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Preprint

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1977

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ABSTRACT

Super-radiant output from D_2O pumped by up to 10 J pulses of the CO_2 P(32), R(12) and R(22) laser transitions gave measured energies of 330 mJ, 240 mJ and 120 mJ respectively. In the R(12) case the emission was at 361 μm and 385 μm in the intensity ratio of 1:2, the average power was 1-2 MW and peak powers of about 5 MW were measured.

(Submitted for publication in Optics Communications)

September 1976

In recent years interest has grown in the development of intense sources of far infra-red (FIR) laser radiation for investigating collective density fluctuations in magnetically confined plasmas having Debye length in the submillimetre range [(1)]. A large number of laser lines with wavelengths between 30 μm and 2 mm have been demonstrated in molecular gases excited by optical pumping with selected spectral components of the output of CO_2 lasers [(2)]. In a previous publication [(3)] we have reported generating over 1 MW of FIR radiation by super-radiant laser action in methyl fluoride (CH_3F). Plant et al [(4)] have observed super-radiant laser action in heavy water vapour (D_2O) at different wavelengths between 50 μm and 385 μm and their results are reviewed in Table I. In this letter we present results obtained in a super-radiant D_2O apparatus pumped by a CO_2 TEA laser at a power level greater than that used by Plant et al. Observations of super-radiant emission in CH_3F pumped by the same laser are presented for comparison.

The pump light was produced in a double discharge CO_2 transversely excited atmospheric pressure 4.5 m long oscillator. Previously [(3)] we used an oscillator-amplifier configuration, but feed back from the KCl window at the entrance to the super-radiant tube caused the CO_2 amplifier to oscillate at 10.6 μm. The optical cavity was formed between an uncoated Ge flat and a 5 cm diameter gold-coated diffraction grating having a dispersion of 0.145 μm per degree. The latter could be rotated to select the CO_2 spectral line required for pumping the different upper laser levels in D_2O. The TEA laser output consisted of a 150 MW gain-switched spike of approximately 60 nsec half-width, followed by a tail lasting about 3 μsec. The total energy in the pulse was about 50 J but only the 10 J spike was instrumental in producing super-radiant laser action. The CO_2 laser beam was approximately circular in cross-section with a diameter of 5.5 cm and its angular divergence was observed to be at most a few mrad. The output appears to be a fundamental mode.

The pump radiation was directed axially into a 4.2 m long 10 cm diameter glass pipe which was filled with the gaseous laser medium at a pressure of a few torr. Pump radiation entered the pipe through a 15 mm thick K Cl flat and FIR radiation emerged at the far end of the pipe through a TPX[5] window whose thickness was 9.6 mm. This window was found to be effectively opaque to 10 μm radiation and practically transparent to radiation at 496 μm and 385 μm. For 94/114 μm and 66 μm radiation, the attenuation length of TPX (x_o in the relation $I = I_o \exp - {}^{x}/x_o$) was measured and found to be 12.4 mm and 8.2 mm respectively. FIR outputs on these wavelengths have been corrected for loss in the output window.

A calorimeter [6] having 1 cm diameter sensitive area was used to measure the energy emitted by the super-radiant apparatus at the various wavelengths excited in D_2O and CH_3F. FIR radiation was found to be emitted over the full 10 cm aperture of the tube and the calorimeter was scanned along horizontal and vertical diameters at the output window, using many laser discharges to construct plots of the spatial distribution of the super-radiant output. An example of such plots made for the 66 μm emission from D_2O at 4.8 torr pressure is shown in Figure 1. The total energy emitted is computed from these plots by a process of summation.

The pump energy delivered to the super-radiant tube could be attenuated by means of sheets of polythene, each of which transmitted about half the energy incident upon it.

For every FIR line, the output energy is found to depend upon gas pressure and pumping energy, and for each value of pump energy there is an optimum pressure for which the laser output is maximum. The FIR energies summarised in Table II were measured at the optimum pressure for each particular line. The manner in which FIR super-radiant output from D_2O depends on pressure at various pumping energies is illustrated for the three CO_2 pump wavelengths in Figure 2. The energy scales on this and subsequent figures must be treated with caution as they may be subject to systematic errors of up to 20%. The effect of correcting for attenuation in the TPX output window is indicated in the cases where this correction is relevant. The same dependence for the 452/496 μm line in CH_3F is shown for comparison. Similar curves, exhibiting a similar shift of peak with pumping energy, measured for CH_3F in the optical cavity configuration, were reported previously [(6)].

