The pressure is measured with a Pirani gauge adequate for the operating range 10-300 m torr and previously calibrated for CH_3OH against an absolute capacitive gauge. Figure 5 shows the pressure dependence of P_{FIR} at 70 μm , 118 μm and 570 μm for six values of the pump power P_{IR} . The latter is determined from a calibration of the IR power meter against the effective IR power injected inside the FIR cavity. The general shape of the pressure diagrams is very similar at the three wavelengths studied. At low pressure the saturation intensity I_{SAT} and the self absorption A_e of the FIR (see section 2) are weak, thus the increasing output power with pressure simply reflects the increasing pump absorption. On the other hand, above some FIR gas pressure the decreasing output level corresponds to the increase of I_{SAT} and A_e , while the fractional absorption term f_{abs} approaches more slowly its limit value and finally a cut-off pressure is reached. Therefore at a given pump power, there is a relatively low optimum pressure which value increases slowly with pump power. The largest wavelength transition seem to reach their maximum at lower pressure [23] and in the same range of wavelength, the optimum pressure is lower for the FIR lines corresponding to the strongest pump absorption

$$(\alpha_{70 \mu\text{m}} \simeq \alpha_{570 \mu\text{m}} > \alpha_{118 \mu\text{m}} [11]).$$

Besides, the relative sharpness of the curves in Figure 5 shows the importance of a precise control of the FIR gas pressure to reach the maximum efficiency.

4.3 PUMP POWER DEPENDENCE OF P_{FIR} AT THE OPTIMUM PRESSURE. — An important result for the

Fig. 5. — CH_3OH laser powers at 70 μm (2.a), 118 μm (2.b) and 570 μm (2.c) monitored continuously as functions of the CH_3OH gas pressure, the pump power P_{IR} being a controlled parameter. The different values of P_{IR} are : 1) 3.5 W ; 2) 5.5 W ; 3) 8 W ; 4) 10 W ; 5) 13 W and 6) 15 W. A dielectric waveguide is used at 70 μm and 118 μm and a 20 mm ID copper waveguide is used at 570 μm .

obtention of high FIR powers is the dependence of P_{FIR} with P_{IR} at the optimum pressure. This variation is represented on figure 6 for the CH_3OH lines at 70 μm and 118 μm . At low pump power ($\leq$ a few watts), the FIR laser gain is near the threshold gain $(G_0 L)_{\text{thresh}} = t + a$ (see eq. (1 bis)) and P_{FIR} rises slowly. On the other hand, optically pumped FIR systems may exhibit large small signal gain [23, 24, 25] at high IR power. In this domain the FIR laser gain overreaches largely the threshold gain and the slope becomes steeper as shown in figure 6. The output FIR power is given in the high gain regime by equation (2) where P_{IR} enters explicitly but also indirectly through $(F_{\text{abs}})_{p_{\text{opt}}}$ and $(F_{\text{trans}})_{p_{\text{opt}}}$. The absorption efficiency at the optimum pressure $(F_{\text{abs}})_{p_{\text{opt}}}$ has been evaluated [8] starting from the measurements of absorption coefficients and IR saturation intensities in CH_3OH [11]. These indicate that $(F_{\text{abs}})_{p_{\text{opt}}}$ remains nearly constant when P_{IR} varies and confirm the explanation of section 2.1. Besides, the small variation of p_{opt} with P_{IR} (see curves of Fig. 5) and the low estimated value of A_e in the range of optimum pressures [27] makes also $(F_{\text{trans}})_{p_{\text{opt}}}$ relatively inde-

Fig. 6. — Optimum CH₃OH laser powers at 70 μ m and 118 μ m as functions of the CO₂ pump power.

pendent of P_{IR} . Therefore the product $(F_{abs} \times F_{trans})_{p_{opt}}$ seems to vary only weakly with P_{IR} which clears up the linear dependence of P_{FIR} with P_{IR} observed above a few watts. This linear variation explains also the tendency towards higher pump powers with more powerful CO₂ laser (≥ 30 W).

