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D.C. Yuan* and M.R. Siegrist

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne
21, Av. des Bains, CH-1007 Lausanne/Switzerland

* Permanent address: Anhui Institute of Optical and Fine
Mechanics, Academia Sinica, P.O. Box 25
Hefei, Anhui, People's Republic of China

Abstract

We have achieved single mode operation in a hybrid optically pumped D_2O far infrared laser. The active volume of the resonator was divided into two sections separated by a thin plastic foil. The larger section served as the main gain medium and the shorter section as mode selective element. The vapor pressure in the smaller volume was either very low or alternatively about 3 times higher than the pressure in the main part. In both cases single mode operation was achieved without any reduction of the total output energy.

Introduction

We have recently reported results of investigations of the mode structure in an optically pumped D_2O far infrared ring laser operating at 385µm [1]. The aim was to achieve single mode operation, an important requirement for plasma diagnostic applications, specifically for the measurement of the ion temperature in a tokamak plasma by means of collective Thomson scattering. The results showed that single mode operation can indeed be achieved in a ring resonator much more easily than in the usual linear resonator type.

In these experiments only plane optical elements have been used, either flat mirrors or meshes and grids. It is well known that it is difficult to control the transverse mode structure and hence beam quality in such plane-plane resonators and also that scaling to larger diameters is not straightforward. In high-power far infrared (FIR) lasers unstable resonators are usually employed in order to achieve large mode volumes [2,3]. While unstable ring resonators can, in principle, be built, this results in practice in a fairly complex structure of large size, plagued by mechanical stability problems.

In the visible or IR region of the spectrum a variety of mode selection techniques have been developed and used with success, and many of them can also be applied to high-power optically pumped far infrared lasers. However, they usually require the introduction of lossy elements into the resonator, resulting in a considerable reduction of output power.

A well known technique which is often used with CO_2 lasers is the so-called hybrid oscillator whereby an active low pressure section is introduced into the main TEA laser cavity [4,5]. This low pressure cell provides an additional narrow gain spike on the line center of the broad main gain profile. A resonator mode coinciding with this peak experiences a sufficiently enhanced gain in order to suppress neighboring modes via mode competition effects during build-up. The output energy of an oscillator is not reduced by the addition of a low pressure section since the losses of the unavoidable windows can easily be compensated by the additional gain.

Optically pumped FIR lasers can operate over a fairly large pressure range, e.g. from less than 1 torr to over 10 torr in the case of the D_2O laser at 385µm [1,6,7]. Over most of this range the gain profile is pressure broadened and thus narrower at low pressure. Hence it is to be expected, that a hybrid oscillator containing a low pressure section should lead to single mode operation in much the same way as in a CO_2 laser [8]. This has indeed been observed.

However, mode competition effects are more complicated in optically pumped molecular systems [9,10,11]. Indeed it has been known for a long time that single mode operation is obtained in a D_2O laser at pressures of 9 torr or more without any mode selective elements, whereas this is not the case at lower pressures [1,6,7]. An explanation for this behavior has been given in [1,6] and will briefly be restated here: the position of the gain peak can shift significantly under the influence of saturating pump or FIR intensities, especially so if the excitation is due to a two-photon Raman transition. Hence established modes at a particular frequency see a reduced gain when the gain peak moves away to a different frequency range due to the continuously varying laser intensities during the pulse, whereas other modes are now able to grow. At lower pressures saturating intensities are easily reached. At high pressures this is not usually the case and hence the gain profiles are much more stable. The increasing width of the gain profile is not so important, since mode competition effects in optically pumped systems are quite pronounced due to the mutual coupling of different modes via the pump field. Hence a strong mode can easily suppress neighboring weaker ones.

In view of this the question arises if a section of higher pressure inside a resonator operated at optimum pressure could also enforce single mode operation. This has indeed been observed. While this is an interesting observation in its own right, the real importance is due to the fact that a hybrid oscillator of this type produces output energies equalling or even exceeding those obtained with an identical single pressure resonator.

Apparatus

The experimental arrangement shown in Fig. 1 is similar to the one described in [1] with an identical pump laser. The FIR cavity of 1.75m length inside a metal tube of 50cm diameter, is formed by two metallic grid couplers of 84% and 10% reflectivities, the latter one being the output coupler. A 50cm long metal tube of 6cm diameter with thin plastic foils at either end is positioned close to the output coupler and centered on the resonator axis. The plastic foils are mounted at an angle of 85° with respect to the resonator axis in order to avoid coupled resonator effects. These are not necessarily undesirable, since they can also lead to mode selection, but had to be avoided in our case to allow interpretation of the results. Since the foils only have to withstand a pressure differential of a few torr, they can be made very thin in order to transmit as much as possible at the FIR as well as at the pump wavelength.

