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MIRADCOM PROGRAM IN SWEPT-GAIN SUPERRADIANCE,(U)
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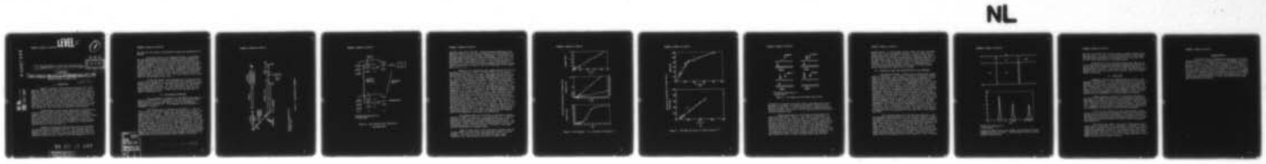

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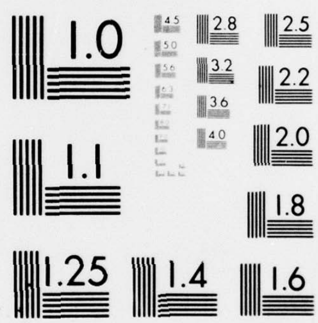

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MIRADCOM PROGRAM IN SWEPT-GAIN SUPERRADIANCE (U)

JUN 1978

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13p.

I. INTRODUCTION

Recently, Bonifacio, Hopf, Meystre and Scully (1), using amplifier theory, predicted that under certain conditions, a noise amplifier, pumped by an impulse excitation traveling at the speed of light in the active material, can produce highly nonlinear spacially asymptotic coherent pulses of electromagnetic energy of anomalous intensity and of anomalously short temporal width. The pulse intensities were predicted to increase as the square of the density of the active material, whereas the temporal width should decrease as the inverse of the density. Also, the pulses are characterized by a temporal delay from the pump cutoff to the peak of the pulse evolution. This process has come to be known as swept-gain superradiance.

Electromagnetic energy having these general characteristics would be useful in application to LADAR systems for propagation, ranging, discrimination and coherent imaging. Other applications would include coupling to plasmas for efficient energy delivery needed for laser induced fusion and for plasma diagnostics. Since the pulses are produced in the amplifier configuration without mirrors, this presents an attractive scheme for production of unidirectional coherent VUV and X-ray radiation.

Because of the strong potential application to Department of the Army missions, MIRADCOM scientists first improved upon the theoretical model of Bonifacio et al. (1) using coherent pumping on molecular species for realistic conditions dealing explicitly with pump pulse characteristics, temporal width and propagation (2). This was done for the purpose of experimental design and interpretation of results.

Using the results of our theoretical model, an experiment was then designed and performed at MIRADCOM using CO_2 pumped CH_3F. In this effort MIRADCOM scientists collaborated with University of Illinois scientists to build the apparatus and to perform the experiments at MIRADCOM. The initial results of this work were reported at an international meeting and will appear in the publication of the Proceedings (3). An updated theoretical development and experimental results was also delivered by one of the authors as an invited paper at the 8th Annual Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, January 15-17, 1978. The final version of our recent work will be published shortly (2,4).

In the next section, the experiment will be described and the principal results given. Section three will be devoted to a discussion of the essentials of the theoretical model and interpretation of the experimental results. The last section will be used to present conclusions drawn from our initial work and to point out the future direction of effort. Further details of the experiment are given in references (3,4).

II. THE MIRADCOM EXPERIMENT

The experimental arrangement for the MIRADCOM experiment is based upon results of our theoretical model and the earlier experimental studies of Dicke superradiance in CH_3F by Rosenberger, Petuchowski and DeTemple (5). The schematic for the experiment is presented in Figure 1.

