VII. QUANTUM ELECTRONICS

A. Laser Applications

Academic and Research Staff

Prof. Shaoul Ezekiel
Dr. Frederick Y-F. Wu

Graduate Students

Salvatore R. Balsamo
James A. Cole
James L. Davis
Stephan C. Goldstein
Richard P. Hackel
George W. Sparks, Jr.

1. FREQUENCY STABILIZATION OF A CONTINUOUS-WAVE DYE LASER

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Shaoul Ezekiel, Frederick Y-F. Wu

The primary objective in this program is the development of an extremely stable, low-jitter, single-frequency cw dye laser for use in a variety of applications such as optical communication and ultrahigh-resolution spectroscopy, and for studying fundamental interactions between radiation and matter.

During the past year we have been concerned with the short-term stabilization of commercially available cw dye lasers. The main emphasis has been on improving performance without major redesign of the cavity.

A Spectra-Physics single-frequency cw dye laser Model 580 was modified by extending the cavity approximately 10 cm and inserting an electro-optic phase modulator within this space. The phase modulator is an AD*P crystal, made by Interactive Radiation, Inc., and is free from resonances over a wide range of frequencies up to 400 MHz.

A composite wideband feedback loop with 2 MHz bandwidth was used to lock the laser frequency to the side of a transmission resonance of an external Fabry-Perot cavity having a 1-MHz resonance width. In this way, the high-frequency response was provided by the intracavity phase modulator and a large dynamic range was provided by the PZT length transducer on which the output mirror was mounted.

The use of this feedback loop reduced the rms jitter from 10 MHz to ~30 kHz. The reduction of the laser jitter was demonstrated by heterodyning two similar but independently stabilized dye lasers. The narrow laser linewidth was also demonstrated by the excitation of narrow hyperfine-structure resonances in a molecular beam of I_2. The 800 kHz measured linewidth of an individual I_2 line included a natural width of 400 kHz and residual Doppler broadening from molecular beam geometry.

2. MEASUREMENT OF THE SPECTRUM OF RESONANCE FLUORESCENCE FROM A TWO-LEVEL ATOM IN AN INTENSE MONOCHROMATIC FIELD

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Shaoul Ezekiel, Robert E. Grove, Frederick Y-F. Wu

The spectrum of resonance fluorescence emitted by a carefully prepared two-level system has been measured. The data were in good agreement with the theoretically predicted spectrum.[1,2]

The $3\ ^2S_{1/2}$ (F = 2)-$3\ ^2P_{3/2}$ (F' = 3) transition in atomic sodium was prepared as a two-level system by optical pumping of the degenerate magnetic sublevels with the resonant circularly polarized laser light. Thus we were able to excite the $m_F = 2$-$m_{F'} = 3$ transition selectively, thereby avoiding the complication caused by unequal matrix elements that connect other pairs of sublevels.

In our experimental arrangement a single-frequency cw dye laser is split into parallel "pump" and "signal" beams, which are separated 1.2 cm and intersect an atomic beam of sodium at right angles. The pump beam prepares the F = 2 ground-state atoms in the $m_F = 2$ sublevel before they interact with the intense signal beam. A weak magnetic field (0.7 G) parallel to the laser beams is required to prevent redistribution of the sublevel populations by stray fields in the region between laser beams. The fluorescence induced by the signal beam is collimated and analyzed by a Fabry-Perot interferometer with a 2-MHz instrument width.

To record the on-resonance spectrum, the pump and signal beams are locked to the F = 2-F' = 3 transition. For off-resonance spectra, an acousto-optic shifter is placed in the pump beam, and the laser is stabilized so that the shifted pump-beam frequency is resonant with the F = 2-F' = 3 transition, and thus the signal beam is held at an accurately known detuning from resonance.

For comparison of theory with experiment, we computed the convolution of the theoretical spectra with the 9.5 MHz wide instrumental line shape of our arrangement. The instrumental line shape, which includes Doppler and Fabry-Perot broadening, was determined by observing the weak field (elastic scattering) spectrum, which ideally is a delta function. The convolved spectra[3] agreed very well with Mollow's theory.[1]

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3. LASER STREAK VELOCIMETRY FOR TWO-DIMENSIONAL FLOWS IN GASES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Shaoul Ezekiel, George W. Sparks, Jr.

The present methods of flow measurement in gases are restricted to point-by-point measurements. A method of simultaneously measuring velocities over large areas and volumes is clearly needed for such applications as nonsteady vortex flow.

