# VIII. QUANTUM ELECTRONICS

## A. Laser Applications

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### 1. ULTRAHIGH-RESOLUTION SPECTROSCOPY AND FREQUENCY STANDARDS IN THE MICROWAVE AND FIR REGIONS USING OPTICAL LASERS

U.S. Air Force — Rome Air Development Center (Contract F19628-80-C-0077)

John E. Thomas, Shaoul Ezekiel

[In collaboration with C.C. Leiby, Jr., R.H. Picard, and C.R. Willis of the Air Force Rome Air Development Center.]

Recent experimental work on three-level resonance Raman transitions, induced by <u>copropagating</u> optical fields in vapors, has shown that exceedingly narrow resonances can be obtained when the initial and final levels are in long-lived electronic states.[1,2] As is well known, the linewidth is determined by the initial- and final-level decay rates, plus a contribution from the intermediate excited states, due to the Doppler averaging in gases.[1] Since the latter contribution is proportional to the initial-to-final-state transition frequency, transit-time-limited resolution in gases is obtainable <u>only</u> for very small Raman-transition frequencies.

In this program, we are considering an attractive possibility for obtaining ultrahigh resolution in the microwave and FIR regions, using optically induced Raman transitions in atomic and molecular beams. For an ideal (perfectly collimated) atomic beam, there is no Doppler averaging. Hence, with long-lived initial and final states, for sufficiently stable optical fields, laser-beam transit time will determine the limiting linewidth. By utilizing the broad tunability of existing lasers, the resonance Raman technique can be applied to study a great variety of molecules and to generate high-frequency standards in the millimeter and FIR regions.

For the cases of interest here, resolution will, in general, be limited by laser-frequency jitter and ultimately by laser-beam transit time. Since the intensity of a resonance Raman signal depends on the difference frequency of the two optical fields, the broadening due to laser jitter can be drastically reduced by generating the two optical frequencies such that both frequency jitters are correlated.[3] For inducing narrow Raman transitions in the microwave region, this is easily accomplished by deriving one frequency directly from the other using, for example, an electro-optical or acousto-optical modulator, driven by an oscillator. In this way, the excellent short-term frequency stability of microwave oscillators can be used to advantage. Extension to FIR Raman transitions can be achieved by locking two optical lasers to a common Fabry-Perot cavity, using existing wide-band stabilization techniques.

For ultrahigh-resolution spectroscopy and for clock applications, the transit-time linewidth can itself be drastically reduced by employing the method of separated oscillatory fields. By analogy to the technique originally used by Ramsey,[4] two spatially separated interaction regions are utilized as shown in Fig. VIII-1.

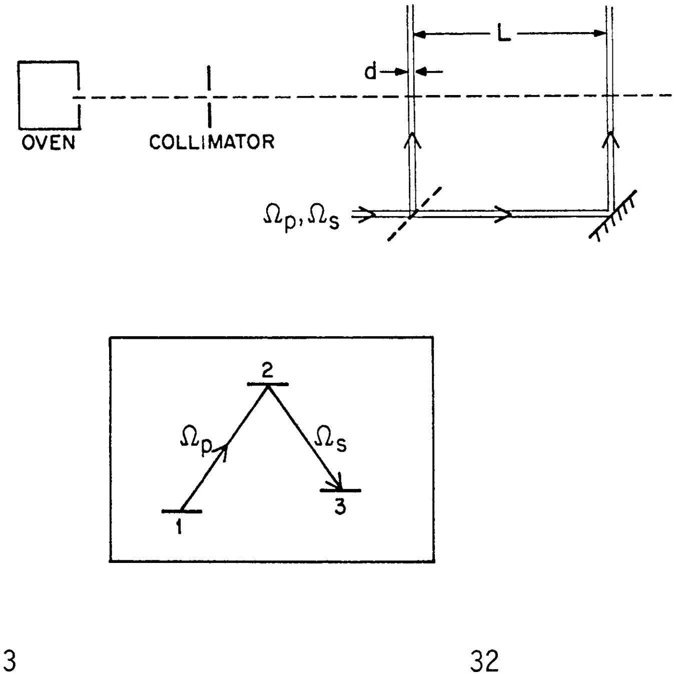

Fig. VIII-1.

In this case, the linewidth is determined by the separation between the two interaction regions, which can be made large, for long-lived initial and final states. Raman transitions are induced by replacing the two microwave regions used by Ramsey with two interaction regions each consisting of two copropagating optical fields. Although optical frequency fields are employed to induce the Raman transitions, the weak-field line shape is identical to that obtained by Ramsey, but is proportional to the product of the intensities of the two optical fields. The excited-state decay rate does not enter into the linewidth.

The Ramsey method previously has been applied to two (equal-frequency) photon[5,6] optical transitions and also to two-level systems,[7,8] and three-level systems.[9] Optical-phase averaging, which reduces the Ramsey fringe contrast, is eliminated differently in each of these experiments. As can be shown, for a general resonance Raman transition, only the difference between the optical phases enters into the fringe signal. Hence, for the cases considered here, phase averaging occurs on a distance scale of microwave or FIR wavelengths, making control of atomic beam divergence and interaction region separation relatively noncritical.

Experiments in a sodium atomic beam using these techniques are currently under way in our laboratory. In addition, a density matrix calculation of the line shape, allowing for the Gaussian intensity distribution in the laser fields as well as optical pumping, has been carried out, assuming a short-lived upper level and long-lived lower levels.[10] Effects of optically induced level shifts and laser-frequency jitter are being determined. Since the time that the atom spends in the "dark" space separating the interaction regions can be made very large compared to the time spent in the interaction regions, it should be possible to minimize such effects. Results and details of the calculations will be presented elsewhere.

## References

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3. Residual line broadening in the case where the jitter in the two lasers is correlated depends upon the jitter rate in relation to the interaction time for the Raman process. For the resonant Raman process considered here, the time scale is the short lifetime of the intermediate state.

4. N.F. Ramsey, Molecular Beams (Oxford University Press, London, 1963).
5. Ye.V. Baklanov, V.P. Chebotayev, and B.Ya. Dubetsky, Appl. Phys. 11, 201 (1976).
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9. V.P. Chebotayev and B.Ya. Dubetsky, Appl. Phys. 18, 217 (1979).
10. For a similar calculation of the line shape for resonant Raman transitions in vapors, including the Gaussian laser-field distribution, see J.E. Thomas and W.W. Quivers, Jr., Phys. Rev. A 22, 2115 (1980).

## 2. INTERACTION OF PHASE-MODULATED LASER FIELDS WITH RESONANT SYSTEMS

National Science Foundation (Grant PHY79-09739)

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and DAAG29-80-C-0104)

Mara G. Prentiss, Shaoul Ezekiel

When a phase-modulated laser field interacts with a resonant medium, the phase and amplitude relations among the field sidebands are altered. If the field is then detected and demodulated at the modulation frequency, the resulting signal contains information about the resonant medium. In the absence of the resonant medium the output of the demodulator is zero.