A CO_2 pulse shape and energy monitor are aligned on either of the two reflections from the entrance window of the D_2O tank. The FIR radiation is directed inside a Faraday cage and analyzed by means of Schottky diodes in video mode or by pyroelectric energy meters.

Measurements

For all the results reported here the CO_2 pump laser produced a single longitudinal mode. This is a precondition for the attainment of single mode operation in the D_2O laser which otherwise shows a complex mode pattern of rather broad bandwidth.

a) Hybrid laser with low pressure section

If the whole volume of the FIR laser (incl. the 50cm long separate section) is filled with a pressure of 5 torr of D_2O vapor maximum FIR output energies are obtained. The radiation is typically emitted in the form of 2-4 neighboring longitudinal modes [12]. At lower pressure and equally at pressures up to about 8 torr multimode emission is also observed at a reduced output energy [1]. Single mode operation can only be achieved at pressures exceeding 9 torr where the energy is less than 30% of maximum. If the separate section is pumped out the behavior is rather similar. The output energies are slightly reduced due to the reduction of overall gain length.

If, however, the separate section of tube is filled with 0.1 mbar of D_2O the conditions change dramatically. This is illustrated in Fig 2: single mode operation has been observed over the whole useful range of pressures in the main section. Fig 3 shows the FIR output energy as function of pressure in the main cell, with and without the action of the low pressure section. As can be seen, the output is higher in the single mode case than if the short section is pumped out, but somewhat lower than for the case of equal pressure in both sections. Hence the energy differences are simply due to the different gain lengths and are not related to the mode structure.

b) Hybrid laser with higher pressure section

Knowing already that single mode operation in a single section resonator is achieved at higher pressures [1,6,7], we decided to investigate the effect of high, rather than low filling pressure in the separate section of tube. The results were rather surprising. It is indeed possible to achieve single mode operation over the whole useful range of pressures in the main cell with a pressure of 13 torr or more in the separate section. This is demonstrated in Fig 4. which shows several pulse shapes. The output energy as function of the pressure in the main cell is shown in Fig 5. The dependance is quite similar to the one obtained in a single cell laser; the maximum output energy is still obtained at 5 torr. Again, the energy is somewhat higher (≈10%), but the main difference is naturally the mode structure.

When the pressure in the main cell is kept at its optimum value and more D_2O is added to the short section, the output energy increases slightly, as reproduced in Fig 6, whereas single mode operation is maintained.

c) Unstable resonator of 4m length

As mentioned above this work was undertaken with the aim to enforce single mode operation in an unstable resonator of 4m length, used for collective Thomson scattering in the TCA tokamak. This resonator, described in [13], is a folded telescopic type, resulting in a parallel output beam with a central hole in the intensity distribution caused by the small convex output coupler mirror. The entire resonator, including the beam focusing system, is contained in a tank filled with D_2O vapor. A section of about 80cm length on the output side of the resonator was again separated from the main volume by a thin plastic foil. This time the foil had to be mounted perpendicular to the beam axis, so that coupling effects could not be excluded. While the beat signal produced by the output beam indicated a reduced number of modes when the separate section was filled with either a higher or a considerably lower pressure of D_2O vapor, single mode operation could never be achieved. The output power was also noticeably smaller than without the foil.

Since the time available for these measurements was rather limited, the conclusions drawn have to be interpreted with caution. It is likely that the axial mode spacing of less than 40 MHz in this long resonator is too small for an efficient discrimination by the effects mentioned above. The reduction in output power could partly be explained by insertion losses due to the foil and partly by the influence of the foil on the mode structure in the resonator. Geometrically only 4% of the radiation incident on the output coupler is reflected back into the resonator. Hence a small amount of parasitic reflection can have a significant effect on the transverse mode pattern in the resonator.

Discussion

The results obtained in the resonator containing a low pressure section can be explained sufficiently well by analogy to the often used hybrid CO_2 laser system. The additional narrow band gain due to the low pressure section favours one particular axial mode throughout the whole pulse duration and due to homogeneous line broadening neighboring modes are suppressed by saturation effects.

