V. QUANTUM ELECTRONICS

A. Laser Applications

Academic Research Staff

Prof. S. Ezekiel

Graduate Students

M. B. Callaham	L. A. Hackel	F. Y-F. Wu
R. E. Grove	P. D. Henshaw	D. G. Youmans

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

Our interest is primarily in the application of lasers to a variety of measurement problems. The available lasers are not suitable in certain cases, and considerable research has to be done to improve laser performance. Several projects are in progress.

1. Long-Term Laser Frequency Stabilization Using a Molecular Beam

U. S. Air Force – Office of Scientific Research (Contract F44620-71-C-0051)

S. Ezekiel

The need for a long-term frequency stabilized laser in the precision measurement of length, that is, in setting up length standards, is the motivation for this work. Such a laser would find application in earth-strain seismometry, in optical communication, and in fundamental measurements; in particular, in fields related to experimental relativity.

The task, at present, is to stabilize the frequency of the 5145 Å argon ion laser.[1-3] The stabilization scheme employs a resonance absorption line that is observed in a molecular beam of iodine as an absolute frequency reference. The absorption is measured by the resonance fluorescence induced by the laser in the molecular beam. This is an ideal reference element because of the isolated and unperturbed conditions in the beam. Moreover, since the molecular beam can be oriented at right angles to the laser beam, the width of the iodine resonance is limited to its natural width, which is inferred from lifetime measurements to be 100 kHz.

Thus far, we have been able to reduce the observed line width of I_2 in the beam to 300 kHz and the argon laser has been locked to the center of the I_2 line. The laser frequency drift was monitored by examining the fluorescence signal associated with the same transition observed in an independent I_2 molecular beam. The long-term stability was found to be better than 5 parts in 10^{14} for an averaging time of 100 seconds. The effect of external magnetic fields was less than one part in 10^{14}/G and the effect of laser intensity was less than 4 parts in 10^{14} for a 10% change in intensity. Preliminary experiments have indicated that the frequency reproducibility is better than one part in 10^{11}.

References

1. T. J. Ryan, D. G. Youmans, L. A. Hackel, and S. Ezekiel, "Molecular Beam Stabilized Argon Laser," Appl. Phys. Letters 21, 320-322 (1972).
2. L. A. Hackel, D. G. Youmans, and S. Ezekiel, "Molecular Beam Stabilized Laser," Twenty-seventh Annual Symposium on Frequency Control, U. S. Army Electronics Command, Fort Monmouth, New Jersey, June 12-14, 1973.
3. D. G. Youmans, L. A. Hackel, and S. Ezekiel, "Long-Term Laser Frequency Stabilization Using a Molecular Beam Reference," Proc. Fourth International Symposium on Molecular Beams, Cannes, France, July 9-12, 1973.

2. High-Resolution Spectroscopy Using Molecular Beams

U. S. Air Force – Office of Scientific Research (Contract F44620-71-C-0051)

S. Ezekiel

We are investigating the use of molecular beams for high-resolution spectroscopy.[1-4] A single-frequency 5145 Å argon laser that can be tuned linearly over 0.05 Å is used to induce resonance fluorescence in a molecular beam of iodine. The resolution that we have achieved is better than 3×10^{-10} but is still limited by Doppler broadening attributable to molecular beam geometry. In the scanning mode, the resolution of this laser is better than 1×10^{-10}, as has been demonstrated by using a Fabry-Perot interferometer.

High-resolution measurements of the hyperfine structure in iodine 127 have been made and the observed spectrum was fitted to obtain the quadrupole coupling strength and the spin-rotation interaction strength.

We intend to make a precision measurement of the iodine natural width, as well as the Zeeman and Stark effects in iodine. Also, by exciting the beam nonorthogonally, we hope to study the velocity distribution in the beam.

References

1. D. G. Youmans, L. A. Hackel, and S. Ezekiel, "High-Resolution Spectroscopy of I_2 Using Laser-Molecular-Beam Techniques," J. Appl. Phys. 44, 2319-2321 (1973).
2. L. A. Hackel, D. G. Youmans, and S. Ezekiel, "Laser-Molecular-Beam Techniques for High-Resolution Spectroscopy," Proc. Fourth International Symposium on Molecular Beams, Cannes, France, July 9-12, 1973.
3. S. Ezekiel, "Molecular Beam Spectroscopy with Argon and Dye Lasers," Proc. Laser Spectroscopy Conference, Vail, Colorado, June 25-29, 1973.
4. D. J. Ruben, S. G. Kukolich, L. A. Hackel, D. G. Youmans, and S. Ezekiel, "Laser-Molecular Beam Measurement of Hyperfine Structure in the I_2 Spectrum," Chem. Phys. Letters 22, 326-330 (1973).

