VIII. QUANTUM ELECTRONICS

A. Laser Applications

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1. DOPPLER-FREE STIMULATED EMISSION SPECTROSCOPY AND SECONDARY-FREQUENCY STANDARDS USING AN OPTICALLY PUMPED LASER

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Stephan C. Goldstein

We have developed, in collaboration with R.W. Field and J.B. Koffend, a new Doppler-free stimulated emission spectroscopic technique using a cw optically pumped laser (OPL). The molecule under study forms the gain medium of the OPL. The technique can also be used to generate a set of laser-frequency standards covering a substantial spectral range. We have demonstrated this technique by observing narrow hyperfine structure features in an I_2 OPL with linewidths of less than 1 MHz. This allowed us to perform high-resolution spectroscopic measurements of the complete hyperfine structure of several rotational-vibrational levels in the ground electronic state of I_2. The data was fitted to obtain values for the nuclear electric quadrupole coupling constant (eQq") and the nuclear spin-rotation coupling constant (C") for v" from 0 to 83. The observed variation in eQq" may be due mainly to the spin-orbit interaction of the $X'\Sigma_g^+$ state with the O_g^+ state, both of which share the common ${}^3P_{3/2} + {}^2P_{3/2}$ dissociation limit. The observed nonzero values for C" are due to the perturbation of the $X'\Sigma_g^+$ state by the 1g component of the ${}^3\Pi_g$ state which dissociates into two ${}^2P_{3/2}$ iodine atoms.

In addition, the I_2 OPL laser has been actively stabilized to one of the narrow I_2 hyperfine components within 1 kHz.

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2. OBSERVATION OF NON-LORENTZIAN ABSORPTION LINE SHAPE OF A STRONGLY DRIVEN TWO-LEVEL ATOM

National Science Foundation (Grant PHY77-07156)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

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

We have conducted careful measurements of the power-broadened absorption line shape of a two-level atom in an atomic beam as a function of the intensity of the monochromatic driving field. The results showed that at low driving-field intensities, the absorption line shape was indeed Lorentzian, as expected. However, the line shape became skewed as the field intensity became much larger than the saturation intensity. This departure from Lorentzian line shape is due to atomic recoil. By allowing for atomic recoil we were able to obtain a very good fit to the observed line shape.

Our experiments were conducted on an atomic beam of Na prepared as a two-level system by optical pumping using a single-frequency σ^+-polarized cw dye laser locked to the $3\ ^2S_{1/2}$ (F=2) - $3\ ^2P_{3/2}$ (F=3) transition as described elsewhere.[1] A second dye laser, also σ^+-polarized, is made to interact with the two-level atoms farther down the atomic beam, and the resulting fluorescence is monitored as a function of laser frequency. This line-shape measurement was repeated for different laser intensities. To ensure uniformity of the laser intensity in the interaction region, the fluorescence detected was limited to that emitted from a small central area of the interaction region.

References

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3. OBSERVATION OF SUBNATURAL LINEWIDTHS USING TWO-STEP RESONANT SCATTERING IN I_2 VAPOR

National Science Foundation (Grant PHY77-07156)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Richard P. Hackel

We have observed linewidths narrower than the natural width using a two-step resonant scattering scheme in a folded configuration in I_2 vapor. The measured width of the lines at 5828 Å is 80 kHz, with the major contributions to the width stemming from instrumental broadening mechanisms and laser jitter in our present setup. These extremely sharp lines which, to our knowledge, are the narrowest recorded in the visible region of the spectrum,[1] have a number of important applications. In addition to

Doppler-free stimulated emission spectroscopy of thermally unpopulated levels, these narrow resonances can be used as unique high-resolution probes for the study of collisional effects on specific energy levels and as reference lines for laser-frequency standards. It should also be noted that because these reference lines, whether in atoms or molecules, can be very sharp, the frequency difference between pump and probe (or between two probes using a common pump) may be established extremely accurately. This suggests applications to spectroscopy and frequency standards in the RF/microwave/FIR regions using optical lasers.

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4. MEASUREMENT OF INERTIAL ROTATION USING A PASSIVE RING RESONATOR

U. S. Air Force – Office of Scientific Research (Grant AFOSR-3042)

Shaoul Ezekiel, Glen A. Sanders, Robert P. Schloss

The drift performance of an optical rotation sensor employing a passive ring resonator has been investigated. With a square cavity, 17 cm on a side, and a 1-mW external laser, the rms flucutation in the measurement of rotation was 0.45°/hour for an integration time of 1 second.[1] This is consistent with shot-noise-limited performance expected for the present setup. Recently we have constructed a larger resonator, 70 cm on a side, using discretely mounted components. The resonator linewidth is 200 kHz and preliminary results have demonstrated an rms drift fluctuation of about 0.15°/hour for an integration time of 1 second which is at least an order of magnitude larger than the shot-noise limit for this configuration. A thorough experimental as well as theoretical investigation of error sources is in progress.