The operation of the laser with a section of higher pressure is more difficult to understand. The mode-selective property at higher pressure seems contradictory to intuition for a pressure broadened gain profile. We show in Fig 7 the gain profiles calculated according to [9] for a D_2O laser operating at 385μm at a pressure of 4 torr (curve 1) and 12 torr (curve 2). The dimensionless field strengths related to the Rabi flipping parameters [9] are $\alpha=4$ for the pump field and $\beta=1.5$ for the far infrared field. These conditions are representative for our D_2O laser. In addition, $\beta=1.5$ corresponds to the far infrared field strength at which maximum gain is obtained at a fixed frequency. For a sufficiently slowly varying pump intensity, the far infrared field strength will automatically adjust to a value close to this gain maximum; the exact operating point depends on the resonator quality.

We have also shown in Fig 7 the small signal gain for the two vapor pressures. The gain values which are proportional to α^2 in this regime are considerably smaller and have therefore been drawn with a different vertical scale. The pump mechanism in a D_2O laser at 385μm wavelength is a Raman process due to a frequency offset of the order of 320MHz between the CO_2 pump line and the frequency of the absorbing transition. In such a system the small signal gain profile shows two maxima of equal height: one at the center frequency of the far infrared laser transition and the second one at the Raman frequency, displaced by the above mentioned frequency difference. The two gain profiles overlap already at a pressure of 4 torr and are completely merged at 12 torr. While each feature individually clearly shows pressure broadening, the total widths of the two gain profiles are comparable under these conditions. This explains why pressure broadening is not a handicap for single mode operation. Another effect seems to be much more important: the pump power induced AC Stark effect which shifts the gain maxima outwards.

Let us assume that a single mode at the Raman frequency develops inside the resonator. This is likely to occur because of the small signal gain peak at this frequency. It is known from theory [9] and has been confirmed by experiment [12] that an additional mode at line center is efficiently suppressed by mode competition effects. This occurs under conditions where the pump intensity is still relatively small ($\alpha<1$) but the far infrared intensity has already reached saturating levels ($\beta>1$). Hence modes at the line center frequency are not usually observed despite the fact that their growth rate is initially the same as for the Raman mode.

Curve 1 of Fig 7 shows the gain a single mode of field strength $\beta=1.5$ would see at a particular frequency, whereas the dashed curve number 5 shows the gain of a weak second mode in the presence of a main mode with $\beta=1.5$ at the Raman frequency. These profiles are not identical since the presence of an intense established mode modifies the gain of a weak mode by mode interaction phenomena. For the conditions shown a weak mode at the frequency of the peak of curve 5 sees a higher gain than the established mode at the Raman frequency and a multimode situation is likely to occur.

At a higher pressure the situation is quite different. The curves 2 and 6 for 12 torr correspond to the curves 1 and 5 for 4 torr. The value of α has not only been adjusted to account for the different vapor pressure, but also to account for 75% absorption of the pump radiation in the main resonator section. If we assume again that a single mode has developed at the Raman frequency, there is now no neighboring mode which experiences a higher gain and it is much more likely that single mode operation is preserved in this case.

The full dynamics of mode competition effects under the influence of the time varying pump and far infrared intensities is very complicated. However, the considerations outlined above provide some qualitative explanation for our observation.

Conclusions

It has been shown that the hybrid laser concept which has been used successfully for many years in CO_2 lasers, can also be applied to optically pumped far infrared lasers. The short resonator section responsible for mode selection can either be operated at a very low vapor pressure or alternatively at a significantly higher pressure. The mechanisms responsible for mode selection are considerably more complicated than in a CO_2 laser. In the discussion we presented a qualitative picture of the mode competition effects based on existing theoretical work.

Acknowledgement :

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Figure captions

Fig 1: The hybrid D_2O far infrared laser resonator:
PB: CO_2 laser pump beam
W: KCl entrance window
$G_{1,2}$ metallic grids
S: separate low or higher pressure section
F: thin plastic foils
L: TPX lens
D_1-D_4: IR and FIR pulse shape and energy detectors

Fig 2: The effect of a low pressure section:
(a) to (f) Single mode operation.
The low pressure section is filled with 0.1mbar D_2O vapor. The pressure in the main cell is 2,3,4,5,6,7 torr, respectively.
(g) to (i) Multimode operation

	pressure in main section	pressure in short section
(g)	3 torr	0 torr
(h)	5 torr	0 torr
(i)	5 torr	5 torr

The time scales are: 0.5µs/div

Fig 3: The output energy as function of D_2O pressure in the main section. The pressure in the short section is for
curve 1: the same as in the main section

curve 2: 0.1 mbar
curve 3: 0

Fig 4: The effect of a short section with higher D_2O pressure (13 torr). Single mode operation is observed for pressures in the main section varying from 2 torr (a) to 7 torr (f) in steps of 1 torr.
The time scales are: 0.5µs/div

Fig 5: Output energy as function of pressure in the main section. The D_2O pressure in the short section is fixed at 13 torr.