The TEA CO_2 laser is operated on the P(20) (λ = 9.55 μm) line to give a single longitudinal and transverse mode by using a low pressure CW CO_2 gain cell. Smooth 200 nsec pulses are produced of about 150 mJ total energy. These pulses are subsequently chopped using an optical breakdown switch which utilizes UV-triggered AC breakdown of clean N_2. The resulting CO_2 pulse is about 65 nsec duration and is cut off on its trailing side in less than 0.1 nsec. This pulse is passed through a CH_3F cell, 6 m in length along the cell axis. The area of the IR beam is approximately 2 cm^2. The resulting FIR pulses at 496 μm were monitored in both the forward and backward directions by a low temperature phosphorous doped silicon detector which operated near 2^oK. At the output end of the CH_3F cell the IR pump pulse which emerges and the FIR pulse generated were monitored simultaneously by using a beam splitter which reflects nearly 100% of the IR and

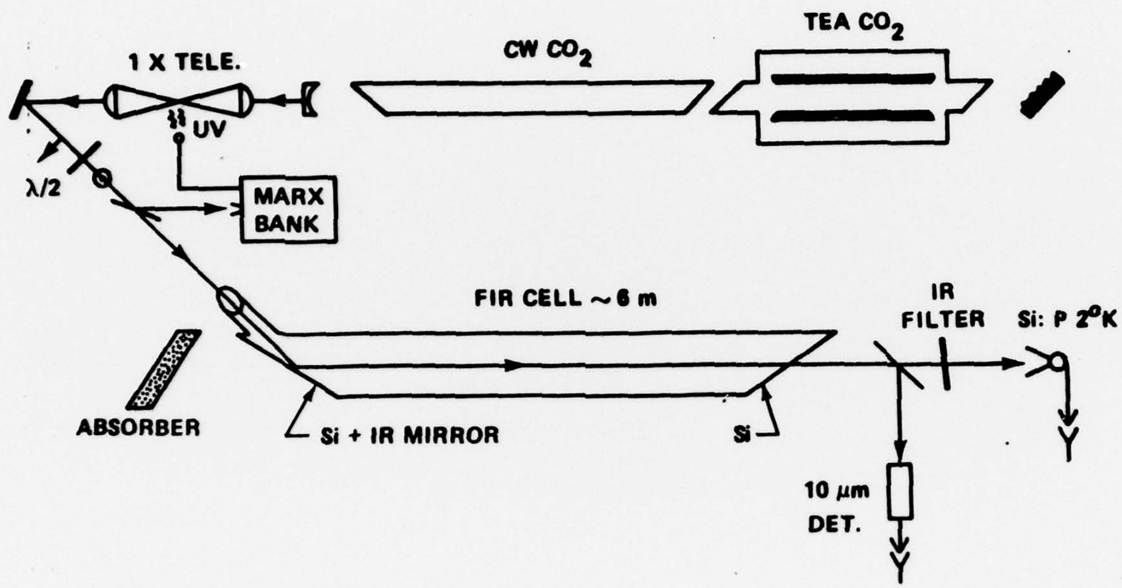

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Figure 1. Experimental Arrangement

