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High Power Optically Pumped Far Infrared Lasers

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Abstract—Intense superradiant laser action in the far infrared (FIR) has been observed in several gases optically pumped with a CO_2 transversely excited atmospheric-pressure (TEA) laser. A maximum FIR power of 100 kW was observed from CH_3F at 496 μm. Characteristics of the system and possibilities of scaling to higher powers are also discussed.

I. INTRODUCTION

SELECTIVE excitation of a pure rotational lasing transition by optically pumping with another laser was first reported by Chang in 1970 [1]. In this instance a Q-switched CO_2 laser operating on the P(20) 9.6-μm transition was used to pump the $v = 1$, $J = 12$ level of CH_3F giving a 496-μm pure rotational lasing transition to $v = 1$, $J = 11$. Since that time, many similar lasing transitions have been reported in various molecules pumped with CO_2, HF, and N_2O lasers. These optically pumped lasers require optical cavities and produce output pulses typically < 100 W. Recently, intense (~1-kW) superradiant laser action has been reported on the 496-μm pure rotational transition in optically pumped CH_3F [2], [3]. It is the purpose of this paper to present a study of similar intense transitions observed in other molecules and in CH_3F.

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II. EXPERIMENT

In Fig. 1 is shown a diagram of the experiment. The grating-tuned transversely excited atmospheric-pressure (TEA) CO_2 laser was of the parallel electrode preionization type and was capable of producing megawatt (MW) pulses throughout the 9.6- and 10.6-μm bands. Provision was also made for suppressing the normal self-mode-locked characteristic of CO_2 and forcing the laser to oscillate on a single longitudinal mode near line center [4]. The far infrared (FIR) cell was 40-mm-ID pyrex tubing,

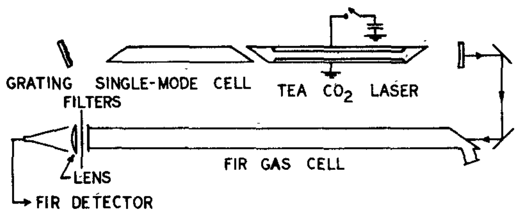

Fig. 1. Diagram of superradiant FIR laser system.

varied from 1 to 10 m in length, and contained a NaCl Brewster entrance window for low transmission loss. The FIR signal passed through a 1-mm-thick high-density polyethylene exit window and was focused with a polyethylene lens into various detectors. The energy content of the pulse was measured with a Golay cell having a diamond entrance window while the temporal behavior of the pulse was examined with an InSb 4.2-K detector or a point-contact metal–oxide–metal (MOM) diode [5]–[7]. Various calibrated attenuators were used to prevent damage or saturation of the detectors. Typical optimum gas pressures were the order of 1 torr.

The FIR lasing wavelengths were measured using a 0.5-m-grating monochrometer and the Golay cell detector. Dry air was passed through the monochrometer and the external FIR path to prevent water vapor absorption of any FIR output. A 1-mm polyethylene window was also mounted near the entrance window of the FIR cell so that any backward wave would be reflected from the NaCl window to a detector.

III. RESULTS

In Table I are listed the observed superradiant transitions found to date using a 5.3-m cell [8]–[10]. Also indicated is the CO_2 pump line and relative FIR energy of each transition. The observed transitions thus span the spectral range from 50 to 500 μm. Evidence of a weak cascade transition was observed in D_2O but was absent in the other molecules.

In addition to the gases listed in Table I, other optically pumped gases including methanol, formic acid, methyl amine, and dimethyl ether were tried in the system but exhibited no superradiant laser emissions. Possible reasons for the lack of lasing in these molecules are that the IR transition may be a hot band absorption and that the FIR may be getting reabsorbed by other nearby transitions.

The FIR beam profile from the 5.3-m cell consisted of a narrow peak of ~3-mrad half-angle superimposed on a broad base of ~20-mrad half-angle. The presence of two beamwidths suggests that the FIR output consists of one pulse propagating as a quasi-guided mode and a second pulse of approximately equal energy propagating along a linear path and geometrically limited by the cell solid angle [2].

In Fig. 2 is shown the maximum FIR output versus cell length obtained by optimizing the pressure for CH_3F and NH_3. The error bars in the figure are shown to indicate the extremes in the detected signal which exhibited pulse-to-pulse fluctuations. The other molecules measured exhibited a similar behavior. It is evident from these data that the FIR output is a highly nonlinear function of cell length and gas pressure. The FIR output for NH_3 apparently saturates at a cell length of ~5 m.