Consider, for example, the case where a single-frequency laser is phase-modulated at a frequency $\omega_m$ and then reflected off a square Fabry-Perot resonator. Figure VIII-2(a) shows the output as a function of cavity tuning which results when the intensity of the reflected beam is demodulated at $\omega_m$. In this case, $\omega_m \approx 10\ \Gamma$, where $\Gamma$ is the cavity linewidth. Figure VIII-2(b) is the calculated line shape for the conditions in the experiment.

As can be seen from Fig. VIII-2, the reflected line shape exhibits dispersive behavior. The central feature corresponds to the region where the cavity resonance is close to the carrier frequency; the two smaller features are associated with the sideband frequencies.

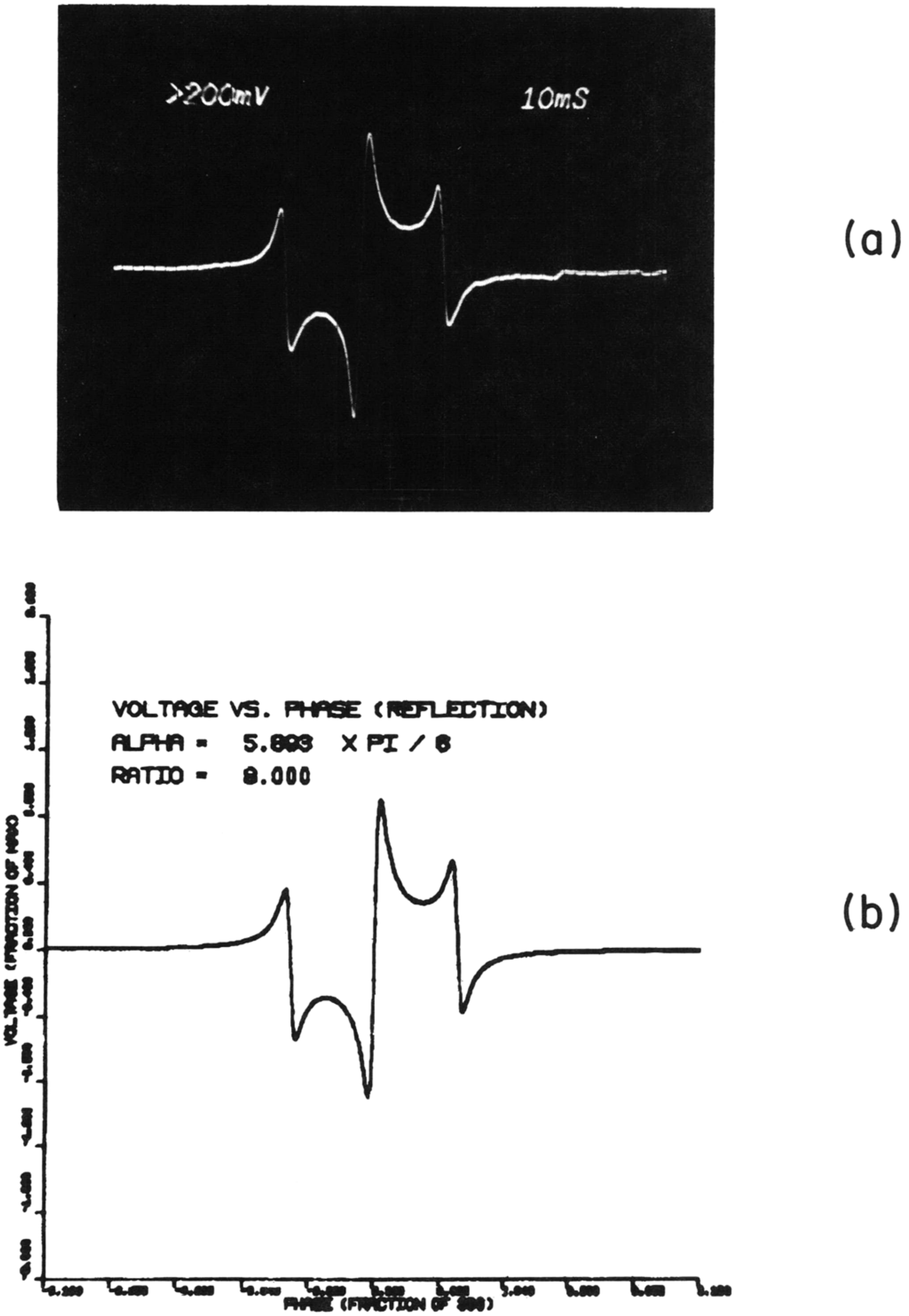>200mV
10mS
(a)
VOLTAGE VS. PHASE (REFLECTION)
ALPHA = 5.803 X PI / 6
RATIO = 8.000
VOLTAGE (FRACTION OF MAX)
PHASE (FRACTION OF 360)
(b)

Fig. VIII-2.

We are now exploring several important applications of this phase-modulation technique. One of them is the use of the derivativelike signal for fast-response laser-frequency stabilization.[1] Another particularly useful application is the locking of a laser frequency to the resonance of a large cavity, using a modulation rate that is much greater than the inverse of the cavity photon lifetime.[2]

We have also studied the use of the phase-modulation technique for Fabry-Perot cavities in transmission. Again, this has a number of applications; however, the modulation frequency in this case is limited by the cavity lifetime.

Another exciting application of phase-modulated laser fields is in absorption spectroscopy, both linear and nonlinear. This is discussed separately in section 3.

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1. R. Drever and J. Hall, International Conference on Atomic Physics, August 1980.
2. This is very important to our research program on inertial rotation measurement using large-ring cavities.

## 3. PHASE MODULATION ABSORPTION SPECTROSCOPY

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and DAAG29-80-C-0104)

Bruce W. Peuse, Mara G. Prentiss, Shaoul Ezekiel

We have developed a new sensitive technique[1] for performing absorption spectroscopy in atomic beams and gas cells. The technique, which involves the use of a phase-modulated (PM) laser, is capable of achieving photon-noise-limited detection as well as high resolution.

In order to achieve photon-noise-limited detection in a typical absorption spectrometer, it is necessary to either subtract out the laser intensity noise or stabilize the laser intensity. Although both of these schemes for eliminating laser-intensity noise are possible in practice, it is still difficult to achieve the photon-noise limit (PNL). Other alternatives for reaching the PNL include modulating the laser frequency; modulating the atomic transition by the Zeeman