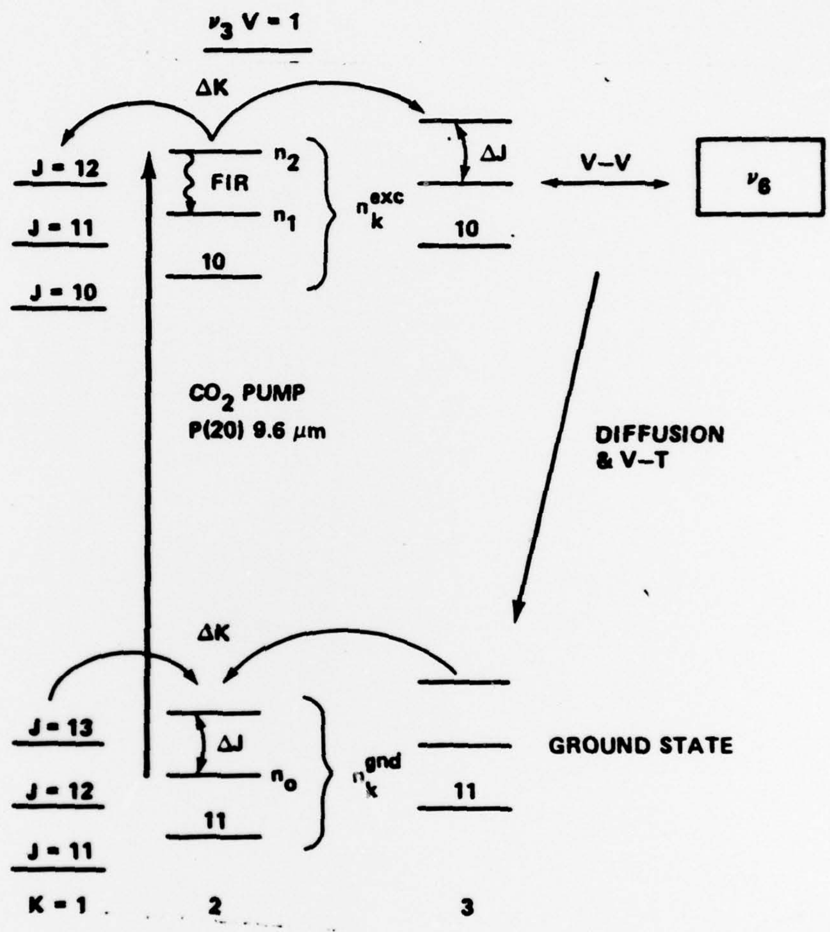

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Figure 2. CH_3F Energy Levels Relevant to the Experiment

transmits about 50% of the FIR. These pulses were displayed in the same time frame on an oscilloscope, whereby the relative temporal positions of the two pulses were easily determined. Further details of the experimental apparatus are given in references (3) and (5). The relevant energy level diagram for CH_3F for the transition involved in the experiment is presented in Figure 2. Since it was possible to couple to two k-level transitions (approximately 45 MHz apart) by tuning the pump cavity, we tuned to the one corresponding to the highest gain, i.e., k = 2.

Results of this experiment were reported earlier (3) and are presented in Figures 3, 4 and 5. In Figure 3(a), the FIR forward pulse intensity at 496 μm is plotted vs the square of the pressure in the CH_3F cell and confirms the linear dependence predicted from theory. In this figure and all subsequent representations of the data, each data point represents the average of three scope traces taken in succession. In this pressure range ($P < 0.2$ Torr), the forward and backward FIR wave intensities are equal. Shown in Figure 3(b) is the FIR forward intensity vs the square of the pressure for the data of Figure 3(a) on a different scale, and including measurements at higher pressure ($P > 0.2$ Torr). The break in the pressure dependency of the intensity occurs at approximately 0.2 Torr. Also represented in Figure 3(b) is the ratio of forward to backward wave intensity (dashed curve and right-hand scale) obtained from the curve of Figure 3(c) through the data points. It is seen from Figure 3(b) that the forward wave intensity becomes greater than that of the backward wave for pressures greater than 0.2 Torr, the point at which the break occurs in the slope of the forward intensity vs P^2 curve. Thus, for $P > 0.2$ Torr the emitted pulses are generated by swept-gain superradiance (1), whereas for lower pressure, $P < 0.2$ Torr (where the forward to backward wave intensity ratios are equal), the pulses are generated by Dicke superradiance (6). The latter has been studied and reported earlier by Rosenberger, Petuchowski and DeTemple (5).

The temporal width of the pulses as a function of inverse pressure is shown in Figure 4(a). The break occurs at $P \approx 0.09$ Torr, which marks the transition from inhomogeneously broadened (lower pressure) to homogeneously broadened (higher pressure) regimes. The pulse width is seen to decrease with increasing pressure and it actually becomes smaller than the absorption line width in the higher pressure homogeneously broadened regime.

