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PARAMETER STUDY AND COMPUTER SIMULATION OF AN OPTICALLY-PUMPED MIRRORLESS LASER AT 496 MICRONS IN METHYL FLUORIDE AND 385 MICRONS IN HEAVY WATER

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ABSTRACT

The effects produced in an optically-pumped mirrorless far infrared laser assembly by varying pumping power, gas pressure, and tube length have been investigated. It is found that absorption of pumping radiation depends only on the number of absorbing molecules, far infrared output peaks when gas pressure is such that approximately two-thirds of the pump radiation is absorbed, and peak far infrared output increases with tube length even though the total number of absorbing molecules remains constant.

A computer simulation for the mirrorless laser based on Javan's three level rate equation model, but retaining one-dimensional spatial dependence is presented and compared with experimental results.

(Paper presented at the Third International Conference on Submillimetre Waves, Guildford, Surrey, U K, March 29-April 1 1978, and submitted for publication in Infrared Physics.)

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May 1978

Far Infrared (F I R) laser development is directed to producing a high power pulsed laser suitable for plasma diagnostics[1]. To give guidance in optimizing the laser configuration, a parameter study of F I R laser output from mirrorless tubes was conducted, the chief consideration being to maximize the F I R output power. The absorption of radiation from the CO_2 laser pump and the emission of F I R power were measured as functions of pumping power, tube length, and gas pressure, and observations were carried out on the 496 micron line of CH_3F and the 385 micron line of D_2O.

The experimental assembly is particularly simple, consisting of a grating-tuned CO_2 T E A laser capable of producing up to 55 J, one third of which is in the gain-switched spike, and a 10 cm diameter FIR tube capable of being varied in length from 1.5 to 7.5 metres. F I R output emerges through a T P X window and is directed by a concave F.2 mirror onto a Laser Instrumentation Ltd model 17 calorimeter. Alternatively F I R output could be directed onto a fast diode for pulse shape and length measurements, or passed through a metal mesh Fabry-Perot etalon which served to isolate the 385 micron line when the 385/359 micron cascade was being investigated.

Figure 1 shows CO_2 attenuation and F I R emission in CH_3F for fixed pumping but varying tube length and gas pressure. The pump irradiance in these measurements was a few MW cm^{-2}, which is an order of magnitude above the saturation value of about 0.5 MW cm^{-2} $torr^{-1}$ measured by analysing the absorption curves in a way similar to that suggested by Temkin and Cohn[2]. It can be seen that as the tube length is increased, the pressure at which a fixed fraction, say two-thirds, of the incident pump energy is absorbed is reduced in such a way that the product of this pressure and the tube length is constant (Figure 2). This implies, as might be anticipated[3], that a fixed number of molecules is required to absorb a fixed fraction of the pump, no matter whether in a long tube at low pressure or in a short tube at high pressure.

Figure 1 also shows that as gas pressure is increased, F I R output rises from zero, goes through a maximum, then decreases again. The pressure at which the maximum occurs depends on the tube length: the longer the tube, the lower the pressure for maximum F I R output.

Moreover, comparison of the CO_2 absorption and the F I R emission curves reveals that maximum F I R output always occurs when a fixed fraction, namely about two-thirds, of the CO_2 laser radiation has been absorbed. This means that the peak F I R output always occurs at a fixed number of molecules for fixed pumping level, but in addition, the maximum output increases with increasing tube length. So the same number of molecules produces a larger F I R peak power when at low pressure in a long tube than when at high pressure in a short one.

The same behaviour is seen in D_2O (Figure 3). Further, if the tube length is kept constant but pump power is reduced, the CO_2 laser radiation is two-thirds absorbed at lower and lower pressure, and the F I R maximum falls in intensity, but continues to be found at the pressure where about two-thirds of the pump radiation has been absorbed. This is illustrated strikingly in Figure 4.

Another observation that can be made in both CH_3F and D_2O is shown in Figure 5, where F I R emission dependence on pressure curves for various tube lengths are superimposed. It can be seen that at low fixed pressure increasing tube length leads to increasing F I R output, but at high fixed pressure, increasing tube length leads, rather unexpectedly, to a reduction in F I R emission.

As a first step towards understanding some of this behaviour a computer simulation based on the Javan three-level rate equation model[4] for amplified spontaneous emission has been constructed. The description of a mirrorless single pass laser, in contrast to an optical cavity configuration, has to retain one-dimensional spatial dependence as well as time dependence. Frantz and Nodvik[5] described single pass amplification analytically by assuming that pumping was completed before the onset of laser action, and other authors[6,7,8,9] have obtained analytical solutions to the rate equations for a one pass amplifier under different simplifying approximations. None of these however, is strictly applicable to the case of F I R amplified spontaneous emission. Indeed, we appreciate that to account for dynamic Stark splitting and Raman effects, one must resort to the more rigorous density matrix or quantum mechanical approach[10,11].