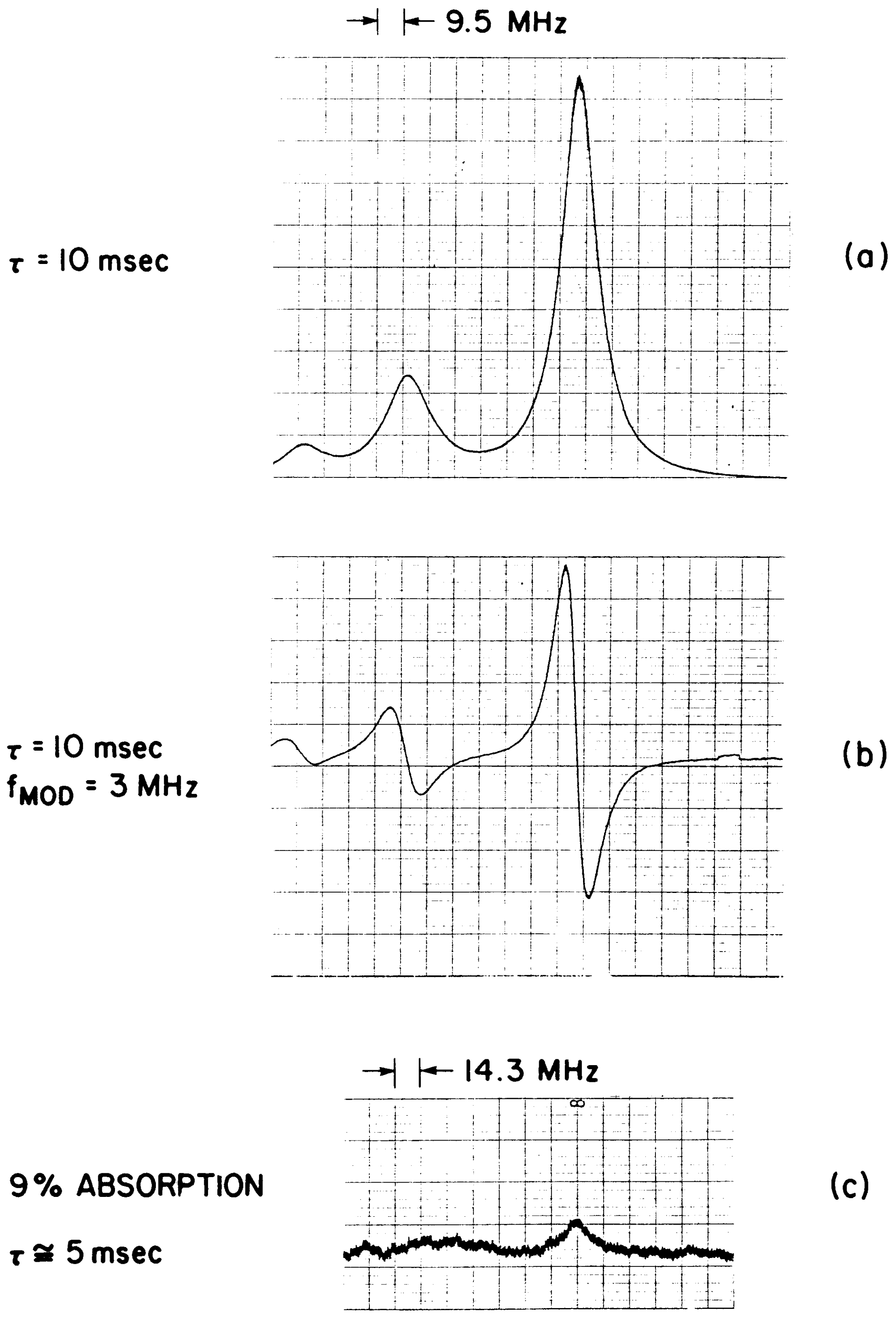
→| |← 9.5 MHz
τ = 10 msec
(a)
τ = 10 msec
f_MOD = 3 MHz
(b)
→| |← 14.3 MHz
9% ABSORPTION
τ ≅ 5 msec
(c)

Fig. VIII-3.

or Stark effect; or modulating the atomic-number density. To achieve the PNL, the modulating frequency must be sufficiently high, depending on the laser noise spectrum.

In our method, the laser is externally phase-modulated and, after passing through the atomic beam, the light is synchronously detected in a lock-in amplifier (LIA) at the modulation frequency. When there is no absorption, the output of the LIA is zero because there is no power at the modulation frequency in a phase-modulated wave. However, when one of the frequency components of the light is within the atomic resonance, it will be phase-shifted which results in power at the modulation frequency which can then be detected.

Preliminary data taken with an atomic beam of sodium for the $3\,^2S_{1/2}$ (F=2) → $3\,^2P_{3/2}$ (F=1,2,3) transitions at a modulation frequency of 3 MHz is shown in Fig. VIII-3. Figures VIII-3(a) and (b) are simultaneous outputs from a photomultiplier tube monitoring fluorescence [Fig. VIII-3(a)] and a photodetector measuring absorption in the laser using the phase-modulation technique [Fig. VIII-3(b)]. Figure VIII-3(c) shows the direct photodetector signal without the phase modulation.

It should be noted that the phase-modulation method [Fig. VIII-3(b)] has a dispersivelike line shape and a large signal-to-noise ratio comparable with that of the fluorescence signal.

PNL detection can therefore be achieved by a suitable choice of the phase-modulating frequency. The details of the phase-modulation method, particularly in regard to resolution and the dispersivelike line shape, are being studied both experimentally and theoretically.[2] The phase-modulation scheme appears to be particularly suited for absorption studies in atomic beams and low-density gas cells. In addition, we have demonstrated its use in Doppler-free saturated spectroscopy. Finally, it may be useful for remote-sensing applications.

## References

1. M. Prentiss and S. Ezekiel, "Interaction of Phase Modulated Laser Fields with Resonant Systems," RLE Progress Report No. 123, January 1980, pages 34-35.
2. The advantages of phase modulation over frequency modulation are also being studied.

## 4. STUDIES OF ATOM-FIELD INTERACTIONS IN ATOMIC BEAMS

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and DAAG29-80-C-0104)

Philip R. Hemmer, Bruce W. Peuse, John E. Thomas, Shaoul Ezekiel

As part of a continuing program in atom-field interactions in atomic beams, we are studying the effects of atomic recoil on strongly driven two-level sodium atoms. Measurements are made using two dye lasers, frequency-stabilized by locking to passive Fabry-Perot reference cavities, and a well-collimated sodium atomic beam. The details of the experimental setup have been previously described.[1] Briefly, one of the lasers provides the driving or pumping field, and is locked on resonance with the $3\ ^2S_{1/2}$ ($F=2$, $m_F=2$) → $3\ ^2P_{3/2}$ ($F=3$, $m_F=3$) transition near 5890 Å. The second laser gives the probing field and is scanned over frequencies near the $3\ ^2P_{3/2}$ ($F=3$, $m_F=3$) → $4\ ^2D_{5/2}$ ($F=4$, $m_F=4$) transition at approximately 5688 Å. Both laser beams are right-circularly polarized, insuring that only the three levels mentioned are involved in the interaction. This is shown schematically in Fig. VIII-4, where levels 1, 2, and 3 refer to the 3S, 3P, and 4D states, respectively, and the pump and probe are labeled by $\omega_p$ and $\omega_s$, respectively.

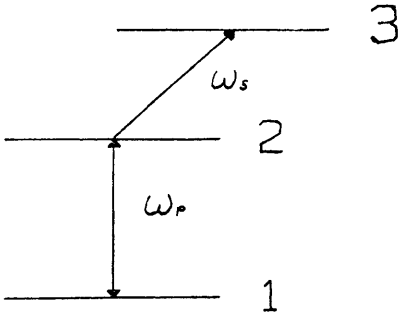

Fig. VIII-4.