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5. MEASUREMENT OF INERTIAL ROTATION USING A MULTITURN FIBEROPTIC SAGNAC INTERFEROMETER

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, James L. Davis

Currently there is considerable interest in using a multiturn fiber Sagnac interferometer for the measurement of inertial rotation. Such a measurement is difficult to perform because the nonreciprocal phase shift (NRPS) induced in the fiber by inertial rotation is very small. For a rotation rate Ω, the NRPS $\Delta\phi$ is given by

$$\Delta\phi \approx \frac{8\pi NA}{\lambda_o c}\,\Omega, \tag{1}$$

where $\Delta\phi = \phi_{cw} - \phi_{ccw}$ is the difference between clockwise (cw) and counterclockwise (ccw) phase shifts in the fiber, A is the area enclosed by the fiber loop, N is the number of turns, λ_o is the vacuum wavelength of the light source, and c is the velocity of light. For example, if $\Omega = 7.3 \times 10^{-5}$ rad/sec (i.e., earth rotation, Ω_E), N = 1000 turns, $A = 100\ cm^2$, and $\lambda_o = 0.6328\ \mu$, the NRPS is $\Delta\phi \approx 1.0 \times 10^{-4}$ radian. Similarly, if $\Omega = 7.3 \times 10^{-8}$ rad/sec or $10^{-3}\ \Omega_E$, then $\Delta\phi \approx 1.0 \times 10^{-7}$ radian.

We are investigating several approaches[1] to the measurement of nonreciprocal phase shift. In particular, we are examining a scheme in which different optical frequencies propagate along the clockwise and counterclockwise directions by means of acousto-optic shifters. In this way, we have achieved a nonreciprocal phase shift modulation of $\pm\pi/2$ at a rate sufficiently high for shot-noise-limited performance. In addition, this 2-frequency scheme is also used to lock the frequency difference so that operation is always at the center of the zero fringe to avoid errors due to laser intensity fluctuations. Thus, the frequency difference of the counterpropagating beams is directly proportional to rotation-induced nonreciprocal phase shift.

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6. AC STARK EFFECT IN A DOPPLER-BROADENED THREE-LEVEL SYSTEM

National Science Foundation (Grant PHY77-07156)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Richard P. Hackel

We are performing experiments extending our investigations of the ac Stark effect in an atomic beam to a gas cell where Doppler broadening and also collisions must be considered. The experiments so far are being performed with molecular iodine in a temperature-controlled vapor cell. The pump beam in this case is a single-frequency argon ion laser at 5145 Å interacting with the $B^3\Pi_{0^+u}$ (v' = 43, J' = 12) ← $X'\Sigma_g^+$(v" = 0, J' = 13) Doppler-broadened transition in I_2. The probe is a single-frequency dye laser tuned to the $B^3\Pi_{0^+u}$ (v' = 43, J' = 12) ← $X'\Sigma_g^+$(v" = 9, J" = 13) transition. In this way, we have a folded three-level system. The lower level of the probe transition is metastable because I_2 is homonuclear. The pump and probe beams are collinear and ac Stark-effect measurements are made for both co- and counterpropagating probe beams. The absorption/gain of the probe is measured by chopping the pump beam and synchronously detecting the probe beam. The data so far appear to be in disagreement with existing calculations.

7. MEASUREMENT OF NATURAL WIDTHS IN I_2 HYPERFINE STRUCTURE: A TEST OF HYPERFINE PREDISSOCIATION

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Robert E. Tench

We are performing high-resolution studies of hyperfine structure associated with the P(13) (0-43) transition in I_2. The primary aim is to measure the natural width of individual hyperfine components so as to separate out the radiative decay contributions to the linewidth from those due to natural and magnetic predissociation of the iodine $B^3\Pi_{o^+u}$ state. Since we have to measure widths ranging from 45 kHz to 150 kHz at about 5145 Å, we have constructed a high-resolution saturated-absorption spectrometer using stabilized argon-ion lasers. This spectrometer will also be used for studying the interaction of I_2 with intense monochromatic radiation in the presence of Doppler broadening.

B. Nonlinear Phenomena

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1. PICOSECOND PULSES FROM SEMICONDUCTOR LASERS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Clifton G. Fonstad, Hermann A. Haus

The capability of lasers to produce picosecond pulses has not been exploited by communications technology, because no compact sources of picosecond pulses are available. Laser diodes are the obvious active component for such applications, yet they have not been successfully mode-locked.