The three level model for CH_3F and the rate equations describing it are displayed in Figure 6. The constants used are listed in TABLE I,

and the idea of the computation is shown schematically in Figure 7. We assume F I R is emitted only in the direction of the pump radiation (though in fact we know from experiment that this is not the case). The total tube length is divided into a sequence of thin slabs each of which is homogeneous with respect to populations of the molecular levels and the radiation intensities. A pump pulse of given time history is introduced from the left, and the programme calculates level populations N_A, N_B, and N_C as functions of time in the first slab, as well as the time dependence of the outgoing pump and F I R leaving the slab towards the right. This process is then iterated along the length of the tube.

It was found that a reasonable fit to experimental data could be secured by adjusting two parameters only, the collision frequency $W_{co} = 1/\tau$, and the pump absorption cross-section, σ_p. Varying W_{co} produced significant changes mainly in the high pressure part of the F I R emission curves, while the low pressure side of these curves was influenced chiefly by σ_p.

The small signal value of σ_p, measured by Chang, Wang, and Cheo[12], was used to initiate the calculations, but since the number of K-levels excited in CH_3F increases with increasing pump intensity[10,11], and since σ_p is proportional to K^2 for this absorption[13], it is reasonable to expect to have to adjust σ_p upwards to obtain a fit to the present, high pump intensity, data. Similarly, the value of W_{co} chosen initially was deduced from pressure broadening of the 496 micron line in CH_3F[14]. But the effective relaxation rate is actually different for each molecular level, and indeed, it is influenced by processes other than collisions. For example, the relaxation rate into level C must be enhanced by the generation of 452 micron radiation which rapidly repopulates this level. Thus, one might expect that increased values of W_{co} as well σ_p would be required to give a fit to data measured under conditions of saturated optical pumping.

The choice of $\sigma_p = 1 \times 10^{-22}$ m^2 and $W_{co} = 5 \times 10^8$ Hz $torr^{-1}$ resulted in the fit to experimental data on absorption as well as emission measured in a 4.2 metre tube, shown in Figure 8a.

Scaling of pump absorption and F I R emission with tube length was investigated with no modification of the parameters beyond that already described above. The model then predicted fairly closely the results actually observed in the 2.7 metre tube, as shown in Figure 8b. For this shorter tube the programme predicts a smaller F I R maximum intensity occurring at rather higher pressure than the maximum in the 4.2 metre tube, in accordance with the actual observations.

Scaling of absorption and emission with pump power was less satisfactory. Reduction of the maximum F I R emission and its shift to lower pressure as pumping is reduced are both reproduced, but amplitudes fail to scale properly with observations. We compare measured data for pump input energies of 600 Jm^{-2} and 300 Jm^{-2} with curves computed for 600 Jm^{-2}, 450 Jm^{-2}, and 300 Jm^{-2}, and tube lengths 4.2 metres and 2.7 metres, in Figure 9. The programme gives a more rapid decrease in output with decreasing pump than actually occurs and this failure becomes more exaggerated as tube length decreases.

To summarize, a parameter study of optically pumped mirrorless laser emission at 496 microns in CH_3F and 385 microns in D_2O is reported, in which the effects of varying pump power, gas pressure, and tube length have been studied. It is found that absorption of the CO_2 pumping radiation depends only on the number of absorbing molecules, and F I R output peaks when gas pressure is such that approximately two thirds of the pump radiation is absorbed. The F I R peak output increases with increasing tube length, even though the total number of molecules, as measured by the product of pressure and length, remains fixed.

A computer model for the mirrorless amplified spontaneous emission assembly based on Javan's three level rate equation picture but retaining one-dimensional spatial dependence has been prepared, and it produced a reasonably satisfactory fit to data observed for CH_3F if unusually large values of the pump absorption cross-section σ_p, and the collision frequency per torr, W_{co}, were adopted. It is recognized of course that these parameters are artificial in that they represent an average over K-levels, and probably vary with pump energy as well. A more satisfactory fit between computed behaviour and observational data may be expected for the case of D_2O where only a single K-level is involved.