Fig 6: Output energy as function of D_2O pressure in the short section. The pressure in the main section is fixed at 5 torr.

Fig 7: FIR gain profiles for a single mode (SM) and a weak probe mode (PM) in the presence of a main mode at the Raman frequency.
The pressures are 4 torr and 12 torr for the main section (MS) and the short section (SS), respectively. The field strengths α for the pump and β for the FIR are expressed in dimensionless
units (see text).
Curve 1: SM, MS, $\alpha = 4$, $\beta = 1.5$
Curve 2: SM, SS, $\alpha = 2/3$, $\beta = 0.5$
Curve 3: small signal gain, MS
Curve 4: small signal gain, SS
Curve 5: PM, MS, $\alpha = 4$, $\beta = 1.5$
Curve 6: PM, SS, $\alpha = 2/3$ $\beta = 0.5$
In the D_2O laser discussed the separation between the Raman frequency and the line center frequency is ≈ 320 MHz.

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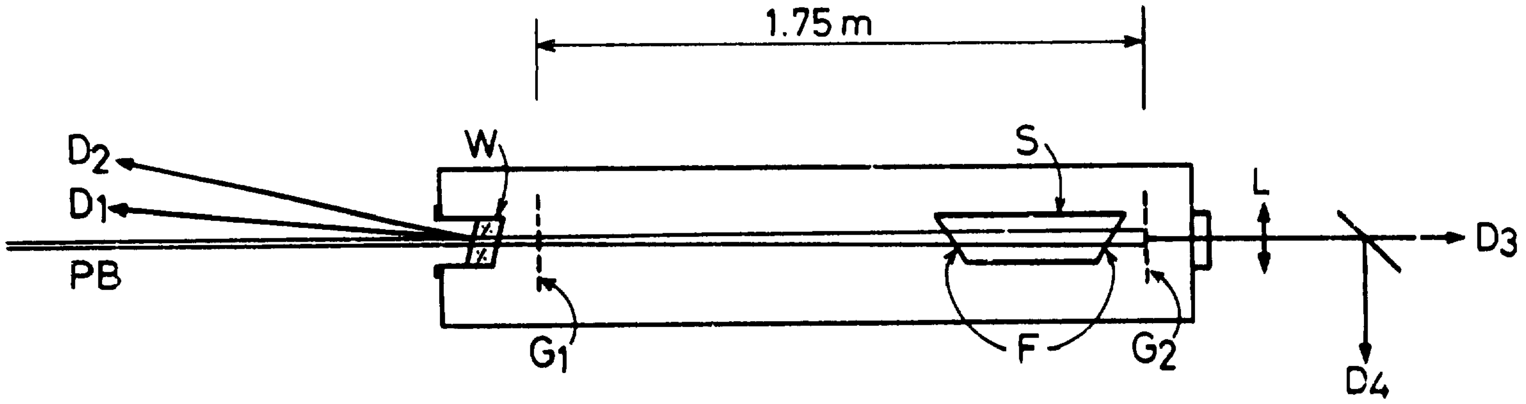
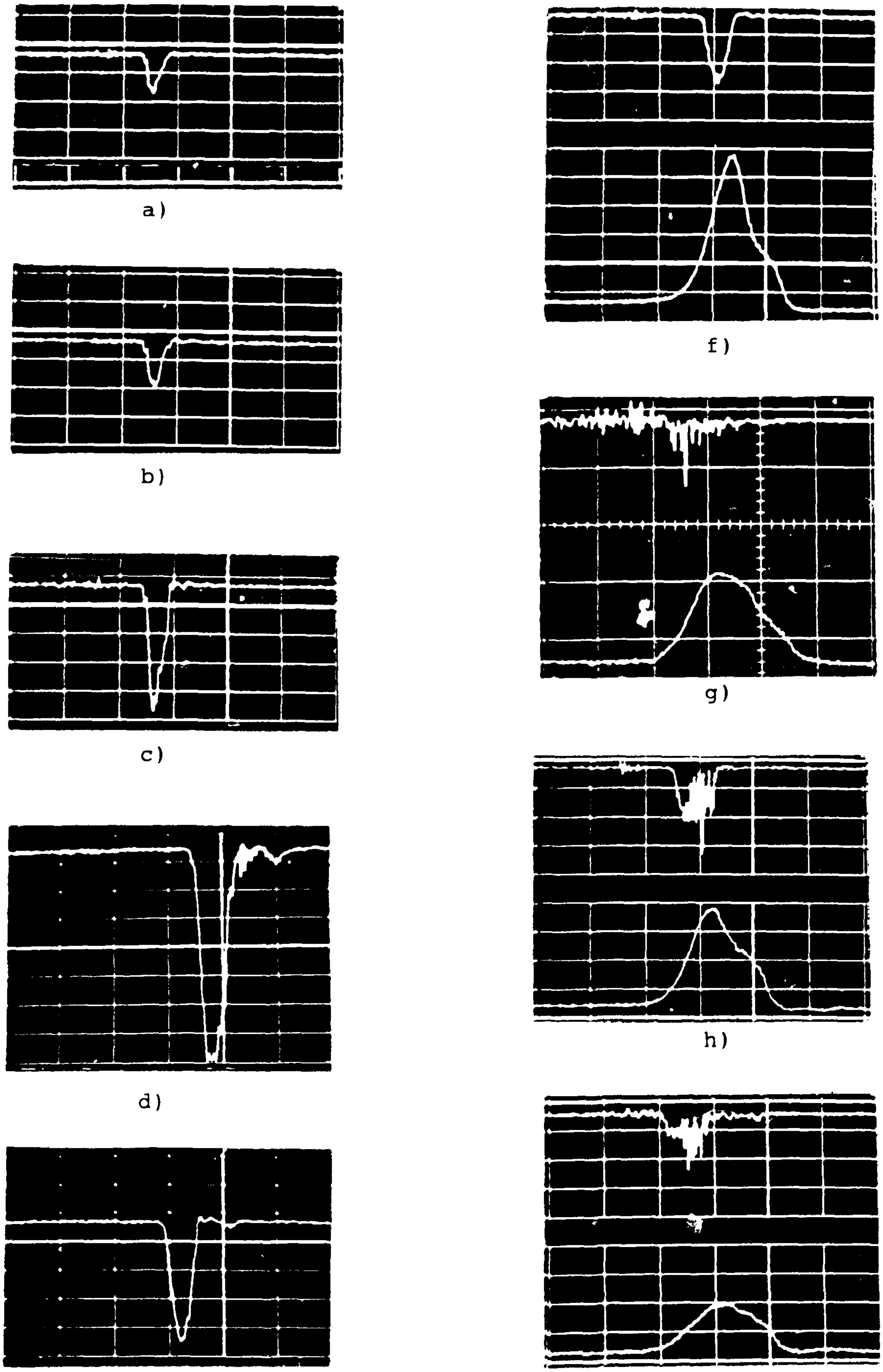