We have initiated a program for the development of sources of picosecond pulses utilizing laser diodes. A year ago we reported our first attempts at mode locking of a GaAlAs laser diode operating at 8100 Å in an external resonator by microwave modulation of the bias current. At that time we determined the effect of the modulation on the microwave spectrum of the detected optical output and found evidence of mode locking in the change of the spectrum. In the meantime, the cw train of pulses has been measured by second-harmonic generation. The pulses were as short as 23 psec at a rate of 3 GHz.[1] InGaAsP diodes operating at 1.2 and 1.3 μ, respectively, have been mode-locked.[2] The shortest pulses obtained from the 1.2-μ device were 18 psec, at a 2-GHz repetition rate.

We do not know as yet the ultimate limits on the achievable pulse lengths. Dispersion of the diode material should play a role only when pulses of the order of 1 psec are achieved.[3] We have shown[4] that the spontaneous emission significantly affects the mode locking. Further, we have observed that the free-running diodes invariably self-pulsed without an applied microwave drive, emitting pulses of the order of three times longer than those achieved with the forced mode-locking drive.[2] Future work will be concerned with the following issues:

1. Design of external resonators with flexibility for length and bandwidth adjustments. Optimization of mode-locked pulses by adjustment of these parameters.

2. Pinpointing of the mechanism of self-locking.
3. Combination of forced- and saturable-absorber mode locking, using one diode as the laser and one as the saturable absorber.
4. Exploration of means of miniaturization of the external resonator through replacement by an optical waveguide.
5. Design of broadband multiplexers and demultiplexers for the generation of 20-Gbit pulse trains.

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4. H.A. Haus and P.-T. Ho, "Effect of Noise on Active Modelocking of a Diode Laser," submitted for publication in IEEE Journal of Quantum Electronics, 1979.

C. Distributed Feedback Structures

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1. SURFACE ACOUSTIC WAVE GRATING RESONATOR MODES

National Science Foundation (Grant ENG77-24981)

Hermann A. Haus

The impetus for our research in grating resonators derives from their potential use in integrated optics. Present-day technology is not yet at a stage where gratings with periods of the order of 2000 Å can be easily manufactured so that ideas developed for grating resonator-filter design have to be tested in their SAW realization.

The potential of SAW filter design using grating structures is great in its own right, and problems peculiar to SAW devices have to be overcome. One of these problems is the spurious response of higher order grating resonator modes.[1]

We have launched an investigation of grating waveguide modes[2] which were shown to exhibit both lower and upper cutoff frequencies.[3] Beyond the cutoff points the modes were shown to become leaky.[3] A normal mode expansion of a SAW excited by a transducer and incident upon the entry plane of a grating waveguide includes both guided modes and leaky modes – the latter contribute to the power escaping from the guide, or the SAW resonator made up of such grating guides.

As part of the investigation of Rayleigh wave loss, bulk wave scatter by grooves[4] and more recently by posts[5] have been the subject of investigation. The latter results are useful in the design of post-support structures for semiconductor superstrates of SAW correlators.

In further support of SAW filter design, we are starting to investigate higher order effects in h/λ_r (where h is the groove depth and λ_r is the Rayleigh wavelength). The Bragg frequency of a SAW grating is a function of $(h/\lambda_r)^2$, and resonator design has incorporated this effect empirically. We have developed a variational principle which seems particularly suited for the theoretical study of second-order effects. One gratifying result was a very simple derivation of the grating reflection coefficient 2r which was obtained by a different and much lengthier method.[4]

We are extending the coupling-of-modes analysis with diffraction[2] to the study of mode patterns in metal-strip couplers. In spite of their importance, no analysis of the two-dimensional mode patterns underneath open-circuited metal strips exists today.

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2. TUNABLE OPTICAL-GRATING WAVEGUIDE FILTERS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Clifton G. Fonstad

We have been engaged in an effort to experimentally realize aperiodic distributed feedback, or grating waveguide, optical-wavelength filters like those proposed by Professor Hermann A. Haus,[1] and already used at acoustic frequencies to design acoustic surface-wave filters. The predicted effects have now been demonstrated at optical frequencies, and a new technique for calculating the filter characteristics of a practical structure including parasitic reflections, etc., has been developed.[2,3] The potential for applying the tunable, narrow-linewidth filters produced in electrically tunable DFB is at present being assessed.

A periodic corrugation on a waveguide surface perturbs the propagation of the normal traveling modes of the waveguide. At frequencies around the Bragg frequency (the wavelength corresponding to twice the corrugation period), reflections off each periodic disturbance interfere constructively, resulting in an intense wave in the reverse direction. This is described mathematically as a periodic coupling between the forward and reverse modes. The calculated reflection spectrum of a uniform-grating waveguide is shown in Fig. VIII-1a.