Absorption of the probe is measured by monitoring fluorescence from the 4D level. The pump and probe beams are counterpropagating and perpendicular to the atomic beam. An improvement made in the original setup to provide better long-term frequency stability for the probe laser is to lock its reference cavity to that of the pump, which, in turn, has been locked to sodium. Scanning of the probe-laser frequency is accomplished using an acousto-optic shifter.

Density matrix calculations predict,[2] for low pump and probe intensities, a Lorentzian line shape for probe absorption whose FWHM is equal to the sum of the widths of the first and third levels, but completely independent of the width of the intermediate level. For our system, level 1 is a ground state with essentially zero width, level 2 has a width of 10.0 MHz, and level 3 a width of 3.1 MHz.[3] A typical low-power line shape with fitted Lorentzian is displayed in Fig. VIII-5. The fitted width is 3.25 MHz. This is well within the 10% tolerance of the predicted value. For high pump intensities, calculations predict a symmetric splitting of the absorption line shape into two peaks separated by the Rabi frequency. A typical high-power line shape is shown in Fig. VIII-6. The observed splitting is clearly asymmetric. The discrepancy can be accounted for by including in the calculations the effects of cumulative atomic recoil.

Net recoil occurs when an atom absorbs a photon from a unidirectional light beam and subsequently spontaneously emits in a random direction. On the average, when this happens, the atom recoils with the momentum of the original photon and experiences a small apparent detuning toward lower frequencies due to the Doppler effect. After a large number of such recoils, the Doppler shift can become significant. In our experiment, multiple absorptions near the $3\ ^2S_{1/2}$ ($F=2$, $m_F=2$) → $3\ ^2P_{3/2}$ ($F=3$, $m_F=3$) transition frequency can result in a large apparent detuning away from resonance and, therefore, asymmetrically split line shapes. In addition, because the number of recoils an atom undergoes depends upon the interaction time, atoms of different velocities in the beam see a different detuning. This results in a broadening of the split line shapes. The dotted curve in Fig. VIII-6 is a line shape calculated including the effects of cumulative atomic recoil and velocity distribution in the atomic beam. As can be seen, the agreement is good both in the magnitude and the sense of the asymmetry.

Future plans are to extend this study to a variety of three-level configurations. Among these are the "V", with $E_1 > E_2 < E_3$, where $E_i$ refers to the energy of a level; and the inverted "V" with $E_1 < E_2 > E_3$. Of special interest is the inverted "V" when levels 1 and 3 are both sublevels of the ground state. In this case, the low-power linewidths would be very small.

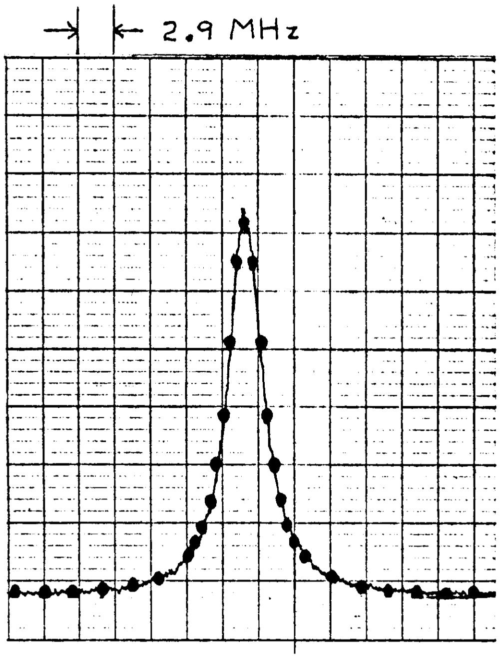

Fig. VIII-5.

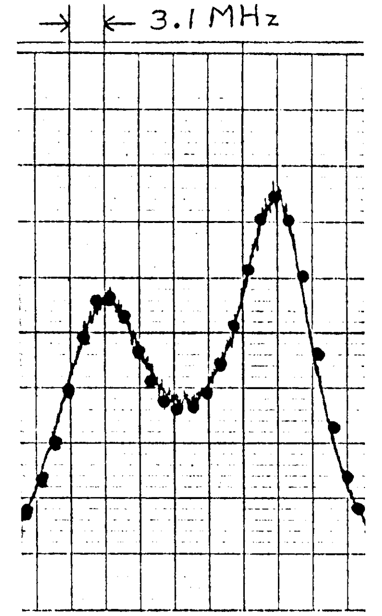

Fig. VIII-6.

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## 5. HIGH-RESOLUTION STUDIES IN FOLDED DOPPLER-BROADENED SYSTEMS

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contract DAAG29-78-C-0020 and DAAG29-80-C-0104)

Robert E. Tench, John E. Thomas, Shaoul Ezekiel

In our continuing study of the interaction of monochromatic fields with folded three-level systems, we have performed extremely high-resolution measurements of Doppler-free resonances in $I_2$ vapor. With weak copropagating pump and probe fields we have observed linewidths of 65 kHz. To our knowledge, these lines are the narrowest recorded in the optical region.[1] We have also obtained line shapes for intense pump fields and compared them with theoretical predictions.

To achieve a resolution of $1 \times 10^{-10}$ in a two-photon experiment, we found it necessary to build a highly stable spectrometer. Our system is built around a single-mode frequency-stabilized argon laser operating at 5145 Å. The laser is locked to an external Fabry-Perot cavity to reduce its spectral width to 3 kHz rms,[2] and its frequency is long-term-stabilized to an $I_2$ hyperfine resonance in a cell. Part of the argon laser radiation is shifted by an acousto-optic modulator and then passed through an electro-optic intensity modulator into a transfer Fabry-Perot cavity. This transfer cavity is locked to one of the AM sidebands of the shifted, long-term-stabilized argon laser frequency. The second laser, a single-mode dye laser at 5828 Å, is stabilized to the transfer cavity which serves both as a long-term and as a short-term reference. To tune the dye laser precisely, we simply change the frequency of the RF drive applied to the electro-optic modulator. In this manner, we can scan the dye laser frequency at rates of

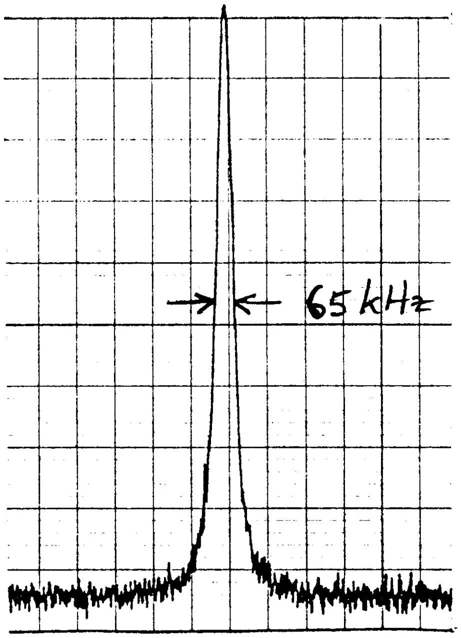

Fig. VIII-7.
65-kHz line generated by weak copropagating fields. $I_{pump} = 4 \frac{mW}{cm^2}$, $I_{probe} = 2.5 \frac{mW}{cm^2}$, $\tau$ = 100 ms, scan rate = 60 kHz/sec.