Fig. 1



a)

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Fig. 2

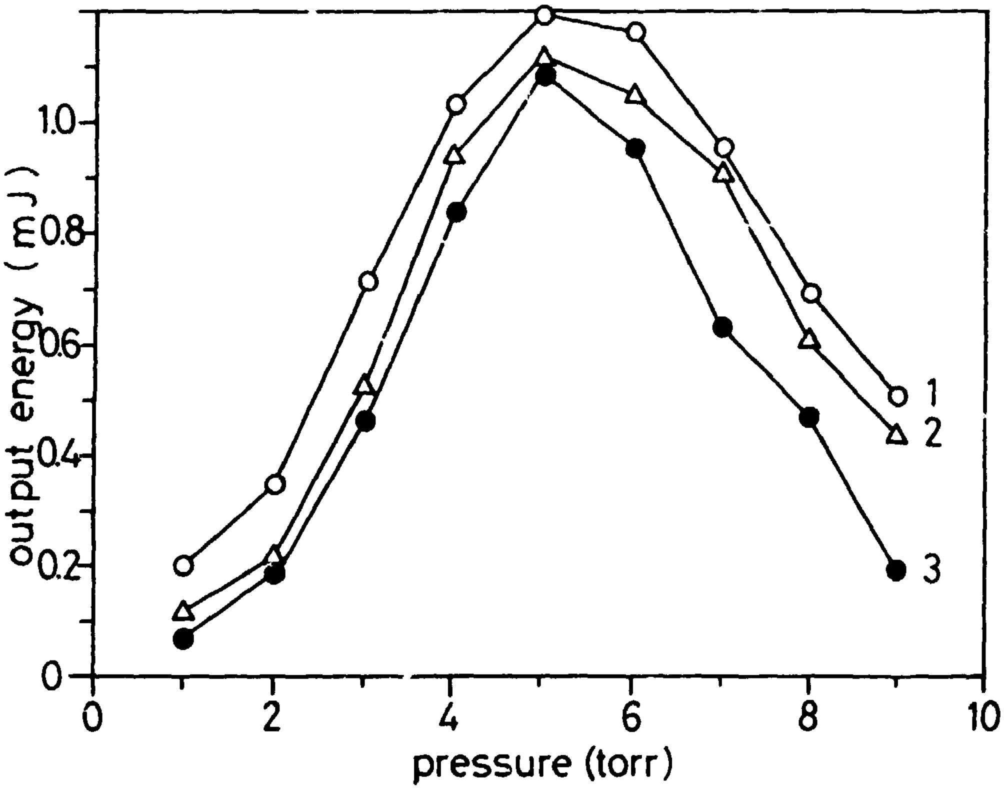
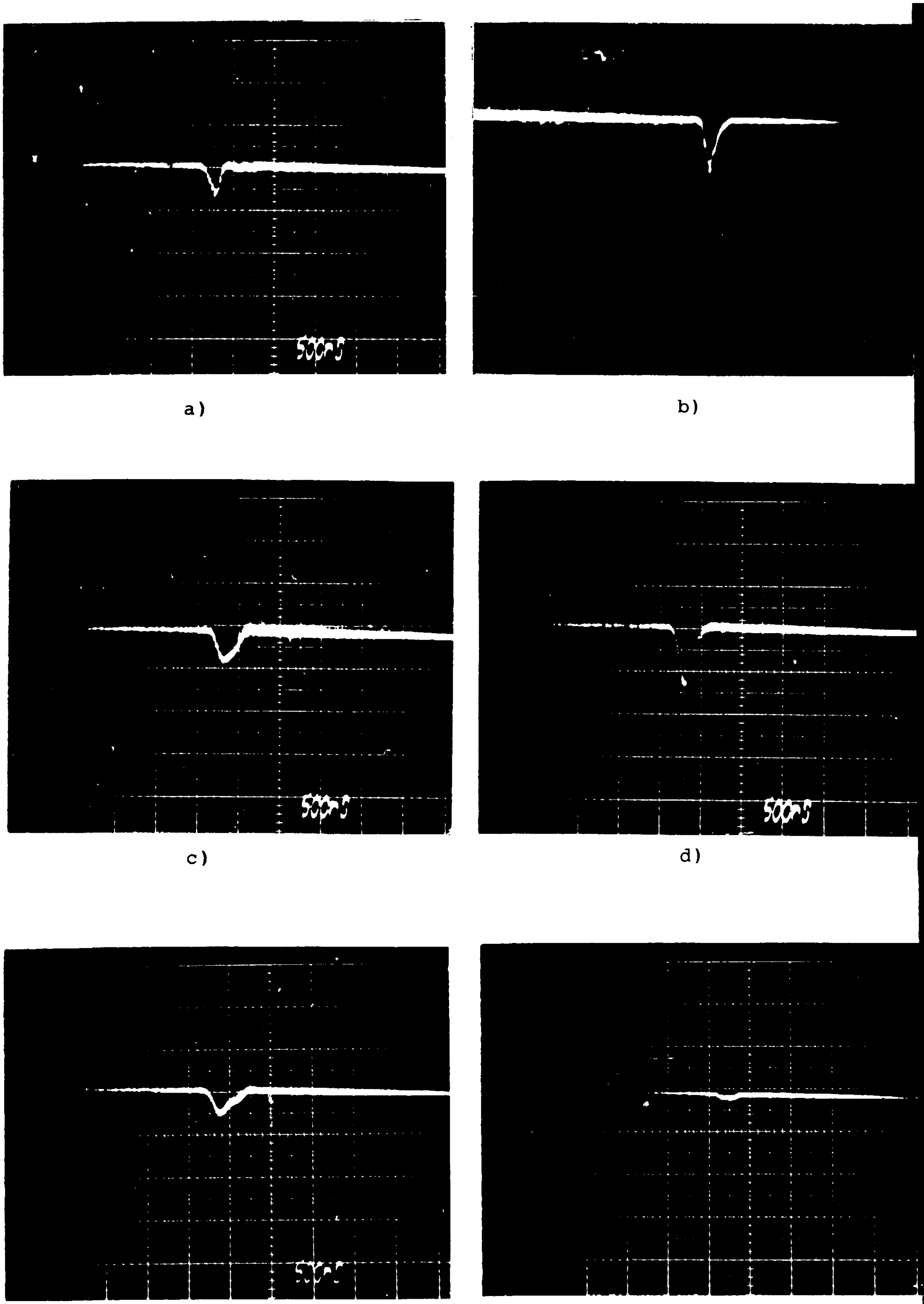


Fig. 3



a)