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Physical Parameters for the Computer Model of the FIR CH_3F Laser

Physical Parameter	Symbol	Value
Population density of level A	N_A	–
Population density of level B	N_B	–
Population density of level C	N_C	–
Equilibrium population density of level A	N_{A_o}	$3{\cdot}19 \times 10^{18}\ m^{-3}$ *
Equilibrium population density of level B	N_{B_o}	$3{\cdot}24 \times 10^{18}\ m^{-3}$ *
Equilibrium population density of level C	N_{C_o}	$4{\cdot}91 \times 10^{20}\ m^{-3}$ *
Intensity of the pump radiation	I_p	–
Intensity of the FIR radiation	I	–
Cross-section for FIR stimulated emission	σ_f	$1{\cdot}1 \times 10^{-19}\ m^2$ †
Cross-section for pump absorption	σ_p	$2{\cdot}5 \times 10^{-23}\ m^2$ §
Frequency of the pump radiation	ν_p	$3{\cdot}138 \times 10^{13}$ Hz
Frequency of the FIR radiation	ν	$6{\cdot}043 \times 10^{11}$ Hz
The rotational-rotational collision time	τ	$8 \times 10^{-9}\ s$ ‡*
FIR spontaneous emission time	t_{sp}	$2{\cdot}3 \times 10^{2}\ s$ ‡
Pump energy density	I_{p_o}	–

Notes:

* Values quoted for a pressure of 1 torr

† Brown and Cohn, 1974

‡ Chang and Bridges, 1970

§ Chang, Wang and Cheo (1969), derived from their measurement of the pump absorption coefficient, α_p (measured to be $1{\cdot}8\ m^{-1}$).

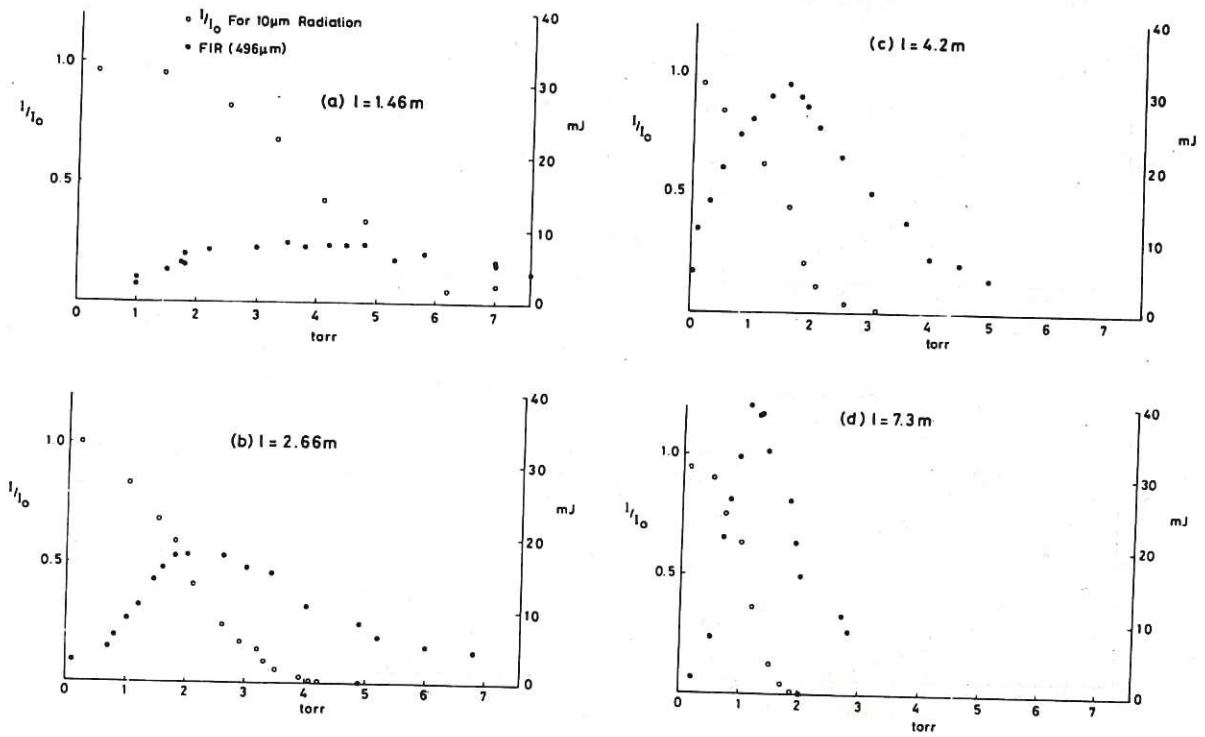


Fig.1 Attenuation of CO_2 pump radiation I/I_0 and FIR emission at 496 microns as a function of gas pressure (torr) for four tube lengths.