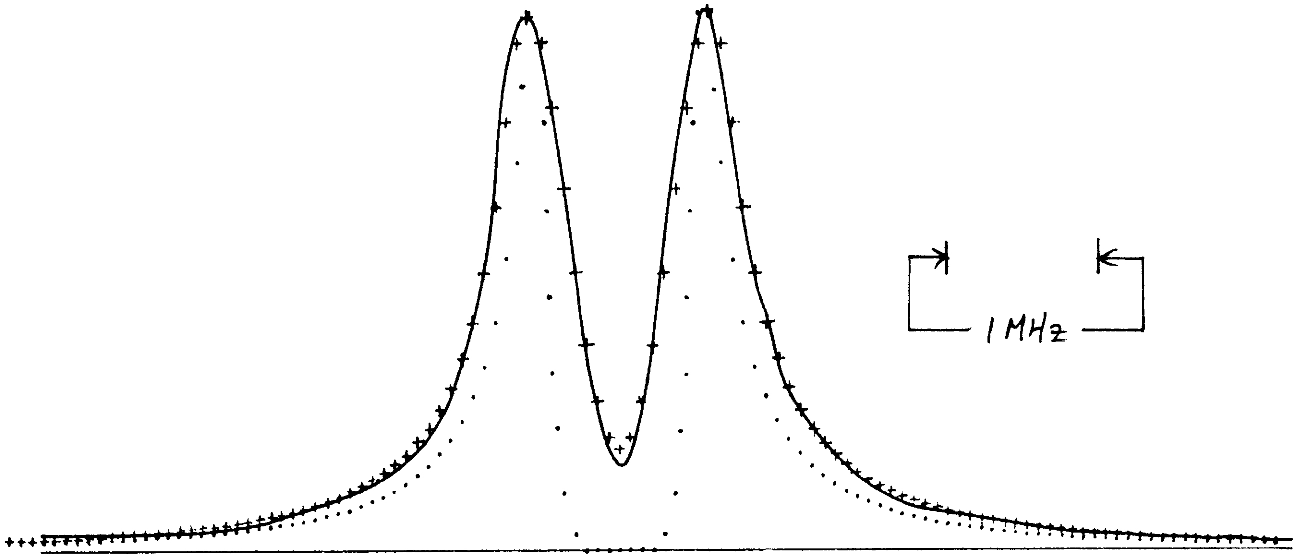

Fig. VIII-8. AC Stark effect in a Doppler-broadened 3-level system. Solid curve is experimental line shape for copropagating fields with $I_{pump}$ = 8.3 W/cm$^2$, $I_{probe}$ = 5 mW/cm$^2$. Dots indicate fit of velocity-averaged theory to data. Crosses indicate fit including effect of M levels and Gaussian intensity distribution.

less than 1 kHz/sec.

In our experiment, the argon laser pump is amplitude-modulated at 2 kHz and combined with the dye laser probe for two passes through a 150-cm-long cell containing $I_2$ vapor. A prism after the cell separates the pump from the probe, which is then synchronously demodulated. Intensity subtraction of probe-beam fluctuations reduces background noise to less than three times the shot-noise limit. Figure VIII-7 shows a 65-kHz line generated by this spectrometer. For weak copropagating fields, the probed linewidth is calculated to be 16.5 kHz.[3] Our resolution is currently limited primarily by the spectral width of the dye laser, and efforts to improve the dye laser stabilization are now under way.

With our system we can use the extremely narrow lines generated by weak copropagating fields as secondary laser-frequency standards in the visible region, or to perform stimulated emission spectroscopy of thermally unpopulated levels. By introducing a noble gas into the cell, we can also use these narrow lines as sensitive probes of the effects of collisions on a three-level system.[4] Finally, the width of a resonance produced by weak counterpropagating fields is almost twice the upper state linewidth for the three-level system under consideration.[3] We are using this increase in linewidth to measure small differences in the widths of hyperfine components of an $I_2$ rovibrational line due to magnetic predissociation.

We have also performed high-resolution measurements of the probed line shape for intense pump fields. The solid line in Fig. VIII-8 shows an experimental line shape obtained at a pump intensity of 8.3 $W/cm^2$. The velocity-averaged steady-state theory for the ac Stark effect in Doppler-broadened systems is shown by a dotted line. In order to apply the theory to our experiment, we must sum over contributions from all rotational M levels and integrate over a Gaussian intensity distribution. This modified theory, plotted with crosses in Fig. VIII-8, fits the data reasonably well. However, we have observed an asymmetry in the experimental line shape when only the central portion of the probe beam is detected. Careful experiments are being conducted to study this asymmetry.

We intend to use our measurements of the ac Stark effect in Doppler-broadened systems to calculate average matrix elements for the hyperfine pump transitions. We will also use the high-intensity line shapes to study $I_2$-noble-gas collisions in the presence of intense laser fields.[4] These techniques are quite general and can be applied to other molecular and atomic systems.

## References

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4. Y. Rabin and S. Mukamel, to be published.

## 6. DOPPLER-FREE SPECTROSCOPY VIA RESONANT DEGENERATE FOUR-WAVE MIXING

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and DAAG29-80-C-0104)

Donald R. Ponikvar, Robert E. Tench, Shaoul Ezekiel

The objective of this research is to perform high-resolution studies of molecular hyperfine interactions in iodine vapor using a new technique based on four-wave mixing.[1,2]

Our setup employs a single, frequency-stabilized argon ion laser to provide counterpropagating pump and probe beams, with the pump beam being offset in frequency and sideband-modulated (carrier-suppressed) using an acousto-optic device. Four-wave mixing occurs in the sample cell containing $I_2^{127}$ vapor, producing an output wave collinear with the probe beam, but shifted in frequency by twice the sideband-modulation frequency. The beat frequency between these beams provides a measure of the signal, which is proportional to the strength of the transition being studied. One advantage of the technique is that the phase delays of the various resonances differ, which allows a simple and direct method of assigning crossover transitions.[2]

Results thus far have been encouraging. Using 10-kHz sideband modulation and intensity noise subtraction, our background noise level is approximately 1.5 times the shot-noise limit, and the observed linewidths are on the order of

175 kHz. Figure VIII-9 shows a scan over an $I_2$ hyperfine line whose natural linewidth (zero pressure) is on the order of 75 kHz. The additional broadening in the data is attributed primarily to geometric effects due to beam misalignment. Recent experimental modifications are expected to reduce such broadening effects.

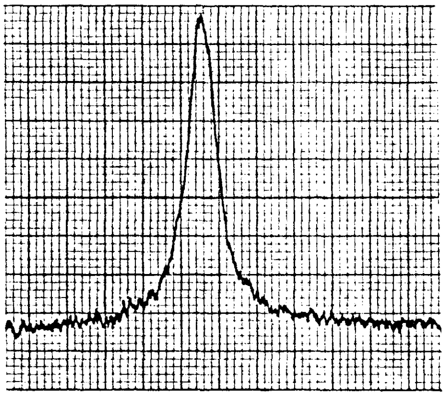

Fig. VIII-9.
$I_2$ hyperfine line, 175 kHz wide (FWHM).

