VIII. QUANTUM ELECTRONICS

A. Laser Applications

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1. PRECISION MEASUREMENTS OF ATOMIC LEVEL SPLITTING AND LEVEL SHIFTS IN INTENSE OPTICAL FIELDS

National Science Foundation (Grant PHY77-07156)

Shaoul Ezekiel, Frederick Y. Wu, Philip R. Hemmer

We have performed high precision measurements of level splitting and level shifts of an excited atomic state in the presence of an intense optical field.[1] Such measurements are important to the understanding of the details of atom-field interaction and in the development of high precision optical clocks. The level we studied is an isolated single magnetic sublevel $3\ ^2P_{3/2}$ ($F = 3$, $m_F = 3$) in sodium when subjected to a strong laser field coupling this level and the $3\ ^2S_{1/2}$ ($F = 2$, $m_F = 2$) level in the ground state. Doppler and collisional broadening were eliminated by employing atomic beam techniques.

The experimental arrangement has a highly collimated sodium atomic beam prepared in one magnetic sublevel $m_F = 2$ in the $3\ ^2S_{1/2}$ ($F = 2$) ground state. The prepared sodium atoms are subjected simultaneously to two collinear but counterpropagating laser fields, aligned perpendicular to the atomic beam. One laser field at 5890 Å, the driving field, is circularly polarized and fixed in frequency either on-resonance or off-resonance with $3\ ^2S_{1/2}$ ($F=2$)-$3\ ^2P_{3/2}$ ($F = 3$) transition. Since the light is circularly polarized, the only allowed $\Delta m = +1$ transition is to the $m_F = 3$ sublevel in the excited $3\ ^2P_{3/2}$ ($F = 3$) state.[2] The second laser field at 5688 Å is tunable and is used to probe the $3\ ^2P_{3/2}$ ($F = 3$, $m_F = 3$) sublevel by inducing transitions to a higher level $4\ ^2D_{5/2}$ ($F = 4$, $m_F = 4$). The fluorescence from the $4\ ^2D_{5/2}$ ($F = 4$) state to the $3\ ^2P_{3/2}$ ($F = 3$) state is detected and used as a measure of probe field absorption.

With a weak on-resonance driving field and a weak probe field, the observed linewidth of the probed transition was very close to the natural width (3.3 MHz) of the $4\ ^2D_{5/2}$ ($F = 4$) upper level even though the natural width of the $3\ ^2P_{3/2}$ ($F = 3$) lower level is 10 MHz. The measured line shape was compared directly with a theoretical line shape based on calculations by Mollow[3] and the agreement was excellent.

With a stronger field, the probed transition became broader and for driving field intensities greater than 100 mW/cm^2 the splitting of the 3 $^2P_{3/2}$ (F = 3) level due to the ac Stark effect became very noticeable. The splitting consisted of two symmetrical components having equal heights and the separation between them is the Rabi nutation frequency $\Omega_R = \frac{\mu \cdot E}{h}$. The measured line shapes for different driving field intensities were found to be in very good agreement with theoretical calculations[3] which predict that the 3 $^2P_{3/2}$ (F = 3) level splits symmetrically about its unperturbed value.

With the driving field set off-resonance by a known detuning $\Delta\omega$, the splitting was asymmetric with respect to the unperturbed level. In this case, the separation between the split components is the effective Rabi frequency $\Omega'_R = \sqrt{\Omega_R^2 + \Delta\omega^2}$, the smaller component is shifted by $\delta\omega = \frac{1}{4}\left(\frac{\mu E}{h}\right)^2 \frac{1}{\Delta\omega}$ from the unperturbed level and the larger component is shifted by $\Omega' - \delta\omega$ in the opposite direction. The sign of the level shift depends on the sign of the detuning of the driving field. Again the data were in very good agreement with theory.[3]

We should point out that in the case of strong on-resonance driving field the shift in the frequency of the 3 $^2S_{1/2}$-3 $^2P_{3/2}$ transition due to atomic recoil became more and more substantial as the atom propagated across the laser field. To overcome such a detuning effect it was necessary to compensate for recoil shift as discussed elsewhere.[4]

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2. ATOMIC ABSORPTION LINE SHAPE IN THE PRESENCE OF A STRONG FIELD

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

Shaoul Ezekiel, Frederick Y. Wu

The simple Lorentzian absorption spectrum of a two-level system, as measured by a nonsaturating, tunable probe field, is greatly modified by the presence of a strong, near-resonant, fixed-frequency field.[1-5] Previous experiments with RF[6] and millimeterwave radiation[7] have given evidence of probe amplification by the saturated two-level system. The experiment described here is designed to measure the absorption spectrum, as it is altered by the strong field.[8]

In this measurement, prepared two-level sodium atoms[8] interact simultaneously with a "driving field" and a "probe beam." The driving field is fixed at or near resonance and can be made very intense, while the probe beam strength is kept well below saturation. The probe beam is tuned across the resonance frequency and its absorption recorded. The probe beam is focused to approximately one-tenth the diameter of the driving field at the interaction region so that only atoms in a uniform field region are probed.