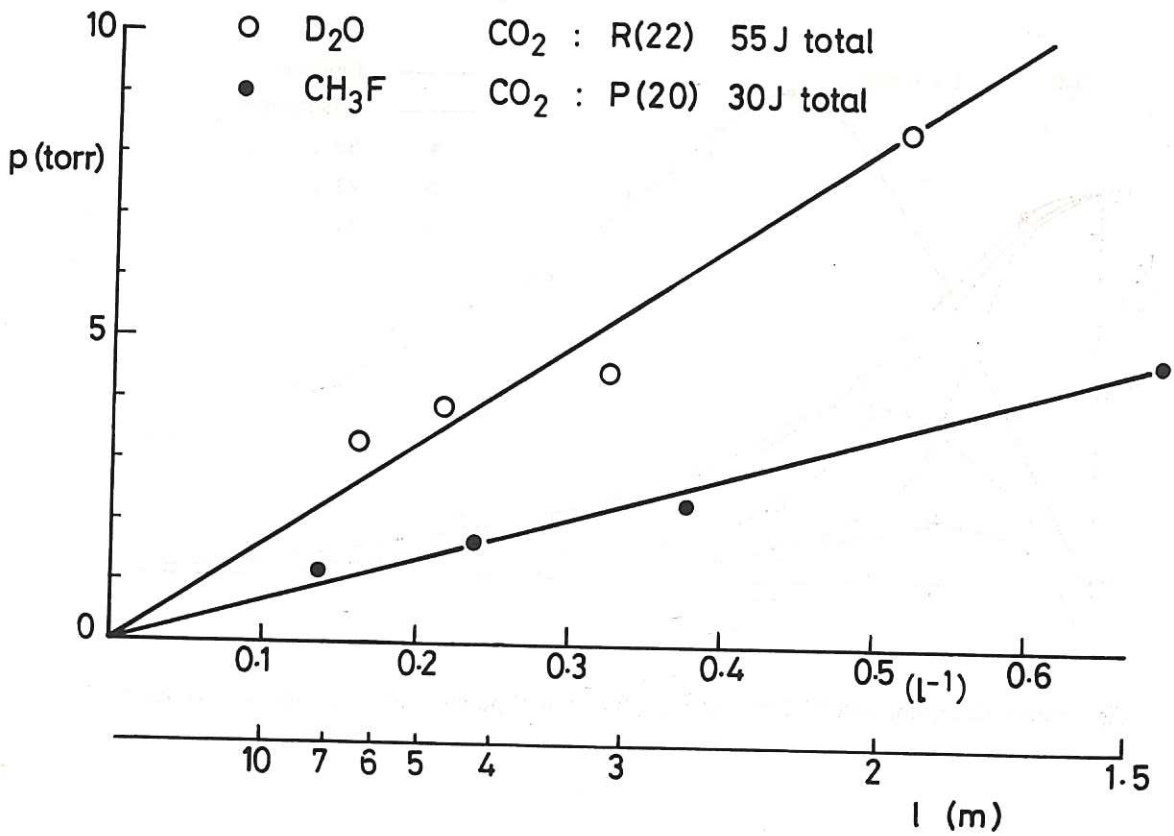


Fig.2 Pressure at which two-thirds of pump radiation is absorbed in D_2O and CH_3F as a function of the reciprocal of the tube length.