We intend to use this scheme to study magnetic predissociation effects on the width of hyperfine lines with different nuclear spin components. In addition, collisional relaxation, including phase-changing iodine-noble-gas collisions at very low pressures, will be examined. The transitions we will study will be the P(13) 43-0 and R(15) 43-0 B-X transitions at 5145 Å, and the R(26) 62-0 B-X lines at 5017 Å. Some of the latter lines have theoretical widths of 10-15 kHz. We will also consider the use of these extremely narrow lines as frequency standards in the visible region of the spectrum.

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## 7. SINGLE-FREQUENCY, STIMULATED BRILLOUIN SCATTERING FIBER-OPTIC LASER

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and
DAAG29-80-C-0104)

Donald A. Ponikvar, Shaoul Ezekiel

The objective of this research is to study the behavior of a fiber-optic laser based on Stimulated Brillouin Scattering (SBS). Our primary goals are to examine the SBS gain characteristics of the fiber laser and to study its frequency behavior.

Our setup consisted of a fiber-optic ring cavity pumped by an argon ion laser at 5145 Å. The ring cavity allowed spatial separation of the pump and backward-travelling Stokes-shifted light, and also minimized coupling back of the pump light into the pump laser. The optical fiber used was single-mode, 83 meters long, with an attenuation of approximately 25 dB/km at 5145 Å. Light is coupled in and out of the fiber using AR-coated 20X microscope objectives. Fiber-cavity tuning and stabilization are accomplished by wrapping several turns of fiber tightly around a piezoelectric crystal which expands radially with an applied high voltage, stretching the fiber slightly, and thus tuning the resonant frequency of the cavity. The pump laser is a single-frequency, stabilized argon ion laser with a residual linewidth of less than 3 kHz rms, and a power output capability of up to 500 mW.

We measured the spontaneous Brillouin scattering linewidth for this fiber to be approximately 105 MHz, shifted from the pump frequency by 34 GHz. The threshold pump power for spontaneous scattering was 350 mW (measured at the input microscope objective).

Lasing at the Stokes-shifted frequency occurred at a much lower threshold (around 60 mW). Our studies show that the optical fiber acts as a homogeneously broadened gain medium; however, we still experienced difficulty in obtaining single-mode operation. An 84-meter cavity has a free spectral range of only 2.4 MHz, which makes the difference in gain between adjacent modes almost indistinguishable against the broad spontaneous gain curve. The matter is further complicated by the inherent mechanical instabilities of a long-fiber cavity. However, by actively stabilizing the fiber-optic ring cavity, we were successful in obtaining a single-output mode, whose short-term linewidth was measured to be much less than 1.5 MHz,

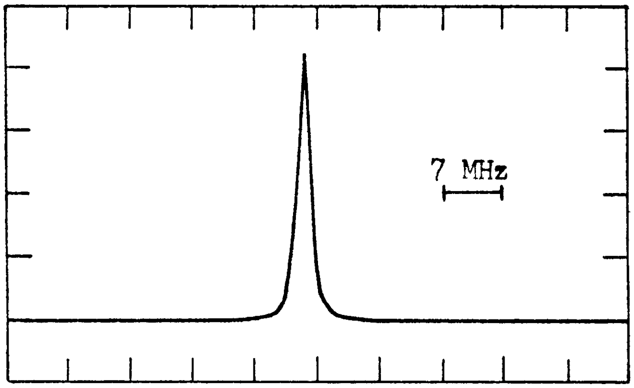

Fig. VIII-10. Fabry-Perot scan over stimulated Brillouin laser.

which is the limit of resolution of our scanning Fabry-Perot as shown in Fig. VIII-10.

We have demonstrated that stable, single-frequency operation of a Brillouin fiber laser can be achieved if care is taken to stabilize the long-fiber optic cavity, but the laser has rather limited tunability due to its homogeneously broadened nature and close spacing of cavity modes.

## 8. MEASUREMENT OF INERTIAL ROTATION USING A PASSIVE-RING RESONATOR

U.S. Air Force Geophysics Laboratory (AFSC) (Contract F19628-79-C-0082)

Glen A. Sanders, Raymond E. Meyer, Robert P. Schloss, Mara G. Prentiss,
Shaoul Ezekiel

The objective of this research program is an investigation into the use of a large-passive-ring resonator for the measurement of inertial rotation.[1] The sensitivity range we are considering is $10^{-6}$-$10^{-11}$ of earth rate which is of considerable interest in geophysics, relativity, and in the testing of precision inertial-grade gyroscopes.

Our present setup is a square cavity, 70 cm on a side, mounted on a super invar table. The difference between the resonance frequencies of the cavity for clockwise (cw) and counterclockwise (ccw) propagation induced by inertial rotation is measured by a 1/2-mW He-Ne laser, mounted external to the cavity.

As shown in Fig. VIII-11, we have reduced the short-term fluctuations in our measurement to 6 x $10^{-4}$ $\Omega_E$ ($\tau$=1s), where $\Omega_E$ is the earth-rotation rate. This is consistent with the photon-noise limit in our present apparatus. However, the drift in the data was negligible over a few minutes and approximately $10^{-2}$ $\Omega_E$ over one hour. This improved performance[2] resulted from our study of the problems of misalignment and backscattering. Further studies of the causes of long-term drift are continuing.

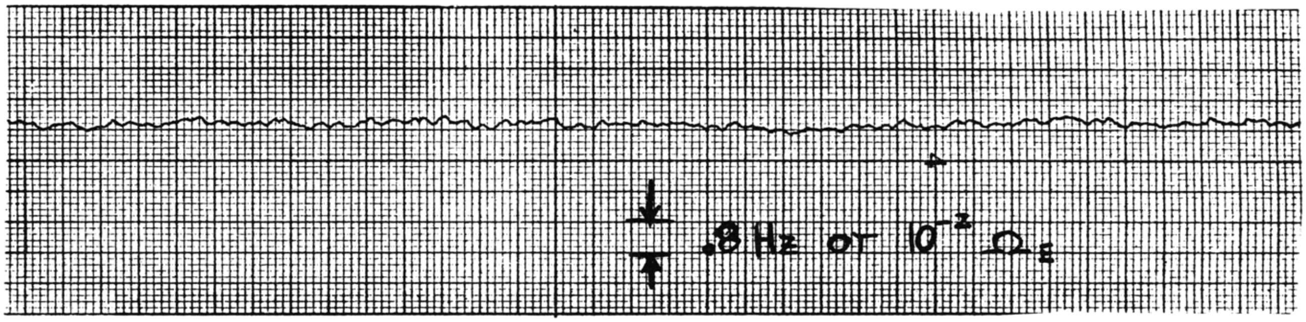

Fig. VIII-11. Drift data over 10 minutes ($\tau$=1s).

Other investigations included: a study of the variation of the effective cavity-resonance frequency as a function of the spatial position of the detector; a detailed calculation of the amplitudes and frequencies of higher order transverse modes excited by beam misalignment and beam displacement; and an experimental verification of these calculations in a two-mirror as well as a four-mirror cavity.