Shown in Figure 4(b) is the pulse delay, measured from the IR pump cutoff to the FIR pulse peak intensity, plotted vs inverse pressure. The FIR pulse is well separated from the IR pump (temporally) at lower pressures and narrows in width, grows

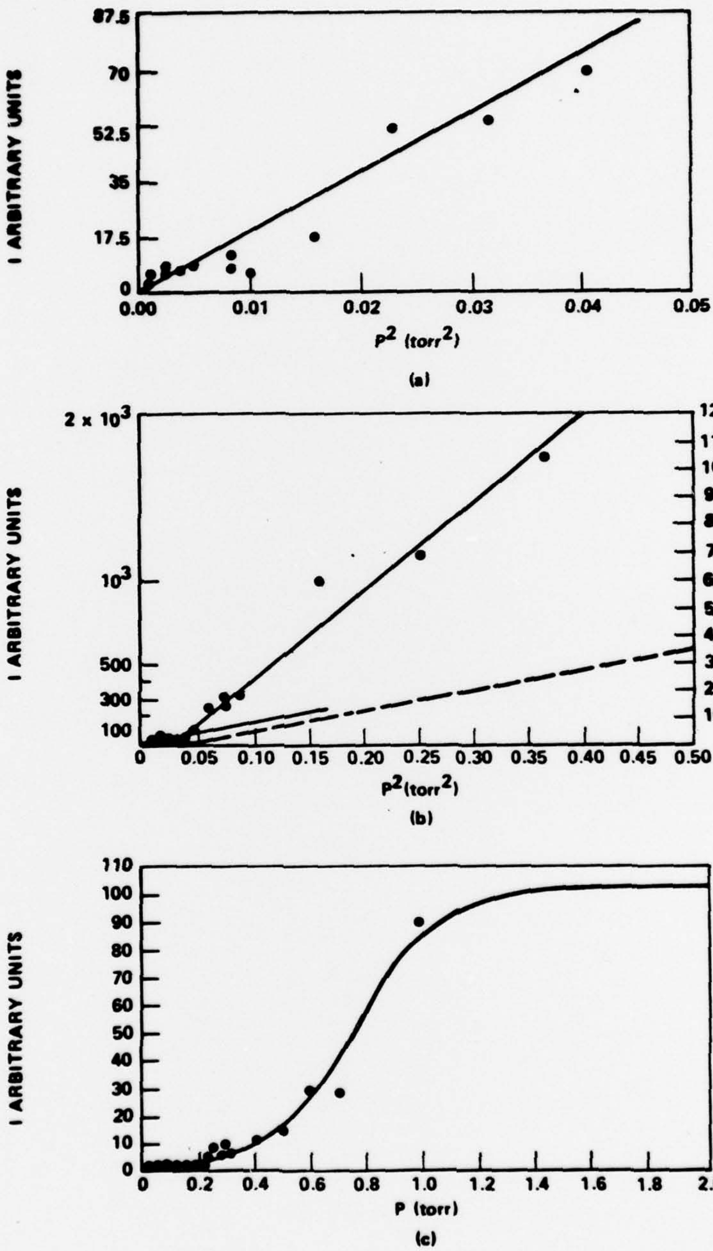

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Figure 3. FIR Intensity I as a Function of Pressure P .