Figure 3 shows the conversion efficiency, defined as FIR energy generated per unit pump energy, for the three D_2O lines and the 452/496 μm lines in CH_3F, plotted as functions of joules in the CO_2 pulse peak or alternatively as pumping power per unit area. In each case the measurement was made at the optimum pressure, and correction for attentuation in the TPX window has been applied. Whereas the 94/114 μm and 361/385 μm lines in D_2O increase monotonically with increasing pump energy until they saturate, both the 66 μm line and the 452/496 μm lines in CH_3F increase rapidly to a peak after which they fall towards an equilibrium as pump power is increased. The outcome is that at high pump powers all the D_2O lines have a higher conversion efficiency than the CH_3F line, but at low pump power density, below 0.33 MW cm^{-2} in our experiment, the relative brightness has the ordering D_2O 66 μm, CH_3F 496 μm, D_2O 94/114 μm and finally D_2O 361/385 μm. The latter ordering, which appears to be characteristic of low pump power density, is that reported previously by Plant et al [(4)].

The gradual increase in conversion efficiency with increasing pump power density exhibited by the 94/114 μm and 361/385 μm lines, in contrast to the rapid switch-on of the 66 μm line, suggests that the pump intensity may be influencing the absorption coefficients associated with the two longer wavelength lines. This may be an example of the off resonance optical pumping (OROP) phenomenon described by Fetterman et al (7).

Although the FIR outputs generated by P(32) and R(12) pump transitions are referred to throughout this letter as 66 μm and 94/114 μm respectively, we have not actually measured absolute wavelengths or spectral compositions in these cases. However a detailed investigation of the spectrum of the emission pumped by R(22) was carried out using a copper mesh Fabry Perot interferometer having a finesse of 13 and free spectral range 10 GHz (3).

Two components having wavelengths 385 μm and 361 μm were revealed and the dependence of their intensities on filling pressure is shown in Figure 4(a). The intensities of both lines rise to a maximum at 4 torr and then fall back to zero around 8-9 torr, in such a way as to keep their ratio constant at about 2. This is in marked contrast to the behaviour of the two-component CH_3F line reported previously (3), and remeasured and replotted here as Figure 4(b). In this case the 452 μm component is quenched at a lower pressure than that at 496 μm, leaving the latter as the solitary wavelength emitted at pressures greater than 4-5 torr in this gas.

Time-resolved traces of the output generated by R(22) pumping were recorded with a Si-W point contact diode and a 100 MHz bandwidth oscilloscope. Figure 5 shows one of the oscillograms obtained in this way. The vertical scale was deduced by performing integration under the curve and equating the result to the total energy emitted, measured by calorimeter. An average power of about 1 MW is observed and the random spikes, each a few nanoseconds duration, into which the 60 nanosecond pulse is resolved, reach powers as high as 4.5 MW.

It proved impossible to detect the 94/114 μm and the 66 μm lines with the Si-W point contact diode. However, assuming pulse length is independent of wavelength, average powers of up to 9 MW and 18 MW respectively are deduced from the measured values of total emitted energy, corrected for attenuation in the TPX window (see Figure 2).

All FIR emission was plane-polarised, the plane being perpendicular to that of the pumping radiation in the case of 496 μm and 452 μm in CH_3F and 385 μm and 361 μm in D_2O. The 94/114 μm and 66 μm lines in D_2O were plane-polarised parallel to the plane of the pumping radiation.

It is also worth observing that atmospheric air was approximately transparent to all the wavelengths investigated except 94/114 μm, for which an attenuation length of 7 cm was measured.

In summary, super-radiant emissions from heavy water vapour (D_2O), pumped by the CO_2 P(32), R(12) and R(22) laser transitions in the form of gain-switched $\leqslant$ 10 J pulses from a TEA laser, have been studied. Maximum FIR outputs, measured outside the TPX window of the super-radiant assembly, of 330 mJ at 66 μm, 240 mJ at 94/114 μm and 120 mJ at 361/385 μm were obtained. Corrected for absorption in the 9.6 mm thick TPX window these become 1.06 J at 66 μm and 520 mJ at 94/114 μm while the 361/385 μm output is unchanged. These values refer to peak pumping and optimum gas pressure conditions. Both 94/114 μm and 361/385 μm lines are found to increase comparatively gradually with increasing pump power, in contrast to the 66 μm line which switches to maximum output at very low pumping. This difference in behaviour may be due to a parametric effect (OROP) of the pump on the absorption coefficients for the two lines concerned, and may account for the difference between the relative strengths of D_2O and

CH_3F lines observed by us and by Plant et al [4]. Spectral resolution of the radiation excited by R(22) revealed two components at 361 μm and 385 μm having intensities in the ratio 1:2 over the whole pressure range, 1-8 torr, at which output was obtained. Time resolution of the same transition disclosed a pulse length of about 60 nsec consisting of a sequence of random intensity, few nanosecond duration spikes, some of which have powers up to 4 or 5 MW. Assuming the same pulse length and structure for the 94/114 μm and 66 μm lines implies average powers of 9 MW and 18 MW respectively.