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Fig. 4

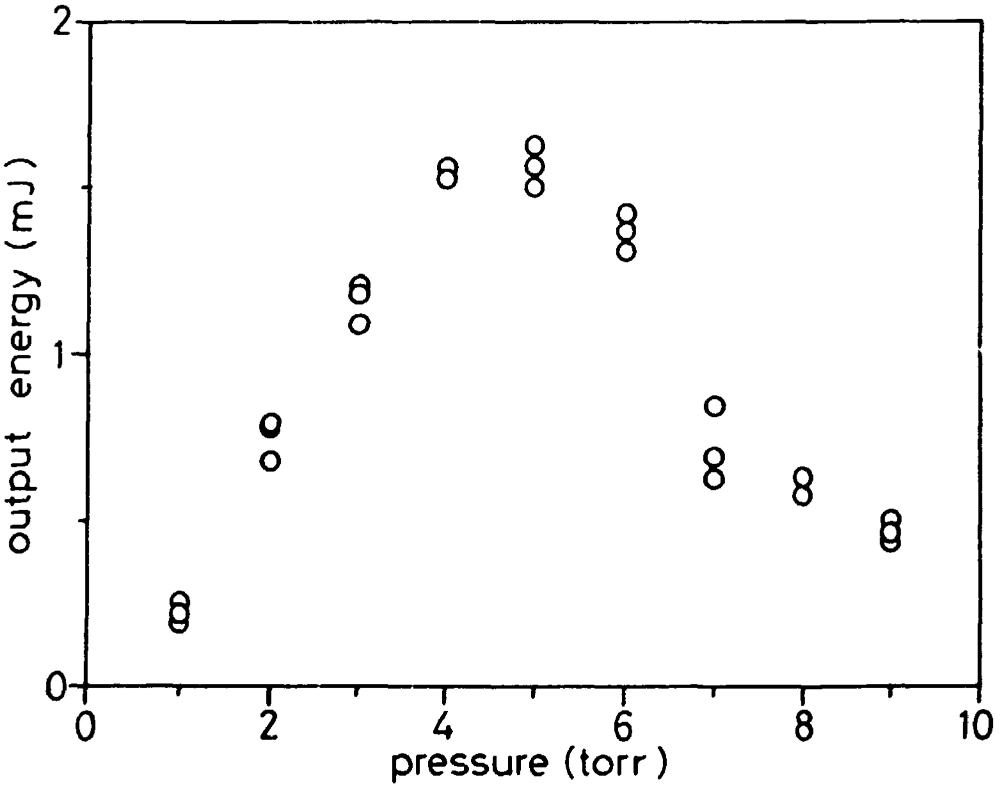

Fig. 5

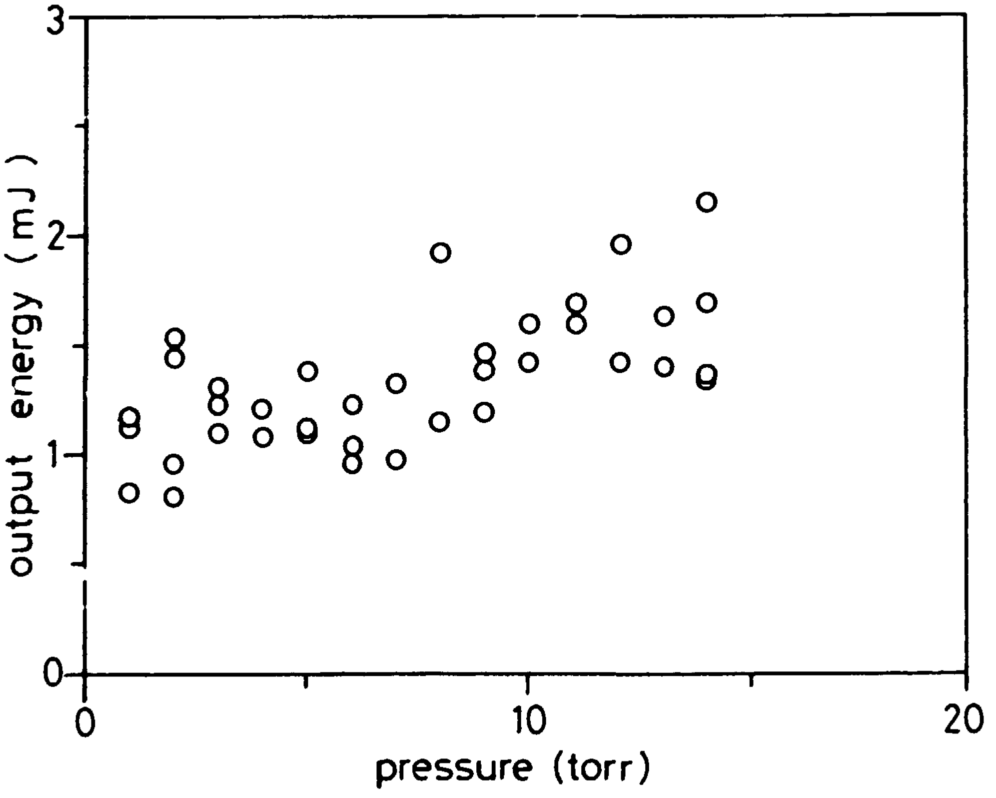