4.4 FREQUENCY OFFSET DEPENDENCE OF P_{FIR} . — We have studied the frequency offset effect with the 118 μ m CH₃OH laser line since the P(36) CO₂ pump

Fig. 7. — Tuning curves of the 118 μ m CH₃OH laser operated at 60 m torr for three values of the pump frequency offset $\delta\nu_{IR}$.

may be tuned exactly on resonance in this favorable case. The exact location of the FIR gas absorption line center on the CO₂ laser tuning curve is obtained from the absorption signal detected in a spectrophone cell operating at low pressure [27, 28]. The frequency CO₂ detuning $\delta\nu_{IR}$ is monitored from the PZT voltage. Figure 7 shows the tuning curves of the 118 μ m laser operated at low CH₃OH pressure (60 m torr) for three values of $\delta\nu_{IR}$. If $\delta\nu_{IR}$ is small (a few MHz) there is only a decrease of the maximum FIR amplitude. At larger values of $\delta\nu_{IR}$ (10 MHz or more) the two peaks corresponding to the emission of the two opposite velocity classes of molecules are quite separated and the relation $\delta\nu_{FIR} = \delta\nu_{IR} \times v_{FIR}/v_{IR}$ is fairly well verified. Although this observed splitting narrows when the pressure rises towards p_{opt} due to the increase of the homogeneous linewidth of the FIR transition, this effect requires repetitive tuning of both the pump and FIR lasers in the course of the optimization of P_{IR} . Figure 8 represents in another way the combined effects of the frequency offset and the FIR gas pressure. The 118 μ m CH₃OH and P(36) CO₂ emissions are recorded simultaneously when the CO₂ cavity length is monitored for a fixed FIR cavity length. Curves

Fig. 8. — Output power of the 118 μ m laser as a function of CO₂ PZT bias voltage. The PZT traverses three CO₂ cavity modes giving the triple-peaked structures. a) and b) : influence of the CO₂ laser coupling to the FIR cavity (curve b) upon the amplitude stability of the pump in free running conditions.

Fig. 8. — c) and d) : narrowing of the CO₂ laser frequency tuning range giving FIR emission at 118 μ m when the gas pressure is shifted from p_{opt} .

c) and d) of figure 8 illustrate the drastic pressure-dependence of the FIR gain in optically pumped FIR lasers. When the gas pressure is shifted from p_{opt} not only the maximum amplitude of P_{FIR} drops (see section 4.2) but also the pump frequency range where FIR emission is observed narrows considerably whatever the FIR cavity length is. In the case of the strong $118\ \mu\text{m}$ CH_3OH line, curve d) indicates that FIR emission is observed almost throughout the 80 MHz frequency tuning range of the CO_2 laser. Besides, the interferograms of the CO_2 laser (curves a) and b)) illustrate the influence of its coupling to the FIR cavity upon the amplitude stability of the pump in free running conditions.

4.5 INFLUENCE OF HOLE COUPLER ON P_{FIR} . — Figure 9 represents the dependence of the available FIR power at $118\ \mu\text{m}$ and $70\ \mu\text{m}$ as a function of the output hole mirror diameter. It must be noted that the FIR transmission of the quartz window is almost 70 %. The optimum hole diameter (4-5 mm) corresponds approximately to a transmission coefficient $t_{\text{opt}} \simeq 4\%$. This low value of t_{opt} is due to the increase of the IR losses and probably to the excitation of higher order modes for larger hole dimensions.

5. Conclusion. — The CH_3OH laser configuration described in this paper shows that stable high FIR power levels may be obtained with a simple waveguide laser design pumped at a moderate range of CO_2

Fig. 9. — FIR powers at $70\ \mu\text{m}$ and $118\ \mu\text{m}$ available outside the output FIR windows as functions of the hole-diameter of the coupling mirror.

power (less than 30 W). We have also stressed the guide lines for selecting the laser parameters and the experiments which are reported underline the more stringent ones. The ratios η/η_{th} of the experimental optical pumping efficiency over the theoretical one which we have obtained are comparable to the results published elsewhere, but are still far from optimum. Continued effort is required to improve the different factors affecting the laser performances i.e. the IR absorption and the FIR transmission efficiencies.

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