3. Single-Frequency Continuous-Wave Dye Laser

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

S. Ezekiel

Continuous-wave single-frequency dye lasers offer the possibility of achieving a laser line of narrow spectral width anywhere in the visible spectrum. This type of laser has many applications, as in optical communication and spectroscopy. The present problem is that the dye laser frequency is not very stable and the frequency tuning is not continuous.

We have been investigating the frequency jitter in a single-frequency cw dye laser that employs a jet stream of Rhodamine 6G dye dissolved in ethylene glycol.[1,2] Thus far, we have achieved a laser spectral width of less than 10 kHz in 0.1 ms and a width of ~1 MHz in 0.1 second. We have been able to observe hyperfine structure at 5900 Å in a molecular beam of iodine with a resolution of 3 MHz. In a preliminary experiment we have locked the laser frequency to an iodine molecular beam resonance and achieved a stability of 2 parts in 10^{11} for an averaging time of 100 seconds.

References

1. S. Ezekiel, "Molecular Beam Spectroscopy with Argon and Dye Lasers," Proc. Laser Spectroscopy Conference, Vail, Colorado, June 25-29, 1973.
2. R. E. Grove, F. Y. Wu, L. A. Hackel, D. G. Youmans, and S. Ezekiel, "Jet Stream cw Dye Laser for High Resolution Spectroscopy," Appl. Phys. Letters 23, 442-444 (1973).

4. Holographic Applications

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

S. Ezekiel

Holography, in particular, holographic interferometry, has generated many new measurement techniques that can be used in nondestructive testing of materials and structures. We have been particularly interested in methods of contour generation and closed-loop holographic interferometry.[1]

In depth contouring we have developed two schemes: one uses a two-frequency pulsed xenon laser, and the other a two-source method that can be reconstructed with white light from a slide projector. In the two-frequency method, we were able to generate depth contours as small as 2.8 μm. Calibrated steel wedges were used to test the accuracy of the contouring. Flash-lamp pumped dye cells were investigated as amplifiers for pulsed ion lasers oscillating simultaneously at two frequencies. An amplification of ten was obtained without noticeable deterioration of either the spatial or temporal coherence of the xenon laser. In the two-source method the object, which was placed behind the holographic plate, was illuminated sequentially, or simultaneously, from two directions with the same laser source. With this method, we have achieved white-light reconstructed depth contour spacings of 15 μm, and we hope to increase this sensitivity by one order of magnitude. The brightness of the holographic image has been greatly enhanced by the development of specialized film-processing techniques.

In real-time holographic interferometry, we have been able to lock the real-time holographic image to the real object by means of a feedback loop. In this way a displacement of the object may be monitored with extreme sensitivity. This method is being applied to the detection of subfringe deformations in diffuse objects and in the measurement of small changes in surface thickness.

References

1. P. D. Henshaw and S. Ezekial, "High Resolution Contour Generation Using a Pulsed Multicolor Ion Laser" Appl. Opt. 12, 2550-2552 (1973).

5. Laser Doppler Velocimeter

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

S. Ezekiel

A Laser Doppler Velocimeter system (LDV) that is capable of measuring two components of velocity in periodic flow fields has been developed.[1] This system was used to measure the axial and radial velocity distributions in vortex rings.[2] The current interest in vortex filaments stems from the hazards of the strong vortex wakes of jumbo jet aircraft and the noise and vibration generated by blade-vortex interaction on helicopter rotors. Since the induced motion and stability of a vortex filament depends on the detailed structure of the vortex core, it is desirable to make experimental measurements within the core.

The vortex rings were generated by pulsing air through a sharp-edged orifice using a loudspeaker; the strength and vortex core size could be controlled somewhat by the duration and amplitude of the pulse. From detailed surveys of the velocity field, both the circulation and vorticity distribution were found for two different rings: one with a relatively thick core, the other with a thin core. The vorticity was found to be rather concentrated for both rings. Streamlines were also calculated and compared with observations. Vortex rings were found to be unstable to azimuthal perturbations; the observed mode number and growth rate are in reasonable agreement with theory.