When the driving field at frequency ω is exactly resonant and very intense, peak absorption is greatly reduced compared with its unsaturated value. At frequencies differing from resonance (ω_o) by less than the Rabi frequency Ω, the probe is amplified, but all spectral features are very small. However, when the driving field is detuned above resonance, the spectrum has one large absorption peak at ω_o' shifted down from the original resonance frequency, and one large gain peak at $2\omega - \omega_o'$. The shift $\omega_o' - \omega$ is known as the "light shift" and is caused by the strong, nonresonant field.[9]

With an atomic beam density which gives 9.4% absorption in the absence of a driving field, the measured peak amplification is 0.7%. This agrees with calculations,[5] which predict that in the limit of high intensities the peak gain occurs when the detuning $\Delta\omega$ is equal to $\Omega/3$, and is 5% of the probe field absorption in the absence of the saturating field.

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3. FREQUENCY STABILIZATION OF A CONTINUOUS-WAVE DYE LASER

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

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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.

We have stabilized the frequency of a commercially available cw dye laser (Spectra-Physics Model 580A) for use in our experiments on the interaction of intense monochromatic radiation with atoms. The stabilization scheme required only a small modification of the laser cavity.

The free-running jitter of the laser is approximately 15 MHz and this was reduced to 20 kHz by inserting an electro-optic phase modulator inside the laser cavity. The E-O crystal enabled us to lock the laser frequency to an external Fabry-Perot interferometer with a servo bandwidth of over 1 MHz.

Two such lasers were stabilized and measurement of laser jitter was accomplished by beating the two lasers. As further evidence of the narrow laser linewidth, we performed high-resolution absorption spectroscopy of I_2 and Na in an atomic beam. In the case of I_2, the linewidth of individual hyperfine structure transitions was 800 kHz which included a natural width of 450 kHz and residual Doppler broadening due to beam geometry of approximately 400 kHz.

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4. PASSIVE RING RESONATOR LASER GYROSCOPE

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

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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.

To determine the feasibility of this new optical gyroscope, a passive cavity made from solid aluminum, measuring 17.5 cm on a side, was constructed.[1] The corners of the cavity were terminated with two flat and two curved mirrors and one of the cavity mirrors was mounted on a piezoelectric transducer. The output from a linearly polarized 1-mW single frequency He-Ne laser (f_0) was split into two beams, each of which was upshifted by an acousto-optic crystal and then coupled into the cavity. The acousto-optic crystals were driven by two stable and independent voltage-controlled oscillators (f_1 and f_2) operating around 40 MHz.

The cw cavity resonance was locked to $f_0 + f_1$ and f_2 was adjusted by a second feedback loop so that $f_0 + f_2$ was held at the resonance frequency of the ccw cavity.

The entire setup was rotated on a turntable. The data, rotation rate vs ($f_1 - f_2$), were linear and free from any lock-in effects. The bias drift was also investigated by monitoring ($f_1 - f_2$) with the turntable stationary. No noticeable monotonic drift was detected in a time interval of one hour. The rms fluctuation in the output for $\tau = 1$ s corresponded to a rotation rate of 0.5 degree per hour which is close to shot-noise-limited detection in our present setup.

Another scheme under investigation uses a passive ring with an intracavity Faraday cell.[2] The possibility of a fiber optic ring is also being considered.

Aside from applications to navagation, we propose to examine the possibility of measuring earth rotation to better than one part in 10^8, using a cavity, 3 m on a side, and a 3-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.

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5. NEW TECHNIQUE FOR HIGH-SENSITIVITY AND HIGH-RESOLUTION SPECTROSCOPY

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

Shaoul Ezekiel, Richard P. Hackel, Jordin T. Kare

The measurement of absorption in a gas cell can be made more sensitive by two to three orders of magnitude if the cell is placed within a high Q cavity. It can easily be shown that for a weak absorber in a cavity, the enhancement factor is approximately $1/1-R$ where R is the reflectivity of the input and output coupling mirrors. This increase in sensitivity is essentially caused by the multipass property of the cavity.