A new velocity measuring technique, Laser Streak Velocimetry (LSV), has been developed for two-dimensional flows in gases.[1] A 2-watt cw argon laser beam is formed into a thin sheet to illuminate a seeded flow in a two-dimensional plane around a body. Short-exposure streak photographs of the seed particles are recorded as they traverse the light sheet, and then the two-dimensional velocity vector is computed from the length and direction of each streak. The validity of this technique has been demonstrated by measuring the velocity profile in the boundary layer of a flat plate; the measurements showed agreement within 4% of theoretical predictions. In order to demonstrate the application to nonsteady flows, a mapping was made of the nonsteady vortex shedding of low Reynolds number flow past a circular cylinder. Because of current interest in low-speed aerodynamics, the LSV method was also used to obtain the velocities over the surface of a 60° delta wing at 15° angle of attack, and the results were compared with a related theory.

The primary advantage of LSV is the simplicity of the arrangement and its operation, coupled with reasonable accuracy and adaptability. Some of the limitations of LSV, such as particle size and uniformity, can be overcome by the design of an automatic generator and disperser of unit-density, spherical, 1-μm particles. A pulsed laser would permit the extension of LSV to velocities approaching sonic, while high-speed scanning of a pulsed sheet can map three-dimensional, nonsteady flows.

LSV has been shown to be an effective research tool, and extensions of the present method will be pursued to explore the full potential of this technique.

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4. PASSIVE RING RESONATOR LASER GYROSCOPE

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Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Shaoul Ezekiel, Salvatore R. Balsamo, James A. Cole, Stephan C. Goldstein

We are developing a new optical rate gyroscope using a passive ring Fabry-Perot interferometer as the rotation sensing element, based on the Sagnac effect. The clockwise and counterclockwise lengths of the cavity, which depend on inertial rotation, are measured by means of two independently controlled laser frequencies. One laser is locked to the center of the cw resonance and the other to the ccw resonance of the cavity.

To eliminate the effect of laser-frequency jitter, we use only one laser whose output is shifted by two independently controlled acousto-optic frequency shifters. For a square ring, 10 cm on a side, with 1-MHz cavity resonance width and 1-mW laser power, it should be possible to detect earth rate in an integration time of 0.5 ms and milliearth rate in several hundred seconds.

The performance of our experimental arrangement shows that such a scheme does not suffer from lock-in phenomena normally associated with ring laser gyroscopes. The rms fluctuation of the bias, at present, is less than 15 degrees/hour for an integration time of one second.

Another scheme under investigation consists of a passive ring with an intracavity Faraday cell. The possibility of a fiber optic ring is also being considered.

Aside from applications to navigation, we propose to examine the possibility of measuring earth rotation to better than one part in 10^8, using a cavity, 10 m on a side, and a 10-W argon laser. Such measurements should give information on polar wobble, continental drift, and changes in the length of the day. The connection between earthquakes and earth wobble may also be examined. Application of such a device in experiments related to general relativity will also be considered.

5. SHORT-TERM AND LONG-TERM STABILIZATION OF MULTIWATT CONTINUOUS-WAVE ARGON LASERS

U.S. Air Force – Office of Scientific Research (Contract F44620-76-C-0079)

Shaoul Ezekiel, Richard P. Hackel

This research is motivated by the need for long-term, as well as short-term, stabilized lasers for applications to earth strain seismometry, optical communication and radar, precision spectroscopy, and fundamental measurements in experimental relativity.

During the last few years we have investigated the use of an I_2 molecular beam as a reference for the long-term stabilization of an argon ion laser. A long-term stability of one part in 10^{13} in an integration time of 200 s has been achieved. The argon lasers used in these experiments were homemade with power output of the order of milliwatts.

Recently, we have extended our effort to the stabilization of commercially made multiwatt argon lasers such as the 15 W Spectra-Physics laser. The short-term absolute jitter of ~30 MHz that is inherent in such a laser was reduced to less than 50 kHz by locking the laser frequency to an external Fabry-Perot cavity. A wide bandwidth (1 MHz) feedback loop was necessary, and was made possible by using an intracavity electro-optic phase shifter. Long-term stabilization was accomplished by locking the reference Fabry-Perot to a hyperfine transition observed in an I_2 molecular beam.

The performance of the laser was measured by heterodyning two high-power argon lasers, each independently stabilized to adjacent I_2 lines. A stability of 7 parts in 10^{14} was achieved in an integration time of 1000 seconds.

The residual short-term jitter of 50 kHz is set by the jitter of the reference Fabry-Perot and not by the bandwidth of the fast feedback loop. The laser jitter relative to the reference Fabry-Perot is less than 10 kHz.

The reproducibility of the laser frequency was studied by using a careful procedure for the orthogonal alignment of the laser with respect to the I_2 beam. A reproducibility of 1.5×10^{-12} was demonstrated.

Many improvements are still to come. In particular, we plan to use the R(26) 62-0 transition in I_2, which matches the 5017 Å argon laser line, as a long-term reference. The advantage of the R(26) transition is its smaller natural width (10 kHz). We anticipate that, by using the R(26) and by optimizing the I_2 fluorescence, a stability of 10^{-14} for a $\tau = 1$ s can be achieved. For longer integration times, the stability is expected to be limited by second-order Doppler shifts $\approx 10^{-17}$ for a 1% change in intensity (estimated). The effect of molecular recoil in the case of a simple absorption in a beam is being investigated.