References

1. J. P. Sullivan and S. Ezekiel, "Two-Component LDV for Periodic Flow Fields" (to appear in J. Phys. E: Scientific Instruments).
2. J. P. Sullivan, S. E. Widnall, and S. Ezekiel, "A Study of Vortex Rings Using a Laser Doppler Velocimeter," AIAA J. 11, 1384-1389 (1973).

V. QUANTUM ELECTRONICS

B. Gaseous Lasers

Academic and Research Staff

Prof. W. P. Allis
Prof. E. V. George
Prof. H. A. Haus
Dr. P. W. Hoff
Dr. C. K. Rhodes
Dr. E. Zamir
J. J. McCarthy
W. J. Mulligan

Graduate Students

N. M. Ceglio
T. Holcomb
J. L. Miller
C. W. Werner
D. Wildman

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

Our general objectives are concerned with a study of the plasma physics of gaseous lasers. At present, we are concentrating our effort on understanding the mechanisms that limit the rapid transfer of electrical energy into a high-pressure gas. This study, both theoretical and experimental, is being applied toward obtaining optical laser pulses of high peak powers from both CO and CO_2 laser systems. We are also devoting a major portion of our effort to obtaining stimulated emission at ultraviolet frequencies from high-pressure noble gases. Laser systems operating in the ultraviolet will be extremely important for, say, satellite-satellite communication links where noise problems associated with solar emissions are minimal. A description of specific programs follows.

1. Ultraviolet Lasers

University of California, Livermore (Subcontract No. 7877409)

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

E. V. George

Our effort to obtain stimulated emission in the vacuum ultraviolet spectrum from a conventionally excited high-pressure discharge continues. Recently[1] we showed theoretically that stimulated emission at 1700 Å should be possible from a suitably prepared plasma in xenon at $\sim$15 atm pressure. We are now setting up an experiment to verify this hypothesis.

Fundamental studies are being conducted to gain a better understanding of the basic loss processes that are operative in these systems. For example, at increasing pressures ground-state absorption begins to play an important part in reducing the optical gain. This phenomenon is not only proportional to the square of the gas density but increases exponentially with increasing gas temperature. Since a large population inversion is required for lasing because of the large bandwidth ($\Delta\omega/\omega \sim 10$), this implies operation at high pressures. It is important, therefore, to obtain information on the shape of the $^1\Sigma_g^+$ ground-state curve.

At these large inversion densities, excited state-excited state losses are important; for example, Penning ionization of the $^{1,3}\Sigma$ states. These losses severely limit the high-power density performance of this laser system.

We have also developed a kinetic model for predicting the performance of the electron-beam-excited ultraviolet lasers. This work has been described in previous reports.[2]

References

1. E. V. George and C. K. Rhodes, "Kinetic Model of Ultraviolet Inversions in High-Pressure Rare-Gas Plasmas," Appl. Phys. Letters 23, 139 (1973).

2. C. W. Werner, Quarterly Progress Report No. 110, Research Laboratory of Electronics, M.I.T., July 15, 1973, pp. 65-77; Quarterly Progress Report No. 111, October 15, 1973, pp. 67-70.

2. CO_2 Laser

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

E. V. George

The CO_2 laser program is designed to study the basic plasma properties of this system. One major objective is to generate intense subnanosecond pulses from a 15 atm system. We are also investigating various techniques for measuring very short CO_2 pulses. Such an investigation is absolutely necessary for correct interpretation of the laser system performance.

The results of our studies on the electrical energy transfer into high-pressure gases has led to the successful operation of a CO_2 laser at a pressure of 10.2 atm. This laser operates with an E/N ratio comparable to the atmospheric pressure systems. We find that this laser operates on several rotational transitions. We are developing a theoretical model to describe this laser's performance.

Our studies on the basic properties of an atmospheric pressure CO_2 laser have led to the development of a high-repetition-rate, high-peak-power laser with excellent temporal and amplitude stability. We are continuing this study along two lines: measurement of basic plasma parameters, and study of the formation of constricted arcs which severely limit the ultimate repetition rate.