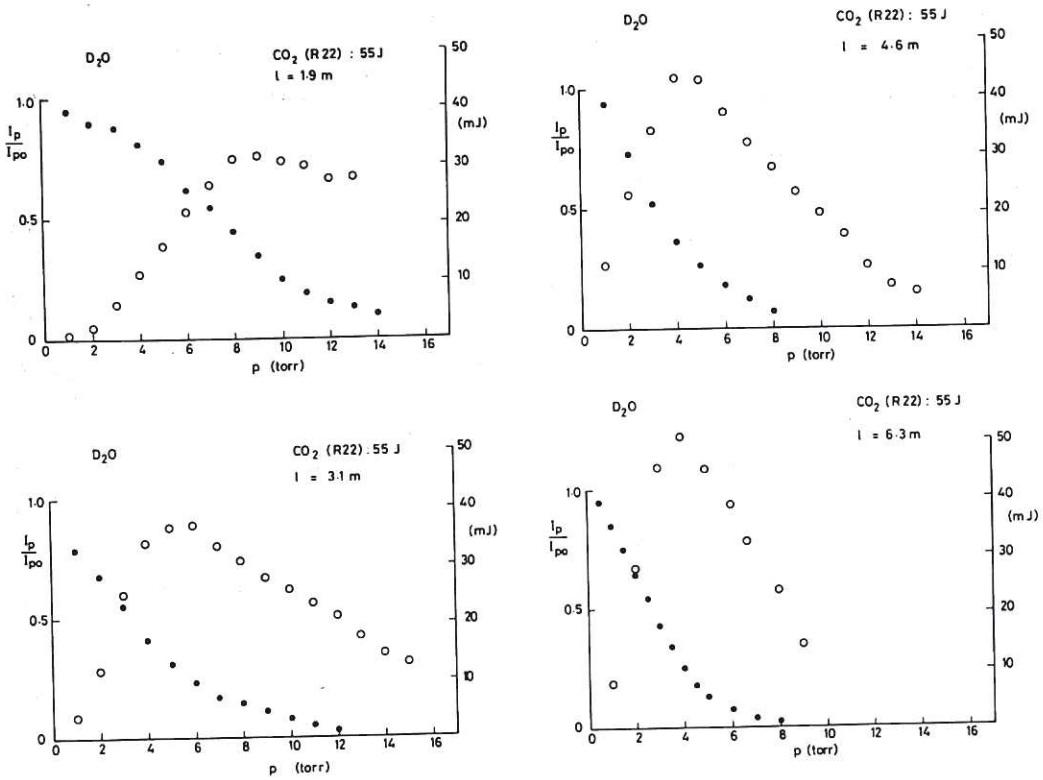


Fig.3 Attenuation of CO_2 pump radiation and FIR emission at 385 microns as a function of gas pressure in D_2O for four tube lengths.

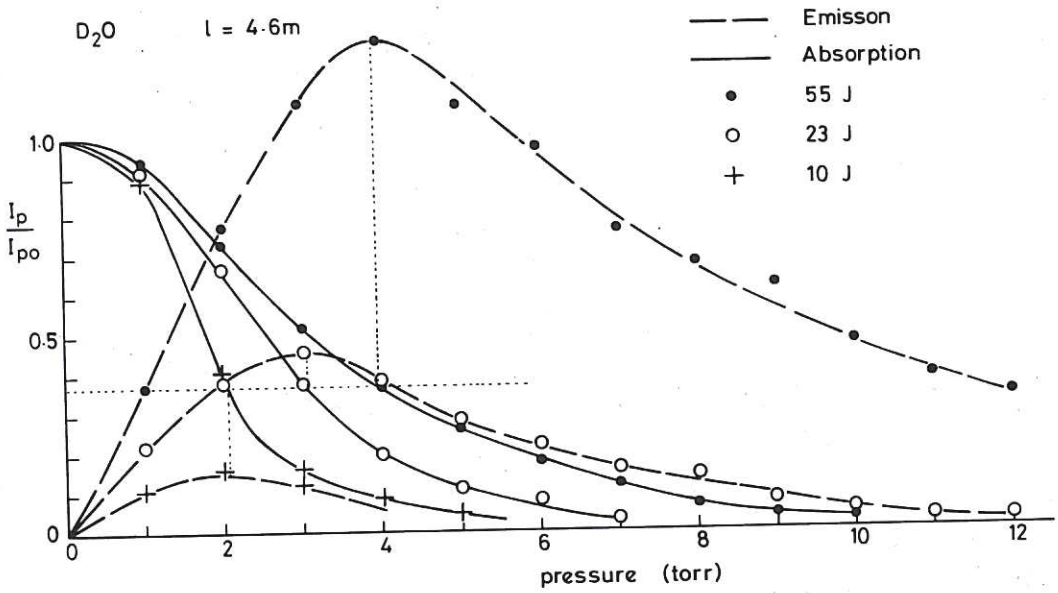


Fig.4 Pump absorption and FIR emission as a function of pump power in a tube of fixed length.