If the gas cell is placed within a ring rather than in a linear two-mirror cavity, it becomes possible to subject the gas to two independently controlled counterpropagating beams. In this way, it is possible to perform high-resolution saturated absorption[1] and saturated dispersion[2] spectroscopy without the Doppler background with an increase in sensitivity of $1/1-R$ over the single-pass case. Moreover, this enhancement is also applicable to two-photon[3] and polarization spectroscopy.[4]

Passive ring cavities with counterpropagating excitation have been investigated recently for the measurement of inertial rotation[5] based on the Sagnac effect. The techniques developed in those studies are very applicable to the spectroscopic schemes we have outlined. Since the two counterpropagating beams are physically separate outside the ring cavity, it is convenient to select the intensity, the modulation, the polarization, and so on of the individual beams. Under optimum conditions, the minimum linear absorption that can be measured in a cavity is approximately $(1-R)/\sqrt{N\eta\tau}$, where N is the number of photons transmitted through the cavity, η is the detector quantum efficiency, and τ is the integration time. Similar expressions can be derived for saturation or nonlinear applications.

We have conducted a preliminary experiment using a single-frequency argon ion laser at 5145 Å and an I_2 vapor cell in a ring cavity. In this experiment the I_2 cell was subjected simultaneously to a weak and a strong counterpropagating beams. The strong beam was modulated by an electro-optic intensity modulator before entering the cavity and the portion of the weak beam that is transmitted through the cavity is synchronously demodulated in a lock-in amplifier as the laser frequency is tuned over the I_2 absorption. (The resonance frequency of the ring cavity is locked to the laser frequency by means of a conventional frequency-stabilization scheme[5] so that the cavity resonance always tracks the laser frequency.) The data show a number of I_2 hyperfine structure transitions with a zero-slope background. The linewidth of the individual lines is 350 kHz at low I_2 pressure. The observed linewidth is at present limited by transit time effects across the laser beam within the cavity.

We are now considering this spectroscopic technique for the detection of very small gas concentrations and for setting an upper limit on parity violation in atomic systems.[6]

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6. 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, Stephan C. Goldstein

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.

So far we have been stabilizing multiwatt[1] cw argon ion lasers (Spectra-Physics Model 170). We have succeeded in reducing the laser jitter to approximately 10 kHz using an intracavity electro-optic phase modulator and a wideband feedback loop, and employing a high finesse Fabry-Perot interferometer as a reference. For long-term stabilization the resonance frequency of the reference cavity was locked to a hyperfine transition in $^{127}I_2$ observed in a molecular beam. A stability of 7 parts in 10^{14} was achieved in an integration time of 1000 seconds. The reproducibility of the laser frequency was also investigated and 1.5 parts in 10^{12} was achieved.

Recently, we have improved the low-frequency performance of the wideband feedback loop. This resulted in a reduction of the laser jitter to less than 1 kHz for observation times longer than 10^{-4} seconds.

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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7. NONRECIPROCAL PHASE SHIFTS IN OPTICAL FIBERS

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M. I. T. Sloan Fund for Basic Research

Shaoul Ezekiel, James L. Davis

Recently, there has been considerable interest in the use of optical fibers for precision measurement applications such as inertial rotation sensing by means of a Sagnac fiber interferometer,[1] an active fiber ring laser or a Sagnac passive fiber cavity.[2] Other applications include remote current measurement in high-voltage cables. In all these applications, phase changes in the fiber as a function of time or fiber environment must be very small, depending on the particular application. In the case of a Sagnac gyroscope-type application, nonreciprocal phase shifts along the fiber must be much smaller than 10^{-7} radian.

We plan to conduct several very basic experiments to measure nonreciprocal phase shift in a single-mode low-loss optical fiber. A Sagnac-type interferometer will be used to detect nonreciprocal phase shift under a variety of conditions. We plan to examine the case with the two counterpropagating beams having the same linear polarization and the case with the beams having orthogonal polarization.

If the results are encouraging, we shall design a large-area multiturn Sagnac interferometer for geophysics relativity-type applications.

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B. Nonlinear Phenomena

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1. PICOSECOND PULSES FROM SEMICONDUCTOR LASERS

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

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Mode-locked dye lasers have produced subpicosecond pulses,[1,2] even though the relaxation times of the laser and absorber dye are much longer than a picosecond. The achievement of short pulses has been shown to hinge on a careful balance of the absorber and laser characteristics.[3] It appears that similar conditions may be achieved in configurations employing semiconductor diodes as the active and absorbing media.

Saturable absorber mode locking of semiconductor diodes encounters difficulties of its own. There is the dispersion of the lasing medium, the power obtainable from cw diodes is relatively small and it is difficult to couple radiation into and out of the diode if an external resonator is used. Short pulses have been observed from semiconductor laser diodes.[4] The reproducibility of these pulses has been unsatisfactory. Within the years following these experiments advances in both semiconductor diode technology and the theoretical understanding of saturable absorber mode locking[3,5] encouraged renewed attempts at mode locking of semiconductor lasers with the goal of achieving compact short-pulse, generating systems.