Any departure from perfect uniformity of such a periodic structure introduces new features in the reflection spectrum. For example, a phase shift at the midpoint of the structure allows the transmission of wavelengths that are reflected in the uniform

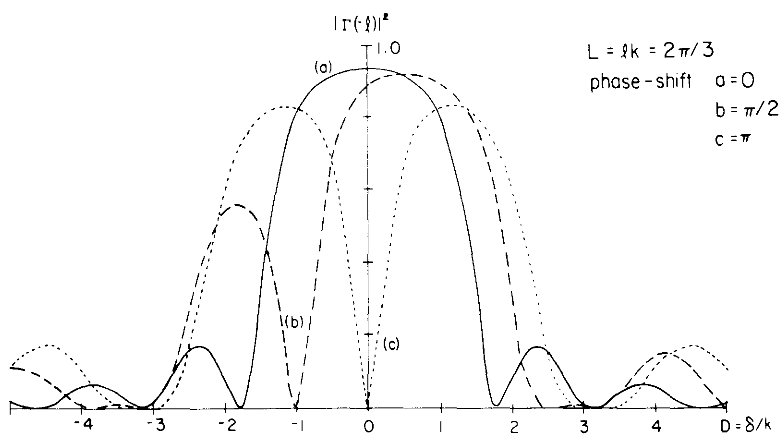

Fig. VIII-1. Reflection spectra for a waveguide with three different phase shifts. $D = (\beta - \beta_o)/k$.

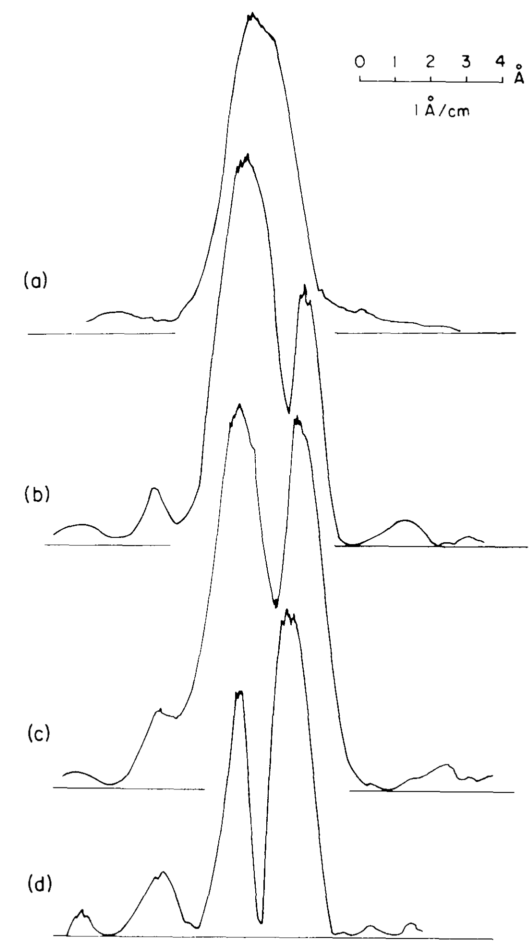

Fig. VIII-2. Three reflection spectra showing the tuning of the passband caused by gradually increasing phase shift.

structure. As illustrated in Fig. VIII-1b and 1c, this is a very narrow passband, and the position of this new passband within the normal Bragg-frequency-centered stopband is tunable by varying the magnitude of the phase shift. Such a tunable spectrum has potentially important applications as a filter, and when utilized in distributed-feedback lasers.

The above behavior can be explained by considering the structure as a Fabry-Perot cavity formed by two grating reflectors separated by a fraction of a wavelength. The new passband is then simply one of the Fabry-Perot modes. The phase shift corresponding to the separation of the two reflectors determines the position of this mode (within the broad stopband). The tuning of the mode is the consequence of the change in the mode separation due to the change in cavity length.

To obtain experimental verification of this behavior, corrugations (gratings) were produced on the surface of sputtered thin-film glass waveguides using interferometric exposure and ion-milling. A phase shift was introduced by reducing the film thickness at the center of the waveguide. This retards the beam in this region so that the beam faces the following grating section at a different phase. Reflection-spectrum measurements made on these filters using a prism coupler and specially constructed dye laser clearly demonstrate the existence and tunability of the predicted passband in optical-grating (DFB) waveguide filters (see Fig. VIII-2). The model developed also accurately fits spectra from filters containing nonuniformities and excess reflection, and provides us with a good measure of the sensitivity of the filter characteristics to practical restrictions.

The application of these concepts in electronically tunable filters and frequency-stable, low-threshold DFB laser diodes is currently under investigation.

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