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B. Nonlinear Phenomena

Academic and Research Staff

Prof. Hermann A. Haus
Prof. Clifton G. Fonstad, Jr.
Dr. Fielding Brown

Graduate Students

Howard L. Dykeman
Peter L. Hagelstein
Ping-Tong Ho

1. SHORT LASER PULSES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Hermann A. Haus

Saturable absorber (passive) mode locking of lasers has the faculty of producing pulses that are much shorter than those of actively mode-locked systems because the depth of modulation of the mode-locking element can be much larger in passive than in active mode locking.

Until recently, the design of passively mode-locked systems has been hampered by the absence of an analytic theory of passive mode locking. Development of this theory[1,2] permits determination of the parameters required for successful passive mode locking. The predicted pulse shapes have been verified experimentally.[3,4] We have attained further verification of this theory with the use of a system that had not previously been passively mode locked and that affords precise experimental determination of its parameters. A microwave system composed of an avalanche diode operating at 10 GHz as the active "medium" and a Schottky diode as the saturable absorber was cw mode locked successfully, with the time constants of the system chosen according to the theory.

The microwave system is of interest in its own right as a generator of nanosecond pulses. It is also of interest to laser mode locking because it provides a test system for novel methods of mode locking, and, in particular, since it permits an adjustment of experimental parameters over a wider range than is possible with any particular laser system.

We are planning to study the combined action of passive and active mode locking on the microwave system, and, using the microwave system as a prototype, we shall explore the potential for fast switching of laser devices.

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2. PICOSECOND PULSES FROM SEMICONDUCTOR LASERS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Clifton G. Fonstad, Jr., Hermann A. Haus

Mode-locked dye lasers have produced subpicosecond pulses with relaxation times of laser and absorber dyes in the nanosecond range.[1] It has been shown that this surprising result hinges on a careful balance between the saturation characteristics of the laser and the absorber.[2,3]

Semiconductor lasers generally have relaxation times of the order of nanoseconds, and hence are candidates for mode locking in configurations approximating dye laser systems.

Short pulses have been observed from semiconductor laser diodes.[4] The reproducibility of these pulses has been unsatisfactory. We hope that with the development of a better theory for passive mode locking a more methodical approach to the design of the mode-locking system will yield better results. Our approach is experimental and theoretical. In the first stage of our work we studied the spectra of commercial GaAs diodes to anticipate the potential for locking of modes in the spectrum in an external cavity. We shall attempt mode locking of a GaAs diode and a GaAs saturable absorber in an external cavity, with proper antireflection coating of one of the diode faces. This configuration corresponds closely to the dye laser mode-locking configuration.

In the theoretical approach we shall attempt a closed-form analysis of saturable absorber mode locking in a distributed system such as that in a physically "short" system realized by a segmented diode, with one segment playing the role of the laser and the other that of the absorber (with no external cavity). We shall try to develop design criteria for successful mode locking of such a distributed system.

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VII. QUANTUM ELECTRONICS

C. Distributed Feedback Structures

Academic Research Staff

Prof. Hermann A. Haus
Prof. Clifton G. Fonstad, Jr.

Graduate Students

Seihee Kim
Karl L. Wang

1. FREQUENCY-STABLE, LOW-THRESHOLD INJECTION LASERS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Clifton G. Fonstad, Jr., Hermann A. Haus

The distributed feedback (DFB) laser gets its feedback from reflection off a spatially periodic variation of index or gain.[1] The usual uniform periodic structure exhibits a threshold degeneracy: modes of equal threshold occur on either side of the Bragg frequency.

A system incorporating two uniform periodic structures, with a $\lambda/4$ (or $(2n+1)\ \lambda/4$) phase-shifting section between them, has a low threshold for one single mode at the Bragg frequency, and hence the threshold degeneracy is removed.[2] We shall investigate theoretically and experimentally the potential of these new structures.

It has been found that uniform periodic structures such as a grating of finite width etched into the surface of a guiding layer provide transverse confinement of the electromagnetic field near the Bragg frequency, thereby confining the field underneath the grating.[3] This property may obviate the need for an optical waveguide structure to confine the field underneath the grating. Modes of such grating structures will be investigated.

Grating structures have been fabricated in quartz with a periodicity of 7500 Å that corresponds to third-harmonic coupling at 5000 Å. The grating will be used with a dye-doped polyurethane layer to provide the lasing medium.

Success in manufacturing laser structures that incorporate the quarter-wave step may point the way toward novel tunable passband filters. If the phase shift in the "quarter-wave" section is changed (say, electro-optically by an applied electric field), the transmission frequency of the structure will be shifted. A theoretical investigation of the potential of this tunable filter design will be made.

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