INVESTIGATION OF COHERENT SOURCES OF INFRARED RADIATION

under the direction of

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INTRODUCTION

This program is concerned with new methods of generating and detecting far infrared radiation and with their applications to problems of physical interest. The over-all purpose is to advance the technology of the infrared region so that it may become as accessible for scientific investigations as the radio and optical portions of the spectrum.

PRESENT STATUS

The approach of this study has been to examine plasma effects in pulsed infrared lasers. It is evident that light at 29 cm^{-1} will have a much stronger interaction with the electrons of the usual gaseous laser plasma than will light at higher wave numbers.

The interaction of light with an electron distribution at frequencies ω such that $\frac{\omega_p}{\omega} \leq 1$, where ω_p is the plasma resonance frequency, may be reflective, refractive, or dissipative. It is reflective if $\omega_p = \omega$. It is refractive if the distribution is inhomogeneous along the ray direction. It is dissipative if energy is removed from the light wave through acceleration of the electrons; this interaction becomes important as the electron-ion collision frequency approaches the light frequency. During the previous report period we carried out calculations under the assumption that reflective effects were dominant. These results were presented at the meeting of the American Physical Society, 18-20 December, 1967 in Pasadena, California. This model provided an explanation for a spectral line splitting reported by other researchers;[1] but the dissipative losses associated with this model and presented in the previous report were extremely high.

During the current report period we have established that refractive effects rather than reflective effects are important in HCN lasers. The Schottky ambipolar diffusion model of the discharge predicts a radial electron distribution which varies as $N_e J_0 \frac{(2.4r)}{R}$, where N_e is the electron density and J_0 the zero^th order cylindrical Bessel function. This constitutes a divergent refracting element decreasing in refractive power as electrons recombine with ions. If the initial electron density is sufficiently high, laser action is delayed until a stable resonator is established. Often laser modes appear which apparently include reflections from the wall of the laser tube; we have shown that convex mirrors unstable in the ordinary sense sustain lasing which is suppressed by absorbers placed along the tube walls.

Suppression of the wall modes lowers the current density threshold for the remaining modes. The apparent output is undiminished, suggesting that efficiency is improved. In addition, these refractive effects largely determine the temporal characteristics of the light emitted; that is, the pulse delay and pulse shape as a function of cavity length. The details of this work will be submitted for publication during the next report period.

1. Experimental Equipment Constructed.

During the report period the indium antimonide electron bolometer was operated yielding noise-free data on the temporal and spatial mode structure as a function of cavity length and other parameters. A second laser power supply and triggered spark gap was assembled providing a selection of capacitors and series inductors, so that pulse length, damping, pulse rate, peak current and peak voltage to 20 kV could be varied. The far infrared grating spectrometer was modified to accept the laser output, permitting time and frequency resolved spectra to be taken simultaneously; attenuation over the 10 m path and through the grating was a factor of ten. A gas manifold was constructed permitting admixtures of buffer gases and operation of the laser on CH_4 and N_2 mixtures. An intracavity gas cell was constructed permitting saturable absorber Q-switching experiments. This cell necessitated two intracavity windows, and vacuum-strength materials were found which were sufficiently transparent to permit laser action under these conditions. This cell was adapted to provide a continuously-variable positive and negative curvature mirror. The curvature of an aluminum-coated mylar film was varied by regulating the relative pressure on either side of the film through needle valves and was monitored by a He-Ne laser optical system with a 5 meter lever arm. Finally, work has begun on a pyroelectric calorimeter to monitor the energy per pulse from the laser. Triglycine sulfate crystals of sufficient size and clarity have been grown from a solution having temperature control to 0.05° C and programmable agitation. These crystals have been x-ray oriented and cleaved; coating evaluation is underway.

2. Experiments and Calculations.

Experimental work proceeded as follows. The peak electron density was inferred by measuring Stark broadening of the hydrogen Balmer H_β line at 4861 Å. This width was determined photographically and time-resolved photoelectrically; the radiation from the n-propylamine discharge was observed through a window in the end of the laser tube. The peak electron density at 0.5 Torr gas pressure ranges from 10^{14} to 2.2×10^{14} per cm^3 for a 4 μsec current pulse having a peak current of 1 to 5 kiloamps.

We can show that electron densities of this magnitude distributed radially as described comprise a temporary refracting element of sufficient strength to strongly affect laser operation. The integral equations for the normal modes of an optical resonator with curved end reflectors have been reduced to a differential equation.[2] Inspection of this equation permits a parabolic radial dielectric distribution to be replaced by parabolic end reflectors characterized by a focal length. The first two terms of the J_0 expansion describe a parabola. We have calculated refracting elements as a function of electron density and combined these elements to obtain the stability curve shown in Fig. 1. This figure refers to an experiment in which one mirror was fixed with a 91-inch curvature while the second curvature was variable.

We obtained weak lasing for second mirror curvatures corresponding to $g_2 = 1 - \frac{L}{R_2}$ as large as 4.5 and as small as -1.8, well ouside stability even assuming no divergent medium. Strong lasing ranged between 2.8 and -0.3.

We then spaced six microwave-absorbing sponge annuluses down the 2 m tube and vignetted the mirrors with the same material from 4 to 2 inches. The curvature range for laser action dropped sharply from 0.7 to -0.3. The current threshold was depressed and multiple modes[3] were absent even at high currents. These effects we attribute to the suppression of modes which include reflections from the walls. The calculated electron density required to narrow the stability range to the observed values is in the neighborhood of $10^{13}/\text{cm}^3$; recombination from the peak electron density measured to this level during the 2 to 6 μsec delay between current and laser pulses is reasonable.