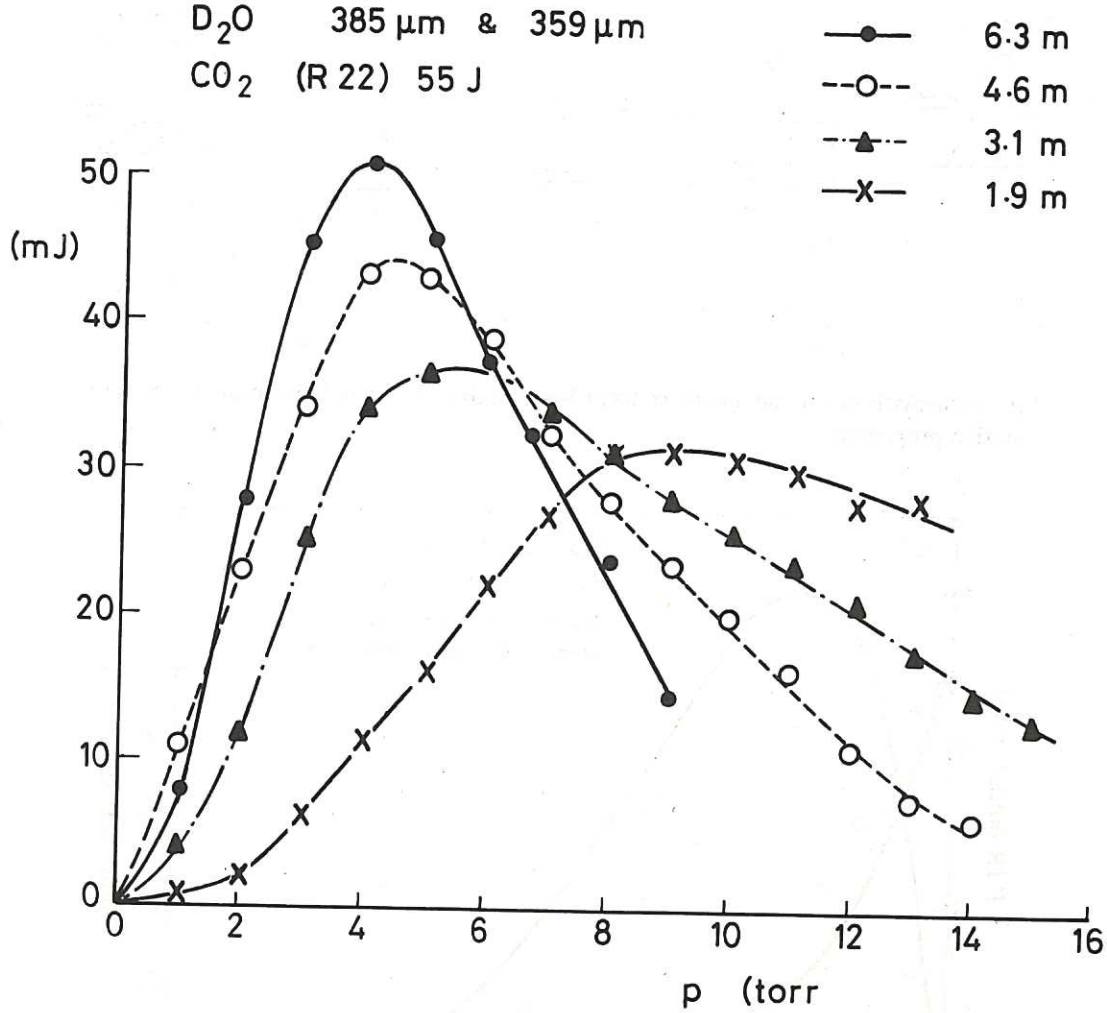
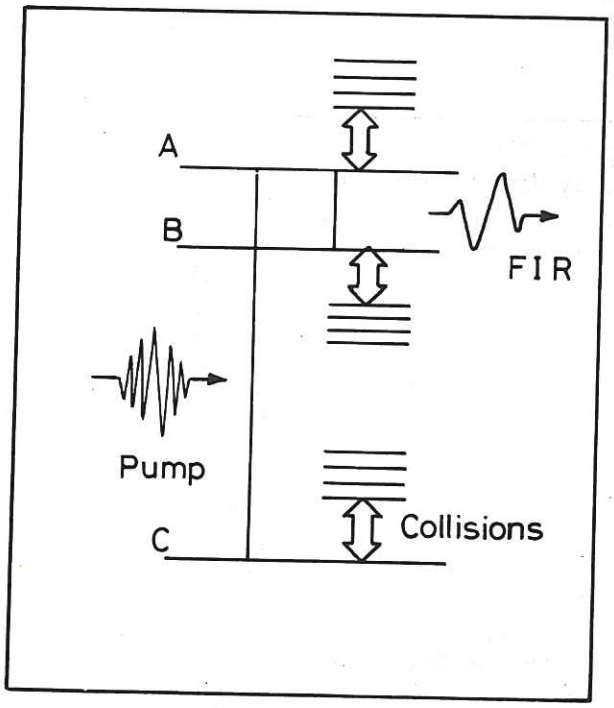


Fig.5 FIR emission as a function of pressure at fixed pump power: comparison of results for increasing tube length.



$$\frac{\partial N_A}{\partial t} = -\sigma_p (N_A - N_C)\frac{I_p}{h\nu_p} - \sigma_f (N_A - N_B)\frac{I}{h\nu} - \frac{(N_A - N_{A_o})}{\tau}$$

$$\frac{\partial N_B}{\partial t} = \sigma_f (N_A - N_B)\frac{I}{h\nu} - \frac{(N_B - N_{B_o})}{\tau}$$

$$\frac{\partial N_C}{\partial t} = \sigma_p (N_A - N_C)\frac{I_p}{h\nu_p} - \frac{(N_C - N_{C_o})}{\tau}$$

$$\frac{\partial I_p}{\partial t} + c\frac{\partial I_p}{\partial x} = \sigma_p\, c(N_A - N_C)\, I_p$$

$$\frac{\partial I}{\partial t} + c\frac{\partial I}{\partial x} = \sigma_f\, c\,(N_A - N_B)\, I + \frac{ch\nu_f}{t_{sp}} N_A$$

Fig.6 Three level model for CH_3F and the rate equations describing it used in the computer simulation.