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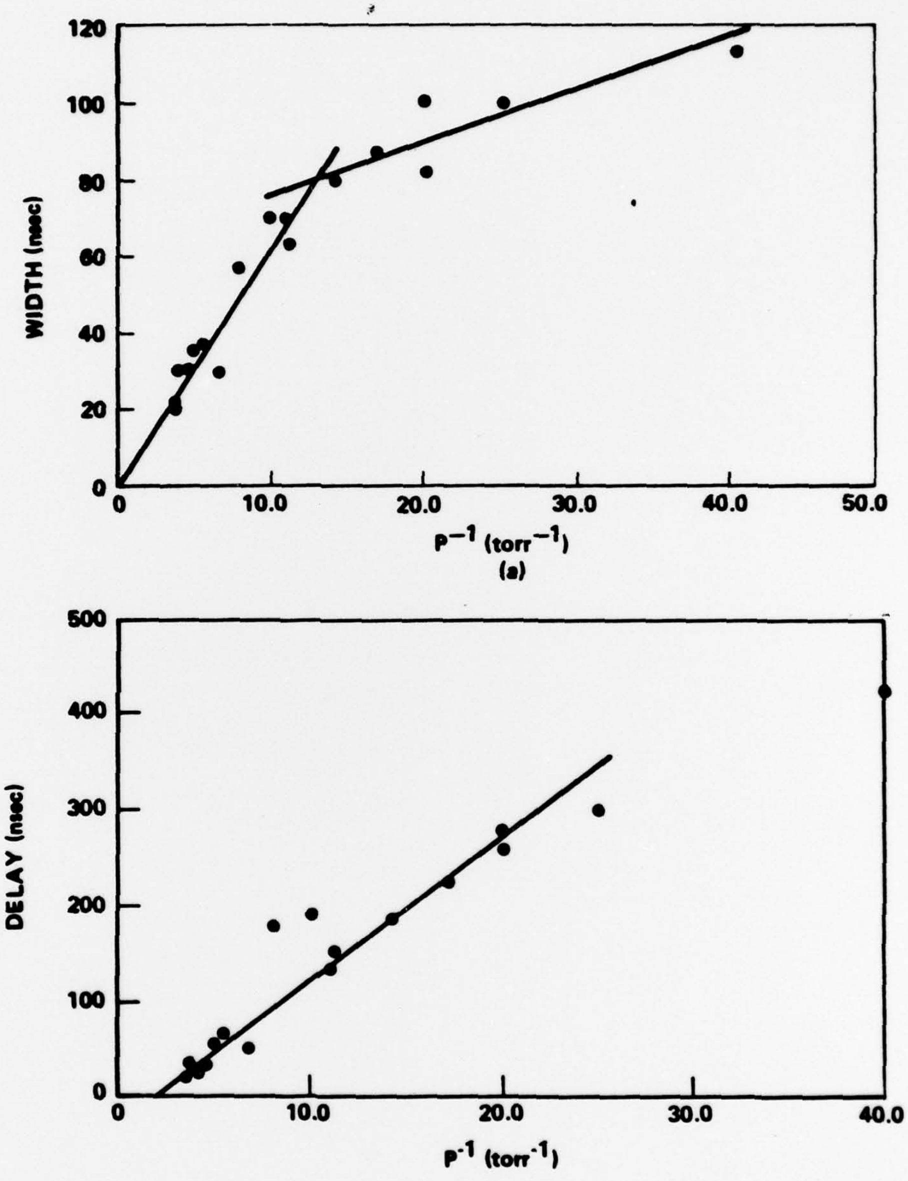

Figure 4. FIR Width and Delay vs Inverse Pressure P^{-1} .

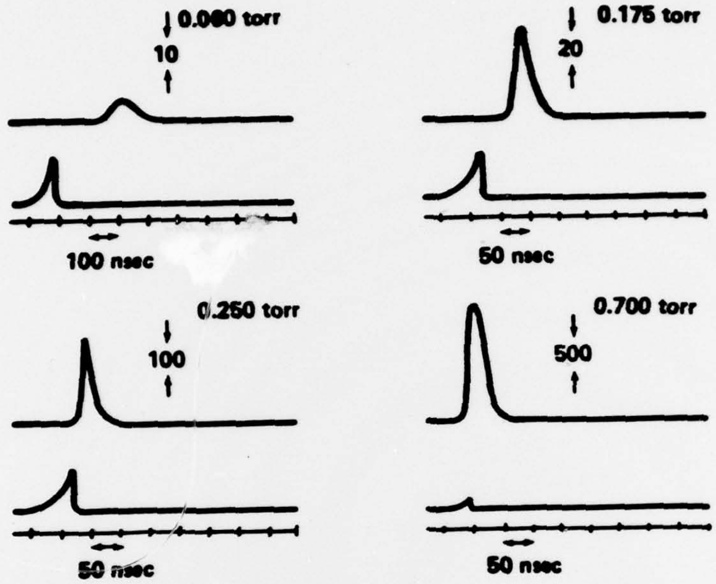

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Figure 5. FIR (Upper) and IR (Lower) Scope Traces

nonlinearly in intensity and moves closer to the pump pulse as the pressure is increased. The negative intercept is due to the fact that the IR pump pulse is not an impulse but is a coherent pulse of non-zero duration, giving rise to an FIR pulse evolution which begins inside the pumping pulse.