Careful measurements of mode shape and delay were made as a function

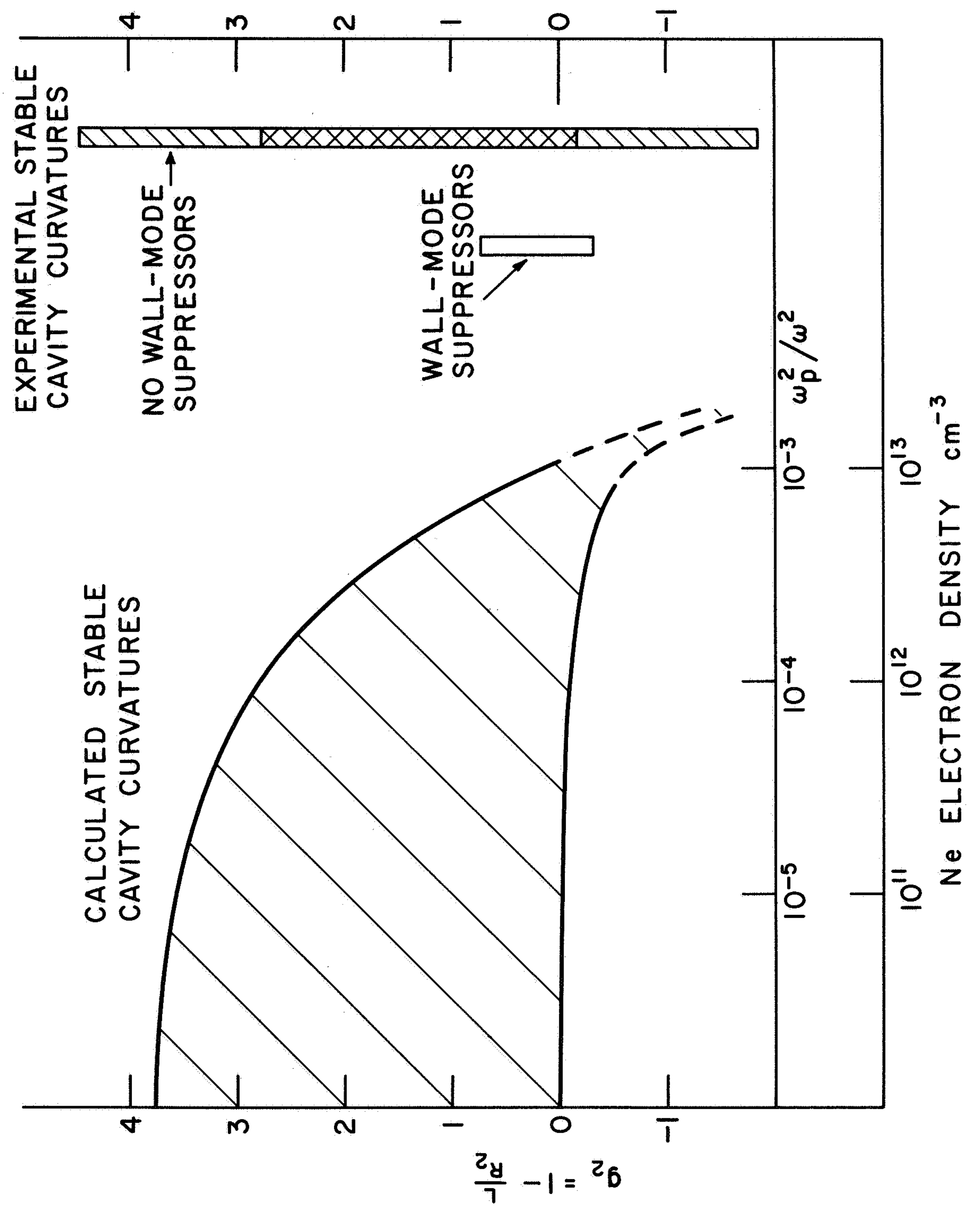

FIG. 1--HCN laser cavity stability.

of laser frequency, mirror curvature, mirror position, and plasma parameters. It is expected that the delay, asymmetry of delay, output with respect to perturbation of cavity length around that of maximum output,[4] double temporal modes, and beat frequencies can be explained according to this model.

These results are important in that the refractive self-Q-switching phenomenon can limit peak power output in many pulsed gaseous infrared lasers including possibly CO_2 lasers. Measurement of the plasma parameters also permits calculation of dissipative losses due to acceleration of the electrons by laser light. Understanding these phenomena will permit enlightened design of high power and efficient infrared lasers.

REFERENCES

1. H. Steffen, J. F. Moser, and F. R. Kneubühl, J. Appl. Phys. 38, 3410 (1967); also

   H. Steffan, P. Schwaller, J. F. Moser, and F. K. Kneubühl, Phys. Letters 23, 313 (1965);

   M. Camani, F. K. Kneubühl, J. F. Moser, and H. Steffan, Z. Angew. Math. Phys. 16, 562 (1965);

   H. Steffan and F. K. Kneubühl, J. of Quantum Electronics, Nov. 1968, (to be published);

   W. Prettl and L. Genzel, Phys. Letters 23, 443 (1966).

2. L. Bergstein and H. Schachter, Synposium on Modern Optics, Polytechnic Institute of Brooklyn, March 22-24, 1967.

3. S. Kon, M. Yamanaka, J. Yamamoto, and H. Yoshinaga, Japan J. Appl. Phys., 6, 612 (1967); also

   M. Yamanaka, H. Yoshinaga, S. Kon, Japan J. Appl. Phys., 7, 250 (1968).

4. H. Steffen, B. Keller, F. K. Kneubühl, Electronics Letters 3 (12), 561 (1967).