Fig. 6

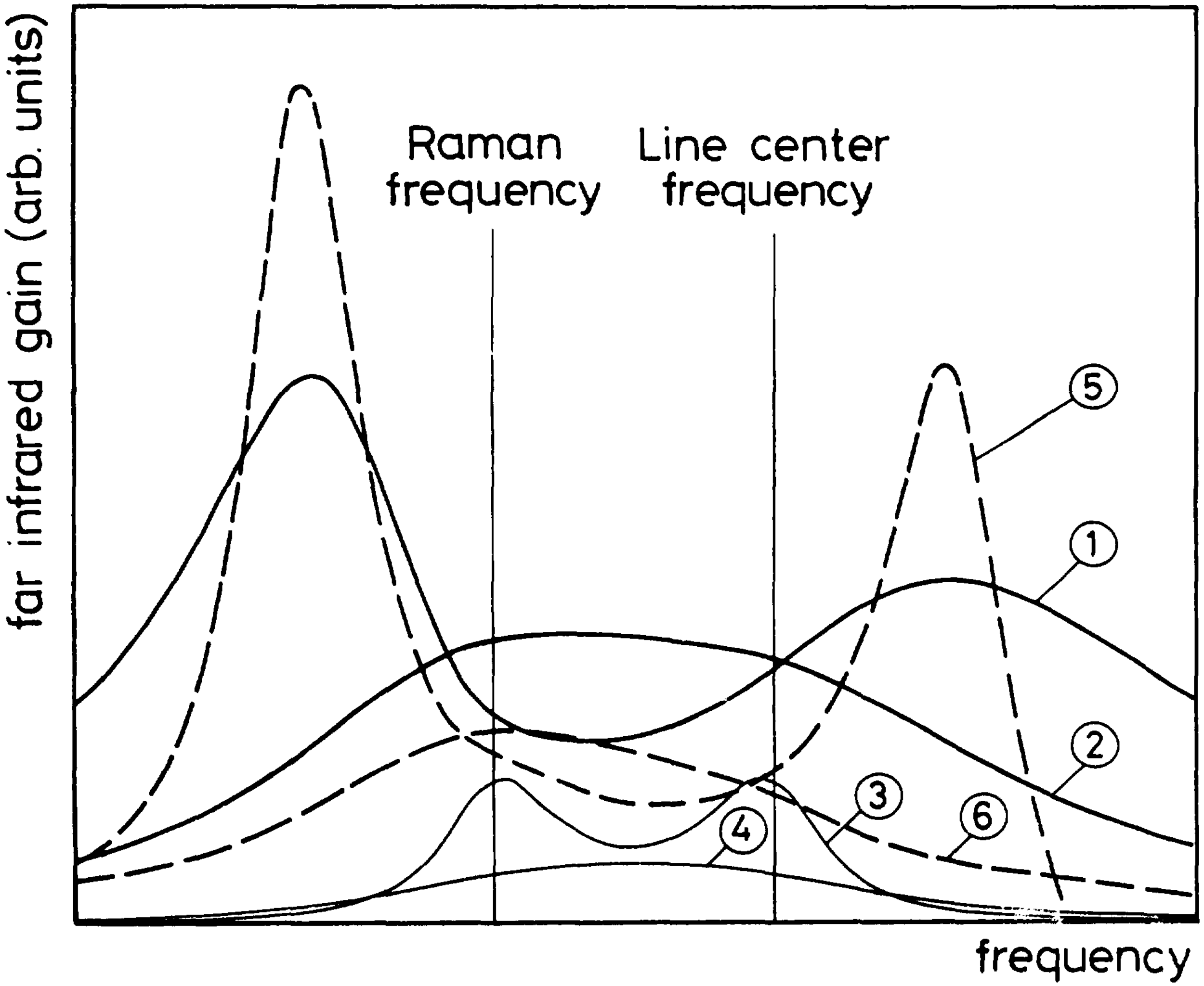
far infrared gain (arb. units)
Raman frequency
Line center frequency
5
1
2
3
6
4
frequency

Fig. 7