Actual scope traces of the IR pump and superradiant FIR pulses are presented in Figure 5. The pulses are presented in the same time frame for four different CH_3F cell pressures. The upper pulse is the FIR at 496 μm and the lower one is the IR pump pulse at 9.6 μm as received by the respective detectors at the forward end of the CH_3F pressure cell (as shown in Figure 1) and subsequently displayed simultaneously on the oscilloscope in the same time frame. The pulses are both traveling to the left in the figure and the vertical scale for the IR pump (lower trace) is the same throughout. The FIR superradiant pulse is seen to become narrower and nonlinearly more intense and move in toward the pump pulse as the pressure becomes greater. At the highest pressure shown, the lower right-hand traces, the FIR and IR temporally overlap. In this regime, the FIR superradiant pulse continues to increase in intensity as the square of the pressure even though the pump energy is markedly depleted. For the case shown, there is less than 10% of the pump pulse energy remaining. The FIR pulse intensity continues to grow nonlinearly until virtually all of the pump energy is gone. It is apparent that in this case the maximum conversion of IR energy to FIR pulse energy occurs consistent with conservation of energy.

III. THEORETICAL MODEL AND INTERPRETATION OF THE EXPERIMENT

The theoretical model is based upon the energy level diagram shown in Figure 6(a). The IR pump is treated as an external coherent source of prescribed shape and temporal duration, propagating at the speed of light in the medium and transfering population from the ground state to the excited state. The subsequent transition of population from the excited state to the intermediate level gives rise to the FIR radiation which evolves. The FIR radiation field is treated quantum mechanically to incorporate spontaneous as well as stimulated decay. Although the intermediate and ground states are not radiatively coupled, because of rotational selection rules in the molecule, (resonant) stimulated Raman transitions transfer population between them and have important manifestations in the results in terms of the time evolution of the gain. It should be noted that these results for coherent pumping pertain to general laser theory as well and have not (to our knowledge), been treated in the open literature. The model incorporates the aspects of multimode dependence for the FIR pulse evolution as well as propagational dependence of both the pump IR and FIR pulses. Due to limitations in space, only one aspect of the results of the model will be presented here. The model and the detailed comparison with the experiment are discussed fully in the references (2,9).

The calculated behavior of the FIR pulse evolution in the high pressure regime when pump pulse and FIR pulse temporally overlap is presented in Figure 6(b) for a set of realistic system parameters. The pump is turned on at $\tau = 0$ (coordinate system moving with leading edge of the pump) and remains on at constant amplitude throughout the plot. What is shown is the evolution of the FIR pulse from $\tau = 0$, where the vertical axis is the FIR intensity in units of IR pump intensity. This predicts that if the pump pulse is sufficiently long, a set of sharp, intense pulses will be generated in the FIR which are phase correlated from one pulse to the next. The damping in amplitude is due to the dephasing time of the transition. This also shows