TABLE I
OBSERVED FIR SUPERRADIANT TRANSITIONS

Molecule	CO_2 Pump 9.6µm	10.6µm	FIR (µm in air)	Relative Energy
CH_3F	P(20)		496	100
NH_3		R(6)	291	2
		P(32)	151	10
			290	20
D_2O	P(32)		83	.3
			66	700
			50.5	.07
	R(12)		114	3
			94	10
	R(22)		385	9
CH_3CN		P(20)	373	2
CH_3Cl	P(42)		333	.02
CH_3Br		R(14)	-	.01

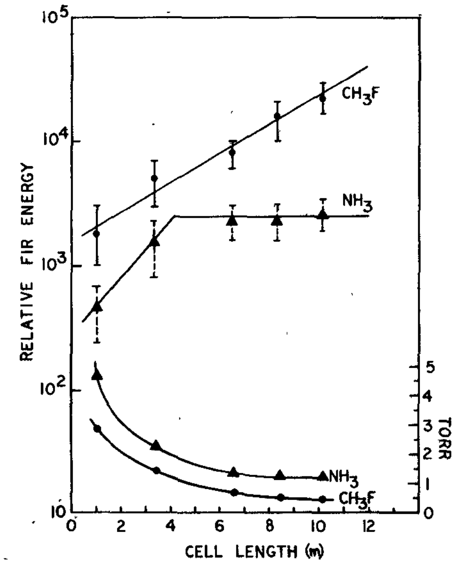

Fig. 2. Relative FIR pulse energy from the Golay detector versus cell length at the optimum cell pressure.

In Fig. 3 are shown typical CO_2 and FIR output pulses for both mode-locked and single mode CO_2 pulses. The CO_2 laser self-mode-locked output consisted of a 150-ns envelope of ~4-ns pulses spaced ~13 ns apart. When the mode locking was suppressed, the CO_2 output was a smooth pulse of ~150 ns full width at half maximum (FWHM). For the P(20) 9.6-μm pump line the CO_2 pulse output energy was 300 mJ for each case.

When the CO_2 laser was allowed to self-mode-lock, the FIR output appeared to follow the mode-locked pulse envelope producing individual FIR pulses $\leq$ 1-ns half-width limited by the response time of the detector–oscilloscope combination. For this situation the peak FIR power of the 496-μm CH_3F signal from the 10-m cell exceeded 100 kW with a pulse energy ~ 0.6 mJ which corresponds

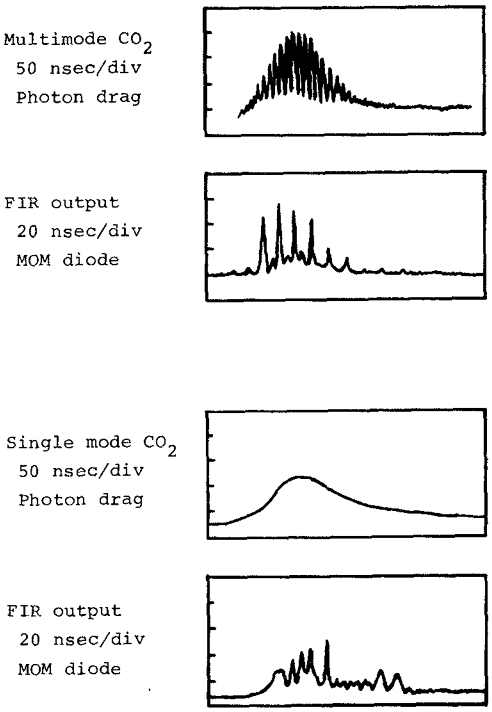

Fig. 3. Transient behavior of the superradiant FIR output. Conditions: 5.3-m cell, CH_3F with P(20) 9.6-μm CO_2 pump, $\sim$1 torr of CH_3F.

to a photon conversion efficiency of $\sim$10 percent. The FIR signal generated in the backward direction was found to be a factor of 10^4 less than the forward wave. Similar behavior was observed for D_2O and NH_3.

When the CO_2 laser was forced into single mode operation, the FIR output was found to be composed of many randomly spaced pulses each $\sim$4 ns wide. Depending on the exact experimental conditions, the resulting FIR envelope varied from 30 to $\sim$130 ns FWHM. For CH_3F the single mode pulse energy was a factor of 10 less than for the mode-locked CO_2 case. Using the 150-ns envelope, this gives a peak FIR power of 0.5 kW.

At low pressures ($\sim$ mtorr) the FIR output was found to be delayed by up to 2.5 μs from the CO_2 pulse. The delay onset was at pressures of $\sim$200 mtorr for CH_3F in the 5.3-m cell. Similar delay behavior has recently been observed in optically pumped HF and attributed to Dicke superradiance [11].

IV. CONCLUSIONS

With a CO_2 input density of $\sim$300 mJ/cm^2 we obtained over 100 kW of FIR output from a 10-m cell. With current state-of-the-art CO_2 lasers and amplifiers, a 100-J CO_2 pump pulse is not inconceivable. Maintaining the same input power density and a 10-m cell length would require a cell diameter of 20 cm. Assuming linear volumetric scaling, such a cell should produce over 3 MW at 496 μm.

An alternative to the superradiant laser as an intense FIR source is to use this highly inverted gain medium as an amplifier for a CW FIR laser. This would have the advantage of very low loss because of the excellent laser mode properties and more important should allow the system to operate at the highest efficiency. It is estimated that a modest 1-mW/cm^2 driver will be sufficient to saturate and convert one half the quantum efficiency of CO_2 pump into FIR. For CH_3F at 496 μm, 1 percent of the pump will appear as FIR which represents a factor-of-five improvement over the normal superradiant mode of operation.

The simplicity of the experimental apparatus and the fact that no FIR cavity is needed make this one of the most convenient and intense sources of FIR currently available. Such an intense FIR source should be very useful for plasma diagnostics, and the possibility of MW pulses represents a significant milestone in the production of submillimeter waves.

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