In order to overcome the difficulties one at a time, microwave mode locking of an A.R. coated GaAlAs/GaAs double heterojunction laser in an external resonator has been initiated, with the mode-locking modulation at 3 GHz. The signal-to-noise ratio of the two-photon fluorescence detection system is not, as yet, sufficient to measure pulses directly, yet observation of the detected modulation of the optical signal, on a microwave spectrum analyzer showed up to 20 dB enhancement of the microwave signal as the modulation frequency was tuned into coincidence with the mode separation frequency $c/2\ell$.

A new support structure of the diode will permit substantially larger amounts of optical power to be sampled from the cleaved back face of the diode so as to measure the pulses directly by two-photon fluorescence. In the coming year the active microwave mode locking of GaAlAs/GaAs laser diodes will be pursued further to ascertain the potential of this method for short-pulse generation with semiconductor lasers.

A microwave analog of a passively mode-locked laser system was constructed and successfully operated[6] at 10 GHz. An IMPATT diode was used as the amplifier, a Schottky diode as the absorber. The system permitted an experimental investigation of combined passive and active mode locking. For this purpose, the Schottky diode was driven by a "synchronizing" signal. A theory of combined passive and active mode locking was developed which incorporates the timing jitter produced by noise perturbations.[7]

Another approach to the mode-locking problem is being taken by utilizing the relaxation oscillations observed in double-section diodes[8] to provide the basic instability initiating the laser pulsing. Feedback at the period of the relaxation oscillation will be provided by placing the diode in an external resonator. Whereas the pulse duration of the relaxation oscillation depends upon the buildup time of the laser oscillation from noise, the pulse duration of the system with feedback is limited only by the unavoidable gain and index dispersion of the laser medium.

Quaternary compound GaInAsP/InP laser double heterostructures[9] with sectioned electrodes are being constructed by graduate student L. Glasser at the Lincoln Laboratory to explore the relaxation oscillation phenomenon on these novel diodes. They will be incorporated in the external cavity design now employed for active mode locking to accomplish the pulse shortening by feedback.

In the coming year we shall investigate further the mode properties of the quaternary diode structures with the aim of accomplishing the short-pulse generation using the relaxation oscillations as the pulse-forming instability.

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C. Distributed Feedback Structures

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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 periodic variation of refraction, or of gain.[1] Because this variation occurs on a scale comparable to a wavelength the mode selectivity of the DFB laser is much better than that of a conventional Fabry-Perot laser. However, the usual uniform periodic structure employed in a conventional DFB laser exhibits a threshold degeneracy – two modes of equal threshold occur on either side of the Bragg frequency – and the structure is, in fact, not optimized for single-mode operation.

A DFB structure with two uniform periodic sections, and a $\lambda/4$ (or $[2n+1]\lambda/4$) phase-shifting section between them, has a lowest threshold for one single mode located at the Bragg frequency, and hence the threshold degeneracy is removed.[2]

We are involved in experimental and theoretical programs to investigate the use of these structures in lasers and as passive filters at optical wavelengths. Initially, first-order gratings at 5000 Å ($\approx$1700 Å period) are being produced in glass substrates. Thin-film waveguides are then being sputtered on these gratings. We are assembling a dye laser for use as a probe with which we will measure the reflection spectrum of the guides, that is, of the DFB gratings. Once the uniformly periodic structures have been characterized, a phase shift will be introduced and its effects studied.

We are also studying the use of an intermediate section with variable phase shift. Such a structure would appear to offer a certain amount of tunability of the filter, or in a laser, of the emission wavelength.

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2. GRATING WAVEGUIDES

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

Hermann A. Haus

The work on distributed feedback structures has stimulated interest in wave propagation in structures with periodic perturbations, in particular, when the transverse dimensions of the structure influence the mode structure. Whereas no such effects have been observed as yet on optical structures, surface acoustic wave (SAW) devices have exhibited mode structures[1] that are attributable to the guidance of waves by reflection off the grating boundaries. The modes of such systems exhibit unusual dispersion characteristics[2,3] that are not encountered in the analysis of simple slow-wave structures because the coupling of forward and backward waves by the grating structure leads to four transverse wave solutions within the grating structure rather than the customary solutions for two waves.

Another aspect of grating structures that promises important applications for optical systems is their use as optical filters. The technology has not yet been developed to control the grating spacings to required tolerances. In the SAW field such tolerances can be met, and promising filter designs[4] have already been realized.

We intend to pursue further the theory of grating structures as it relates to their potential use as guiding structures, to obviate the need for transverse confinement of the optical wave in a thin film.

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