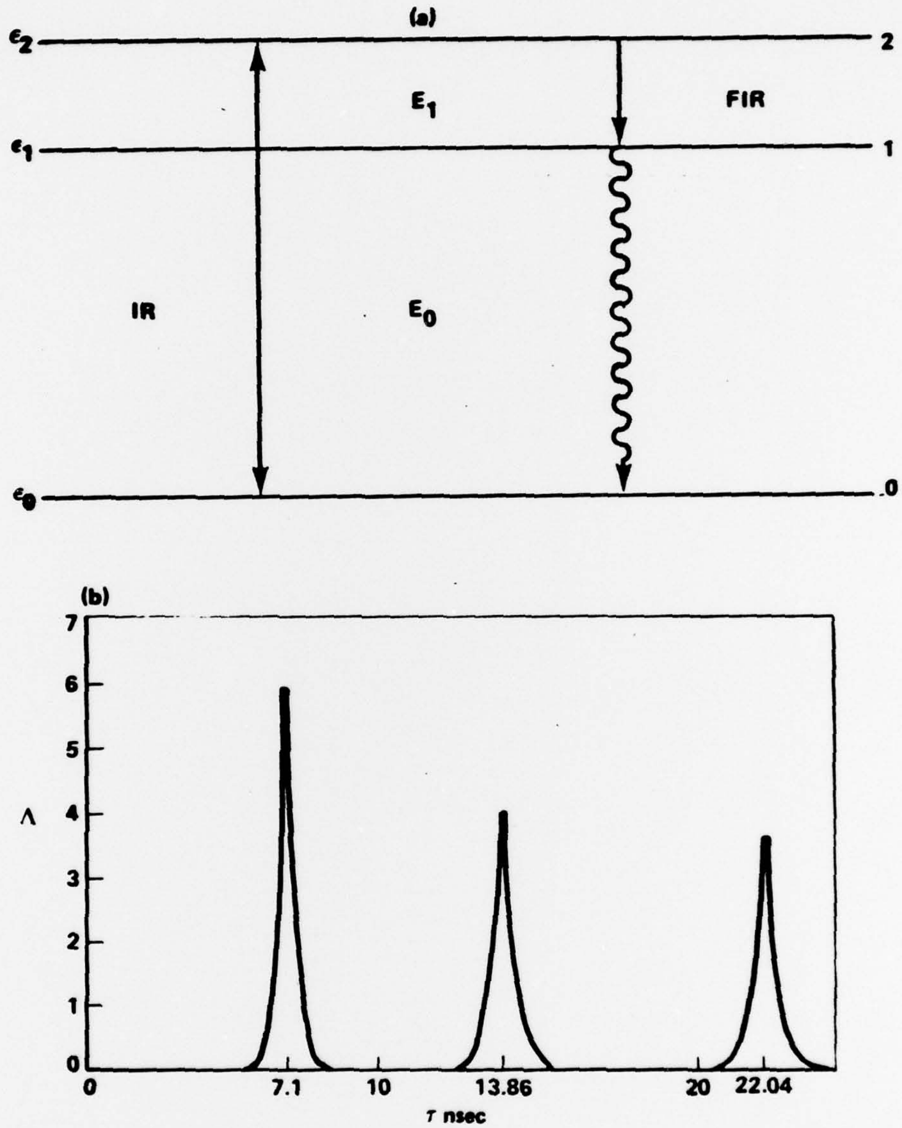

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Figure 6(a) Model Energy Level Scheme; (b) Calculated FIR Pulse Sequence Evolution vs Time τ from IR Pump Turn-on for a Step Function Pump Envelope.

that one can achieve short (2 nsec) pulses of greater intensity than the pump pulse. This does not violate conservation of total energy since the pulses generated in this manner are "off" more than they are "on" during the duration of the pumping pulse.

Pulse chains of this type have actually been observed (3) in our experiments when we have temporally extended the pump by turning off the N_2 gas breakdown switch (which chops the pump pulse in the experiment, Figure 1). Pulse chains of this type should be quite useful in many field applications where coherent, short and intense pulses are desired.

IV. CONCLUSIONS

MIRADCOM scientists have demonstrated for the first time swept-gain superradiance. It was shown experimentally that pulses of anomalous intensity and short temporal widths could be produced and the width and intensities controlled by varying the pressure in the cell. Furthermore, it was predicted by theory and experimentally observed (3) that sets or chains of phase coherent pulses of the superradiant type can be generated by coherent pumping. Pulses of this type have obvious Department of the Army mission applications.

Further research is planned for continuing development of the theory (for deeper understanding of the phenomenon) and further experiments are planned to confirm predictions and to determine practical limitations on power density, pulse compression and pulse shaping. A portion of this research is presently underway. Peak powers of 1-2 megawatts and pulse durations on the order of nanoseconds are not unreasonable to anticipate at submillimeter wavelengths.

It is also our intention to carry these studies to materials giving rise to shorter wavelength radiation consistent with the myriad of applications which are possible. We intend to determine the effects of incoherent pumping (Bluemline discharge (7)) on swept-gain superradiance pulse evolution for optical and VUV wavelength pulse generation.

Our initial work opens a vast area of investigation over a broad range of wavelengths for the production of coherent, intense, short pulses generated from noise (and without mirrors) which can be shaped and compressed by control of the pressure and/or cell length. Theory predicts that pulses of this nature will be produced in any medium for which the gain to loss ratio is greater than unity and for which the total gain is greater than one.

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