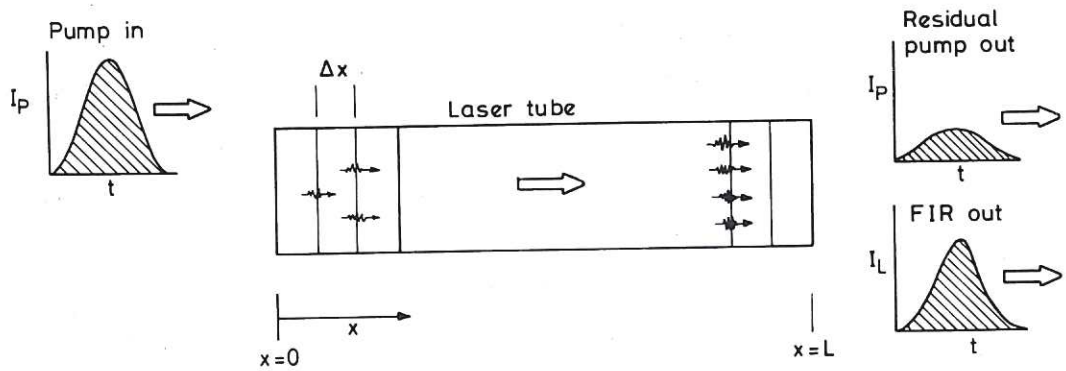


Fig.7 Schematic of the slab model concept for retaining one spatial dimension in the rate equation programme.