ACKNOWLEDGEMENT

The authors wish to thank Mr David Gordon for assistance with the initial measurements.

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TABLE I

Molecule	CO_2 Pump		FIR (μm in air)	Relative Energy
	9.4 μm Band	Wavelength (μm)		
CH_3F	P(20)	9.55	496	100
D_2O	P(32)	9.66	83	0.3
			66	700
			50.5	0.07
	R(12)	9.32	114	3
			94	10
	R(22)	9.26	385	9

Table I Results of Plant et al[4] obtained for super-radiant laser action in D_2O and CH_3F.

TABLE II

Molecule	CO_2 Pump		Total Peak FIR Energy (mJ)	Relative Energy
	9.4 μm Band	Wavelength (μm)		
CH_3F	P(20)	9.55	33	100
D_2O	P(32)	9.66	330 (1.06 J)	1000 (3200)
	R(12)	9.32	240 (0.52 J)	700 (1500)
	R(22)	9.26	84	250

Table II **FIR energies summarised above were measured at the optimum pressure and the highest pumping level for each line. The numbers in brackets are energies corrected for absorption loss in the TPX window.**

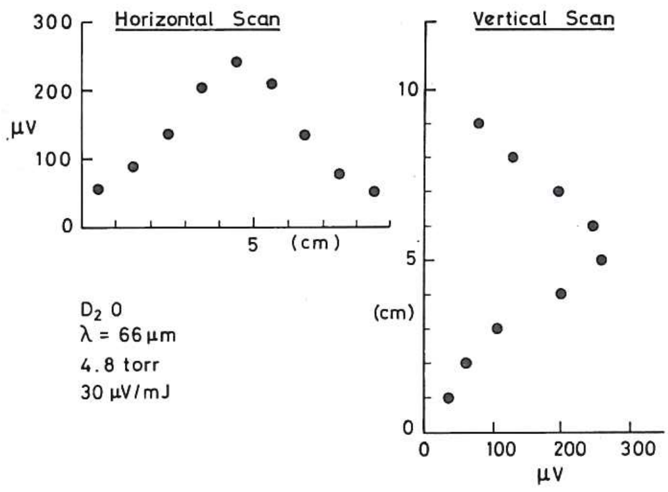

Fig.1 Spatial distribution of FIR output at 66 μm showing profiles measured along horizontal and vertical diameters using 1 cm aperture calorimeter. This data is uncorrected for attenuation in the 9.6 mm TPX window.