In the near future, we plan to set up a 30 m x 30 m cavity in an isolated area below ground. With an external 3-watt argon ion laser, the photon-noise limit for this setup should give a rotation measurement uncertainty of a few parts in $10^{-11}$ $\Omega_E$ for an averaging of 1 hour. In order to reach this photon-noise limit, we must modulate the laser frequency or the cavity length at a high enough rate. Because of the long photon lifetime in a large cavity, the conventional modulation techniques cannot be used. With this in mind, we have studied a phase-modulation method which utilizes the electric-field phase change on reflection around the cavity resonance. We have studied this technique, both theoretically and experimentally, and have demonstrated the feasibility of achieving photon-noise-limited detection regardless of the cavity photon lifetime.

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## 9. MEASUREMENT OF INERTIAL ROTATION USING A MULTITURN FIBEROPTIC SAGNAC INTERFEROMETER

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and DAAG29-80-C-0104)

James L. Davis, Shaoul Ezekiel

We are continuing to study the use of a multiturn fiber Sagnac interferometer for inertial-rotation measurement. Current experiments involve a system where laser light at 6328 Å is injected into the interferometer via a short length of single-mode optical fiber. Aside from providing good mode matching into the main fiber, it makes alignment insensitive to laser-beam pointing error, and spatially filters the light output before detection. The optical path of the interferometer is defined by a 200-meter length of single-mode fiber bracketed by linear polarizers on each end. Orienting each polarizer in the same direction ensures reciprocal behavior within the fiber.

In order to measure rotation-induced nonreciprocal phase shift with shot-noise-limited sensitivity, we are currently employing a time-delay modulation scheme. This method takes advantage of the 1 μsec transit time of light in the fiber and is implemented using a conventional phase modulator located near one end of the fiber coil. Finally, we detect the second harmonic present in the interference signal rather than the fundamental because of the reduced intensity noise at the second harmonic. Offset null capability is provided by incorporating acousto-optic frequency shifters into the optical path.[1]

A sample of data using this system (Fig. VIII-12) shows little drift over a

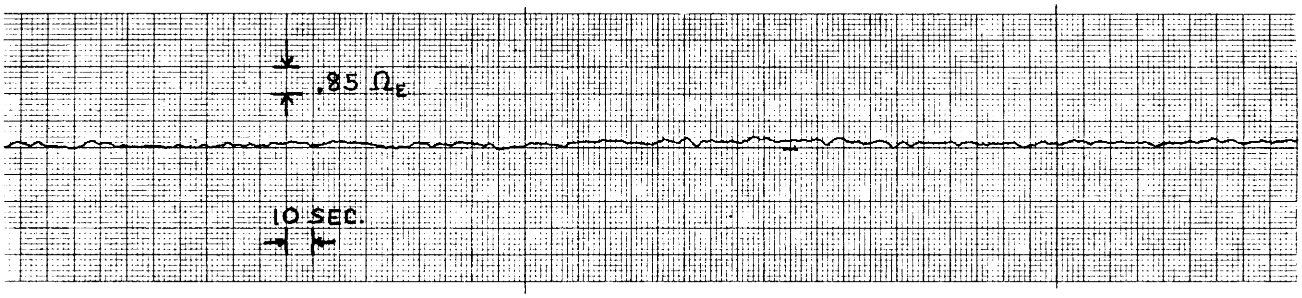

Fig. VIII-12. Drift data ($\tau$=1s).

10-minute interval and a short-term rms noise of approximately 0.05 $\Omega_E$ ($\Omega_E$ = earth-rotation rate) using an integration time of one second. Although this performance is the best reported to date, nevertheless it is still about 15X larger than the shot-noise limit.

Future work will concentrate on several possible noise sources, including extraneous interference due to diffuse backscattered light, stress and temperature effects in the fiber, polarization effects, and misalignment. The advantages of polarization-preserving fiber will also be investigated.

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# VIII. QUANTUM ELECTRONICS

## B. Nonlinear Phenomena

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## 1. SEGMENTED-CONTACT GaAs/GaAlAs DOUBLE-HETEROJUNCTION LASER DIODES

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and DAAG29-80-C-0104)

National Science Foundation (Grant ECS79-19475)

Clifton G. Fonstad

Multiple-segment stripe-contact (MSSC) GaAs/GaAlAs double-heterojunction (DH) diode lasers have been fabricated for the purpose of studying some of the effects produced by nonuniform current pumping along the length of the laser stripe.[1,2] This work is preliminary to the development of monolithic mode-locked diode lasers capable of emitting picosecond-duration pulses at gigabit per second rates.

The current density along the laser stripe in these diodes is controlled through the use of an eight-segment contact to produce nonuniform carrier density and optical gain in the cavity of the laser. For different combinations and magnitudes of current density into the segments, these lasers exhibit a variety of modes of operation including self-pulsing, optical switching, bistability, hysteresis, and extremely high external-differential quantum efficiencies.

The MSSC lasers were fabricated from commercially grown GaAs/GaAlAs double-heterostructure wafers.[3] The active region was 0.2 microns thick and lateral definition took the form of an 8 μm shallow-proton bombardment defined stripe. The lasers operated cw at room temperature.

The MSSC lasers were operated as two-section lasers with some of the segments biased to the same current density, producing one "bias" section, while the remaining segments, which formed a "control" section, were operated at a second current density which was varied to vary the light output. Families of plots of light output versus current density in the control segments were generated with the bias-section-current density as the parameter. The slope of the curves, the external-differential quantum efficiency (EDQE), increases smoothly to a maximum value (EDQE') which exceeds the EDQE of a uniformly pumped laser and which increases as the bias current is increased.

In an MSSC operated with the inside 4 segments used as the control, and the outer 4 segments used as the bias, EDQE' as large as 240% per mirror has been observed. With the opposite choice of control and bias segments, the output becomes bistable and shows hysteresis as a function of control current, i.e., the laser switches off at a control current that is up to 1 mA smaller than the turn-on current. The measurements of the switch-on and switch-off times have been detector-system-limited to 1 nanosecond.

The segmented-contact structure also permits direct observation of the saturation of optical gain and absorption in the active region. The diode voltage measured at the contact pad of a segment is directly related to the carrier concentration under that segment, and any saturation of stimulated gain or absorption under a segment causes a change in the carrier concentration which can be determined by the change in the diode voltage.

To explain the observed performance characteristics of MSSC lasers, and as an aid to optimizing the desirable features of these devices in terms of their design and the manner in which they are operated, a computer model has been developed which describes the essential features of the lasers. This model, which is based on a simple first-order dependence of gain on carrier concentration and conventionally accepted rate equations, is capable of predicting both qualitatively and quantitatively the observed output characteristics, including the switching. It is significant that the essential features and nonlinearities of the output characteristics can be predicted by such a relatively simple model.

The present work represents the first extension of very early work (pre-1970) on two-section lasers to incorporate state-of-the-art heterostructure geometrics and multiple segments, and demonstrates the usefulness of this concept both to study fundamental features of device operation and to control the laser output. The study of MSSC lasers is proving helpful in understanding conventional devices, as well as in our research program to design and study novel optical devices, specifically, the monolithic mode-locked diode lasers.