3. CO Laser Systems

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

H. A. Haus

We are studying a room-temperature TEA CO laser to optimize its performance and ultimately to be able to scale operation to higher gas pressures and power levels. TEA structures of the pin type and the so-called three-electrode type have been examined; most of the experiments have been conducted on the latter. The laser operates on pure CO typically at pressures of 50-150 Torr. Operation in a gain-switched mode produces lasing on several P transitions of several vibrational bands, thereby causing simultaneous operation on as many as 35-55 lines. Total peak power is typically 1 kW with the output lasting several microseconds.

Measurements of the laser output at various operating voltages and gas pressures revealed that there was a maximum output power that could not be exceeded when the operator was scaled to higher operating pressure. Since gas kinetics in this time range is controlled by collision-induced energy exchanges between excited CO molecules, the saturation parameters, and hence output power, should be proportional to pressure. Temperature effects from heating the gas during the discharge are insufficient to explain these observations.

A computer program was written to solve numerically the equations governing the transient CO vibrational-level population distribution. The computed results agree qualitatively with experimental results but predict an output power proportional to pressure. The computer model also shows that the details of laser operation are quite sensitive to the assumed electron distribution. We are now making gain measurements on the TEA laser. By using a cw CO laser as a probe, the gain on a selected transition can be followed as it evolves in time. These measurements will furnish information on the level populations vs time and indirectly on the pumping rates and cross sections, and the results will be used to improve the computer model.

C. Nonlinear Phenomena

Academic and Research Staff

Prof. E. V. George
Prof. H. A. Haus
Dr. A. H. M. Ross

Graduate Students

C. P. Auschnitt
Y. Manichaikul
J. L. Miller

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

1. Laser Locking over a "Wide" Frequency Range

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

H. A. Haus

It is well known that high regenerative gain can be obtained by locking a free-running oscillator to a low-power driving oscillator, provided the frequency deviation of the driving oscillator from the center frequency of the free-running oscillator is small compared with the bandwidth of the free-running oscillator. It has been shown recently that it is possible to design a laser cavity by using a grating and curved mirrors capable of supporting a continuum of modes over a band of frequencies; modes with axes of slightly different orientation have different frequencies. We propose to study the use of such a cavity for regenerative amplification and to determine the limitations on the rate at which the driving oscillator may be swept while still maintaining locking.

In a related development, it was found that a modification of the grating cavity may be used to decrease the sensitivity of the cavity frequency to dielectric "constant" changes in the laser medium. Changes in dielectric constant during the laser pulse lead to chirping. TEA CO_2 lasers are known to chirp over a frequency range of the order of 30 MHz within the duration of one pulse.[1,2] The chirping problem could be greatly improved by a system with a frequency-stable master oscillator and a pulse amplifier. It is believed, however, that a single TEA laser oscillator can be constructed that would be stable within approximately 1 MHz. Our program is directed toward constructing such an oscillator. The grating can partially compensate for the change in phase which is caused by changes in refractive index of the gas because of the shock generated in a TEA current pulse. Tests will be performed on such a cavity to ascertain the increase in stability and decrease in chirp caused by the novel construction.

References

1. W. A. Stiehl, "Measurement of the Spectrum of a TEA CO_2 Laser, Quarterly Progress Report No. 106, Research Laboratory of Electronics, M. I. T., July 15, 1972, pp. 63-69.
2. W. A. Stiehl and P. W. Hoff, "Measurement of the Spectrum of a Helical TEA CO_2 Laser," Appl. Phys. Letters 22, 680 (1973).

2. Short Laser Pulses

U. S. Army Research Office – Durham (Contract DAHC04-72-C-0044)
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H. A. Haus

In a study of amplification of high-energy pulses through a TEA laser amplifier, a mode-locked laser oscillator has been constructed from which two or more consecutive pulses could be selected electro-optically. The pulses, each 2 ns long with 500 kW peak power, were passed through a laser amplifier and the effect upon the gain of the second pulse was investigated. Gain recovery was found at a rate that corresponds to the vibrational relaxation rate measured by other means by Szoke and his co-workers.[1]

In the expectation that generation of very short CO_2 laser pulses could be achieved by mode-locking high-pressure transversely excited laser systems, a study has been undertaken of saturable absorber mode locking of a TEA CO_2 laser system. A saturable absorber that is a hot CO_2 cell is being used because such a cell is less prone to damage than a crystal utilizing forced mode locking when it is utilized in a high-energy high-pressure system. Saturable absorber mode locking has been observed and a theory of such mode locking is now being developed, in order to ascertain the limitations set by the laser medium and absorber medium parameters upon the mode locking. In developing this theory, a concise way of explaining forced mode locking has been found, and will be reported separately. The major thrust of future work will be in the direction of attempting to gain an understanding of mode locking by saturable absorbers, with the aid of obtaining a closed-form theory that will predict analytically the influence of the parameters of the laser medium and the saturable absorber medium upon the mode locking. The theory will be checked on CO_2 laser systems at atmospheric and higher pressures.