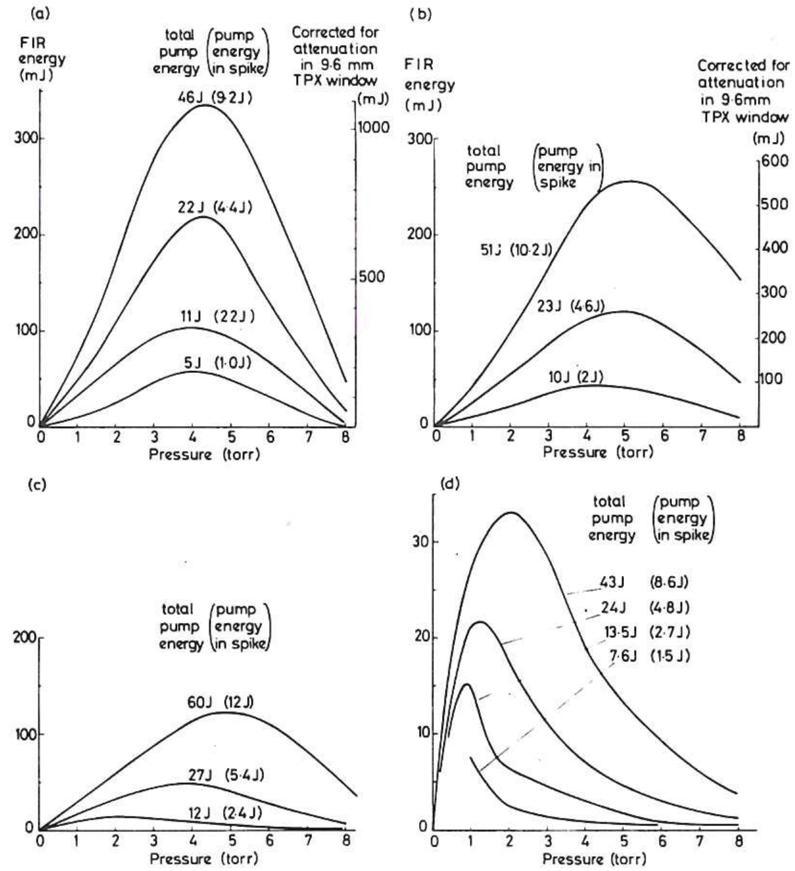

Fig.2 Super-radiant output as a function of laser gas pressure for different values of pumping energy. (a) Emission (at 66 μm) for D_2O when P(32) CO_2 line is the pump. Both emerging energy and energy corrected for loss in TPX window are plotted. (b) Emission (at 94/114 μm) from D_2O when R(12) CO_2 line is pump. Correction for attenuation in TPX is shown. (c) Emission (at 361/385 μm) from D_2O when R(22) CO_2 line is pump. No measurable attenuation in window. (d) Emission (at 452/496 μm) from CH_3F shown for comparison.

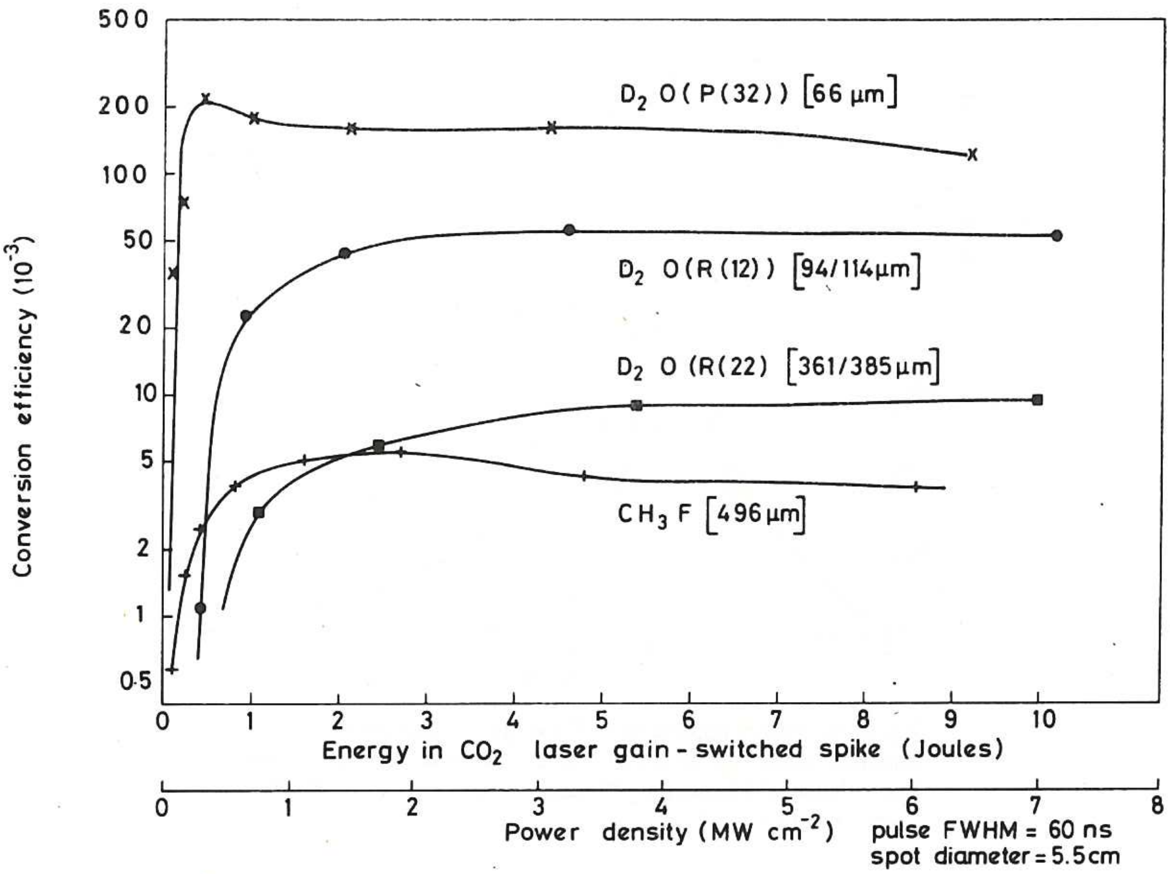

Fig.3 Conversion efficiency = FIR output energy/pump energy. Energy at optimum pressure is taken in each case. Correction for attenuation in TPX window has been applied.