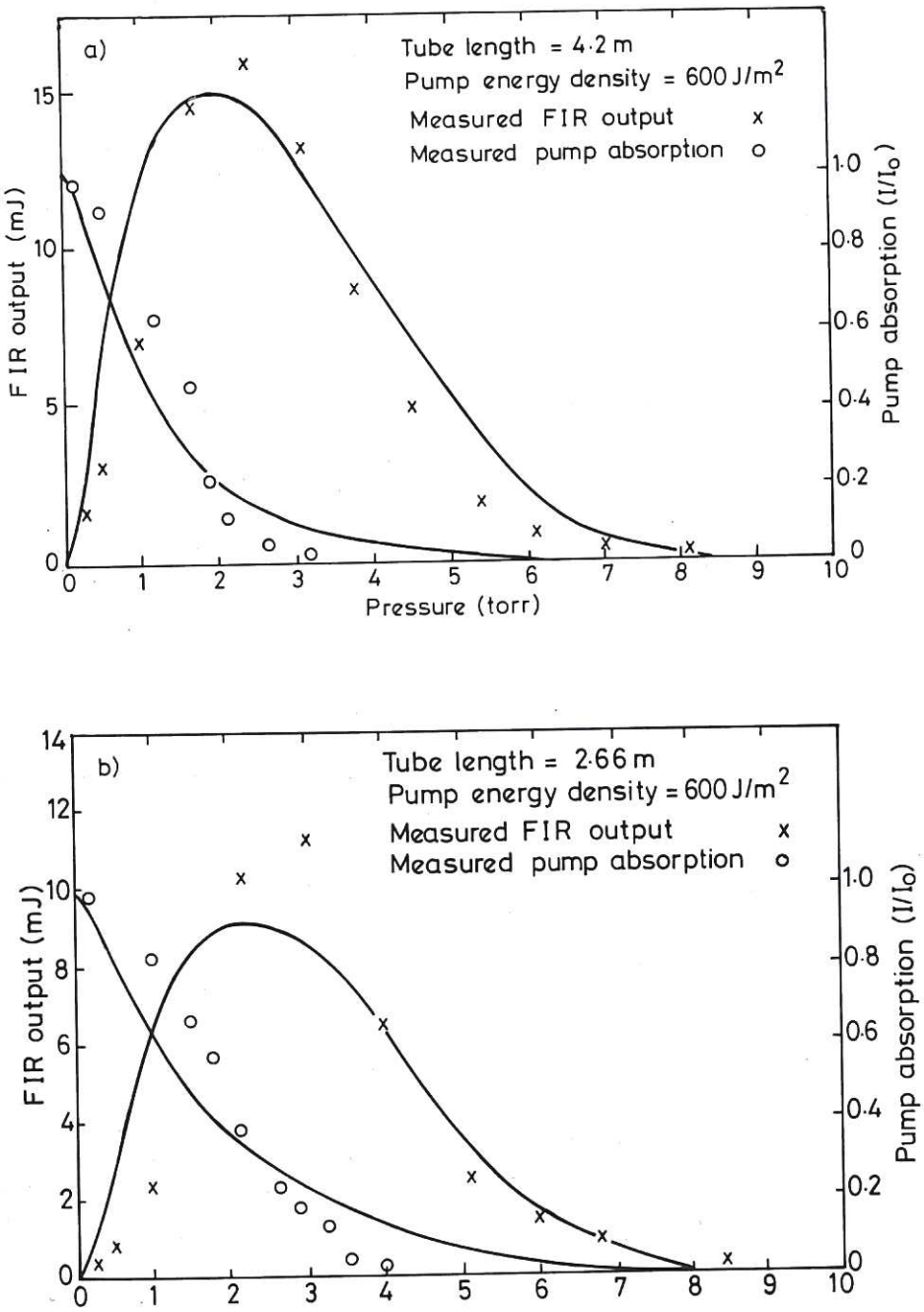


Fig.8 Comparison between observational data and computation for pump energy 600 Jm^{-2} (a) 4.2 metre tube, (b) 2.7 metre tube.

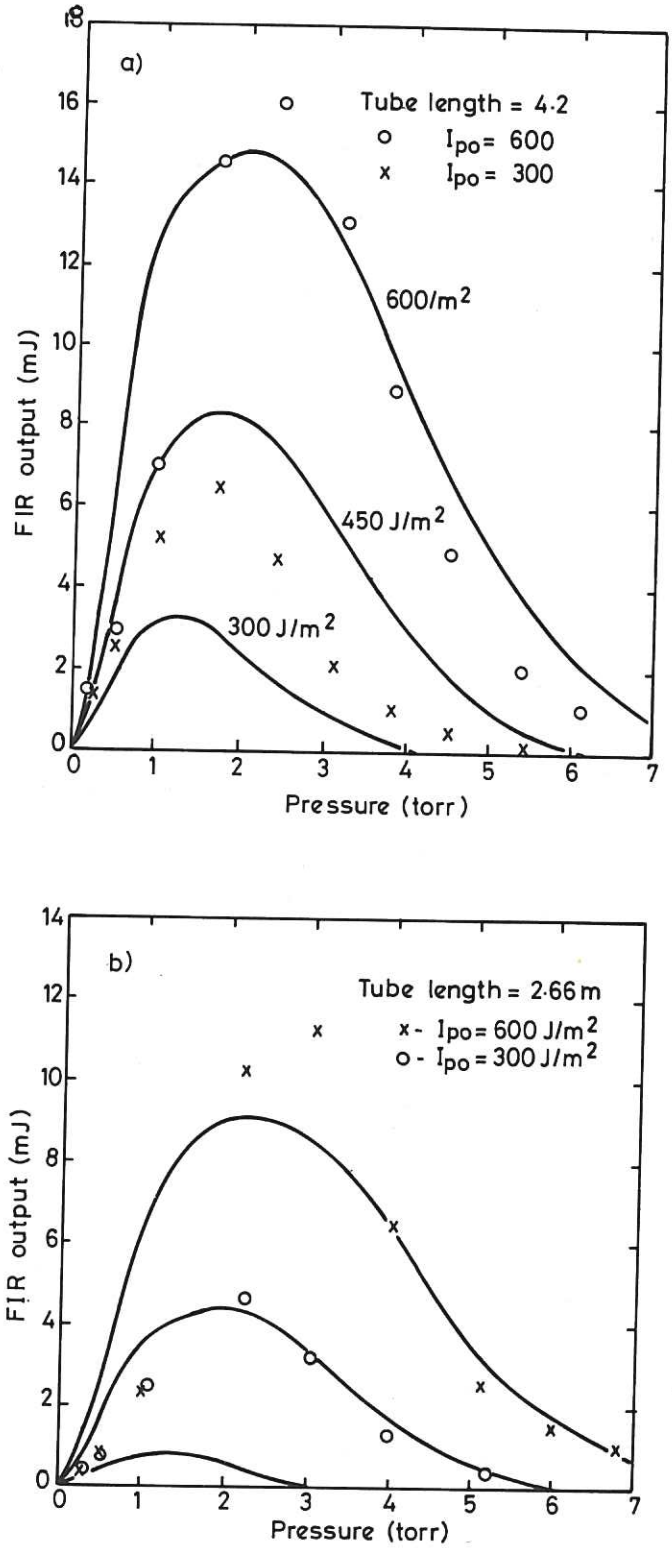


Fig.9 Comparison between experimental data for pump energy densities 600 Jm^{-2} and 300 Jm^{-2}, and computed emission curves for 600 Jm^{-2}, 450 Jm^{-2}, and 300 Jm^{-2}, (a) 4.2 metre tube, (b) 2.7 metre tube.