A better understanding has been obtained of the vibrational excitation of laser systems by electrons through the development of an analytic theory. By making suitable approximations, closed-form expressions were obtained for the pertinent excitation rate in e-beam laser systems. Details of this work have been presented in past reports; the results will be published in the January 1974 issue of the Journal of Applied Physics under the title "Electron Distributions in Molecular Lasers."

References

1. I. Burak, Y. Noter, and A. Szoke, "Vibration-Vibration Energy Transfer in the v_3 Mode of CO_2," IEEE J. Quant. Electronics, Vol. QE-9, No. 5, pp. 541-544, May 1973.

3. Model of CO_2 Laser Plasmas

National Science Foundation (Grant GK-37979X)
U. S. Army Research Office – Durham (Contract DAHC04-72-C-0044)

H. A. Haus

Kinetic modeling of CO_2 laser plasmas continues in support of the design of a 1-ns, >10 J short-pulse oscillator amplifier system. Construction of the initial model of this system has begun, although it is not yet operational.

Analysis is based on the model discussed in Quarterly Progress Report No. 111 (pp. 109-112). Initial conditions for this model are taken from experimental measurements of small-signal gain, and thus the uncertainties inherent in models of the electrical discharge are by-passed. It is possible to do this because the stimulated emission rates involved in short-pulse amplification are extremely fast compared with the electronic pumping rates, and the effect of the pumping during the amplification can be neglected.

Approximate solutions for a prototype design have shown that a 1-atm, 2-m amplifier can give a power output in excess of 5 GW from a 1-ns, 1-mJ input pulse. The system was taken to be four 50-cm discharge modules, the first, third, and fourth of which were used as straight-through amplifiers, and the second of which was used as a 5X magnification, three-pass beam-expanding stage. The input beam was assumed to be 1 cm in diameter, the output a 5-cm annular beam. Since small-signal gains between 3%/cm and 5%/cm have been reported for devices of the spark preionized type, a small-signal gain of 4%/cm was taken for the prototype. A 1-ns FWHM, 10^6 W/cm^2 Gaussian input pulse was found to produce a peak output power of approximately 5×10^9 W, while broadening to approximately 2.5 ns. At this pressure, the effect of saturation steepening of the leading edge of the pulse is negligible because of the relatively long time for extraction of the energy from rotational sublevels.

Although operation of such devices at higher pressures is still not known to be practical with respect to maintaining stable, arc-free discharges, the kinetic code was also run for a 5-atm fill with the other parameters (in particular, the small-signal gain) kept constant. The output intensity was found to grow approximately in proportion to the increase in pressure, while the pulse width shrank nearly to the input width. This is principally because of the scaling of the saturation intensity, which in the crudest model would be expected to be proportional to P^2.

Preliminary checks of the modeling will be performed with the TEA lasers now available. Construction of a mode-locked oscillator and 1-m amplifier module is under way, and we are taking great care to ensure that they will have the ability to perform accurate measurements of spectrum and gain. Because of the extremely noisy environment created by the pulsed discharges in these devices, such measurements, while simple in principle, are quite difficult to achieve in practice. The mode-locking and shuttering technology is now well known and will not be described here.

Recent work in our laboratory has shown that operation of extremely high-pressure TEA laser oscillators (5-15 atm) encourages multiline output. Since the energy extracted from a high-pressure amplifier system will increase approximately in proportion to the number of lines in the input, there will be a substantial advantage in operating such a device as the master oscillator.

We expect that the final system will be a 5-10 atm mode-locked oscillator followed by an amplifier chain at 2-3 atm. At these pressures the fidelity of reproduction of a 1-ns pulse will be reasonable, while the electrical problems will still be manageable. The scaling of required fields with pressure and the large apertures mean that discharge voltages of more than 100 kV will be necessary.