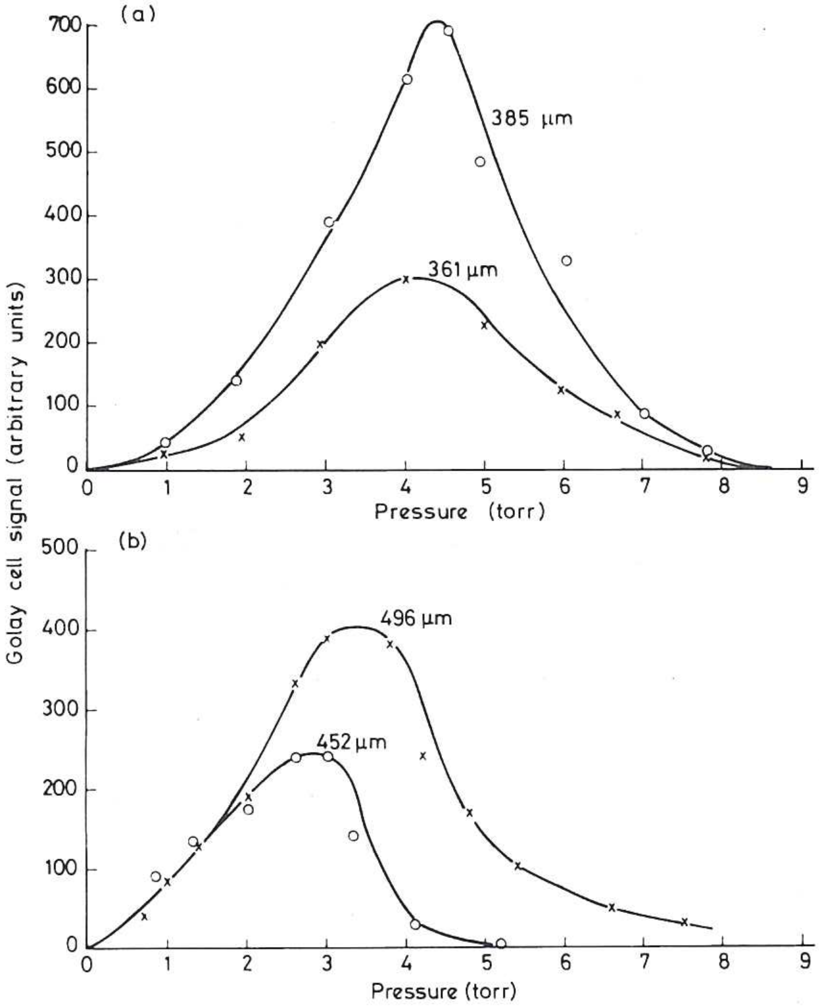

Fig.4 (a) Presure dependence of 361 μm and 385 μm super-radiant emission excited by R(22) CO_2 laser output in D_2O. (b) Pressure dependence of 452 μm and 496 μm emission excited by P(20) CO_2 laser output in CH_3F.

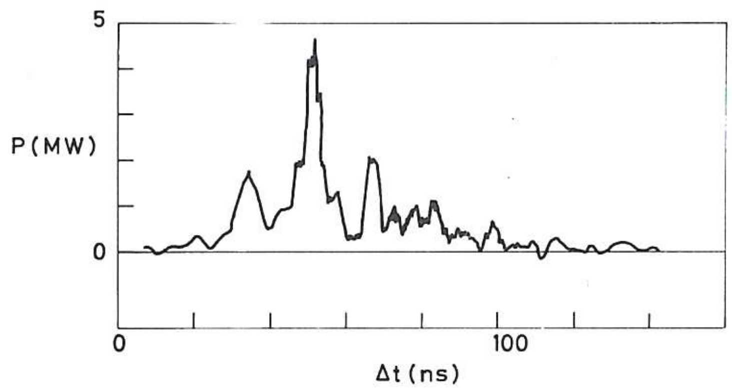

Fig.5 Oscillogram of time-resolved pulse of 361/385 μm super-radiant output, recorded with Si-W point-contact diode.