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3. The heterostructure wafer was supplied by Dr. A. SpringThorpe, Bell Northern Research, Ottawa, Canada.

## 2. PICOSECOND SAMPLING

National Science Foundation (Grant DAR80-08752)

Hermann A. Haus

Optical waveguides and integrated optical components have very large absolute bandwidths (>$10^{12}$ Hz). In combination with microwave drives they have the potential for very-high-speed signal processing. The microwave drive signals can be cw sinusoids, circumventing the constraints imposed by the narrow (relative to the optical) bandwidth of the microwave circuits.

We are in process of developing optical waveguide structures for high-speed sampling. The structures are derived from the Mach-Zehnder waveguide interferometer originally proposed by Martin.[1] The individual interferometers are modulated by cw microwave electric fields (voltages). Through cascading of samplers driven at successively higher frequencies, or voltages, very short sampling "windows" may be achieved. Thus, the calculated sampling-window width is 2 ps spaced 50 psec for a cascade of four interferometers driven at 10 GHz at voltages of 2.6, 5.2, 10.4, and 20.8 volts.

We have made tests on a cascade of two interferometers with low-frequency drives.[2] The experiments bear out the theoretical predictions, although the uniformity of the waveguides was not maintained to a satisfactory degree over the total length of the interferometer cascade. The work is carried out jointly with Dr. F.J. Leonberger of Lincoln Laboratory. He achieved excellent performance characteristics with a single interferometer that gave him a 30-dB extinction ratio and of the order of 1-dB loss in excess of the waveguide loss due to the waveguide junctions.

The work is now concerned with the construction of interferometer cascades and microwave structures that overcome transit-time effects (that become important for drives at frequencies greater than 10 GHz).

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## 3. DEVICES FOR HIGH-RATE OPTICAL COMMUNICATIONS

National Science Foundation (Grant ECS79-19475)

Hermann A. Haus, Clifton G. Fonstad

The purpose of the program is to construct multiplexers and demultiplexers with quaternary semiconductors (InGaAsP) and to develop an integrated version of the mode-locked laser.

We are presently studying optical waveguiding at 1.0-1.5 μm in InGaAsP/InP structures with the goal of developing gigabit-rate multiplexers and demultiplexers for picosecond 1.3 μm pulse trains. Relative to $LiNbO_3$, waveguide and coupler technology is at a primitive stage in the III-V's, particularly in InGaAsP. However, the potential this quaternary system offers for monolithic integration of sources and detectors, as well as switching elements, on a single wafer, and its match to the optimum wavelengths for operation with glass fibers, makes it an extremely attractive system. Nonetheless, much basic materials and waveguide work is required before this potential can be realized.

The heterostructures under study are being grown by liquid-phase epitaxy, and considerable effort has been spent in the past year on developing growth techniques capable of producing low carrier concentrations, optically smooth (flat) InP layers which are usable as optical waveguides. Additional layers have been obtained from Dr. S. Groves of MIT's Lincoln Laboratory.

A complete waveguide testing system has also been assembled and put into operation in the past year.

The device, toward which the present effort is directed, is a directional coupler with reversed $\Delta\beta$, structured and designed so that it can be driven with gigahertz-frequency sine waves. A basic metal-gap guide will be used. Initially, the metal will be deposited on a semi-insulating InP layer approximately 2 $\mu$m thick on a $p^+$ or $n^+$ substrate. In later designs the semi-insulating InP layer will be replaced by InGaAsP, also semi-insulating. This will increase the optical confinement in the vertical direction, permitting use of a thinner layer. This, in turn, will reduce the power dissipation, which will scale as the layer thickness, t. In certain structures it may also be useful to put a thin (200-400 Å) insulator layer between the metal and the semi-insulating III-V layer, but this is not necessary to the intrinsic device operation.

Before considering "optimized" structures, however, there are numerous issues relevant to the basic structure which must be addressed. The strength of the in-plane guiding and of the coupling between adjacent guides, the critical electric fields which must be achieved to operate a stepped-$\Delta\beta$ coupler, and the losses introduced by ion-implantation damage (used to create semi-insulating regions), as well as the loss in virgin layers, are a few of the issues which are being studied. While models exist with which these quantities can be calculated, our knowledge of basic material parameter values is so limited that they must be determined experimentally if we are to do a realistic design of more nearly optimized structures.

The use of ion implantation is possible because of the recent availability of an ion implanter, acquired recently by the Center for Materials Science and

Engineering, with assistance from the Research Laboratory of Electronics, as well as from NSF and MIT. Another technology area which is newly available to the program is that of Professor H. Smith's Submicron Structures Laboratory, another RLE/CMSE-associated laboratory. We want to reduce the waveguide separation in the couplers to the minimum possible, and anticipate operating at separations below 1 micron. This, in turn, reduces the coupler length which will reduce the power dissipation and will make it possible to place guides in series to produce multichannel multiplexer/demultiplexers.

The integration of a mode-locked semiconductor laser with its external resonator[1,2] is being pursued in a version in which the entire length of a uniform structure in GaAlAs, 8 mm long, is biased. In this way, the laser and waveguide resonator form a single structure onto which a microwave signal is applied via segmented electrodes. Carney successfully constructed several shorter-segmented lasers[3] and operated them cw (see previous section). Several longer laser units have now been constructed and will be tested in the course of this year. Attempts will be made at actively mode locking these lasers.

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# VIII. QUANTUM ELECTRONICS

## C. Grating Structures

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### 1. SURFACE ACOUSTIC WAVE GRATINGS

National Science Foundation (Grant ENG79-09980)

Hermann A. Haus

The motivation for our study of grating structures derives from their potential use in integrated optics. Ideas for grating filters and reflectors for optics applications are conveniently tested in their surface acoustic-wave realizations. As surface acoustic-wave devices they present interesting problems in their own right.

We have studied higher order effects (in $h/\lambda_r$) in groove-grating reflectors both at normal and oblique incidence;[1,2] here h is the groove depth and $\lambda_r$ is the Rayleigh wavelength. The normal incidence case is of importance for the prediction of frequency shifts from their design value of groove-grating resonators as a function of groove depth. It was found that the shift is a strong function of groove profile, a sinusoidal profile giving the least shift for a given reflection per groove.

The oblique incidence case is of importance in Reflective Array Compressors (RAC). Here P.V. Wright discovered a closed-form solution for the propagation of the SAW including multiple reflections.[3] No such solution was known. Through its use, the computer time required for the evaluation of RAC performance has been greatly reduced, with the added benefit that effects not taken into account in previous analyses have now been included. Some unexplained effects found in RAC's with large time-bandwidth products are accounted for by the new theory.

Future work will be concerned with the extension of the higher order grating-reflection analysis to metallic reflectors. This will be done by extending the variational principle approach to include piezoelectric effects.

The theoretical study on the coupling of surface acoustic waves to bulk waves[4] has been applied to the design of a filter structure based on the frequency dependence of this coupling. Structures are currently being built and tested.

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