

VIII. QUANTUM ELECTRONICS

A. Laser Applications

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1. HIGH-RESOLUTION STUDIES OF THE AC STARK EFFECT IN AN ATOMIC BEAM AND THE INFLUENCE OF ATOMIC RECOIL

National Science Foundation (Grant PHY79-09739)

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

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

We have performed careful measurements of the ac Stark effect in an atomic beam of sodium and have found the influence of atomic recoil to be significant. Such measurements have been of much interest, recently,¹ because they provide important information about the effects of resonance radiation on two-level systems. Previous observations of the ac Stark effect in an atomic beam² have been generally qualitative. Our present measurements, however, allow, for the first time, a precise quantitative comparison with theory.

The experiment was performed on an atomic beam of sodium which was prepared as a two-level system by optical pumping techniques.³ The relevant states are the $3^2S_{1/2}$ ($F=2$, $m_F=2$) and the $3^2P_{3/2}$ ($F=3$, $m_F=3$) hyperfine levels of sodium. Transitions between these states are driven by a near-resonance pumping field which is collimated to give an extended region of uniform intensity. A weak probing field, focused on the driven atoms, induces transitions from $3^2P_{3/2}$ ($F=3$, $m_F=3$) to the $4^2D_{5/2}$ ($F=4$, $m_F=4$) hyperfine levels, and the resulting fluorescence is monitored with a cooled photomultiplier.

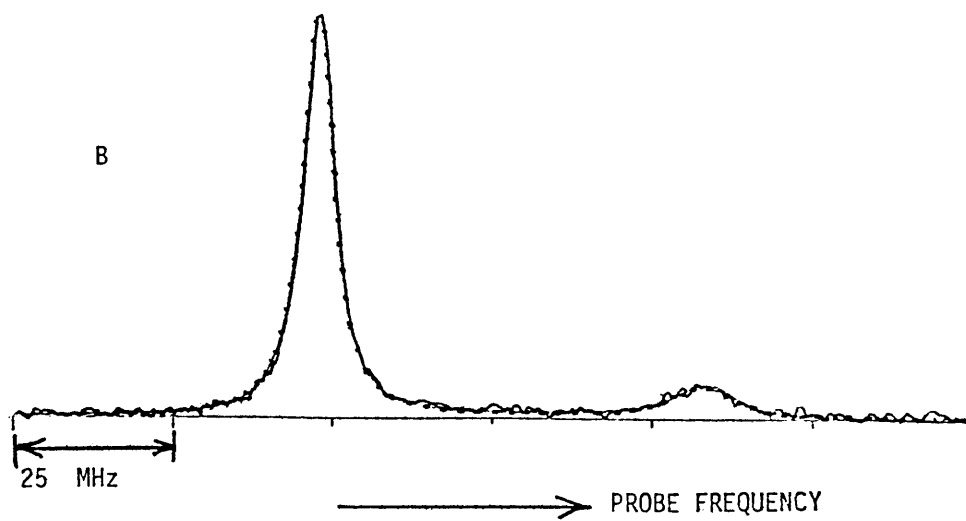
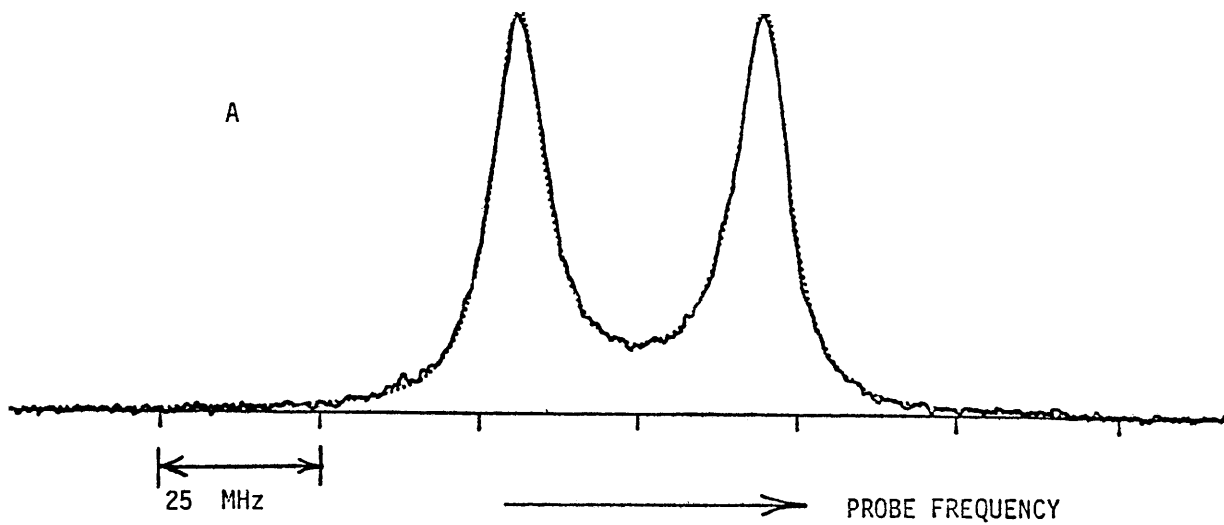


Fig. VIII-1.

The line shapes obtained at low pump intensities resemble, as predicted, Lorentzians with widths approaching the 3.3 MHz width of the $4^2D_{5/2}$ ($F=4, m_F=4$) state. At higher pump intensities, an asymmetry appears in the line shapes, for exactly on resonance pump field, which is not predicted by three-level theory. Symmetry can be restored by cocking the angle between laser and atomic beams slightly away from orthogonal, but at the expense of introducing a broadening. The discrepancies at high pump intensities can be explained by taking into account the many momentum-conserving recoils which must take place as the two-level atoms traverse the extended region of intense, resonant, pumping radiation.

Net atomic recoil⁴ occurs whenever an atom absorbs a photon from a unidirectional light beam and, subsequently, spontaneously emits in a random direction. When averaged over an ensemble of atoms, this results in a fixed net increase in velocity in the direction of light propagation, and therefore an apparent negative detuning of the pump-field frequency due to the Doppler effect. Because of the distribution in velocities along the atomic beam there will also be a spread in this apparent negative detuning. If the many recoils as well as the atomic velocity distribution are included in the calculation, excellent agreement between theory and experiment is obtained. Figure VIII-1A shows the probe absorption line shape for an on-resonance, 230 mW/cm^2 pump with laser and atomic beams cocked approximately 2 mrad away from orthogonal. Figure VIII-1B is the line shape for a pump-frequency detuning of -40 MHz away from resonance. The dotted curves in both figures are calculated from theory and include the effects of recoil and the atomic velocity distribution.

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2. FOLDED DOPPLER-BROADENED THREE-LEVEL MOLECULES IN
INTENSE MONOCHROMATIC FIELDS: HIGH-RESOLUTION
STUDY IN I_2 VAPOR

National Science Foundation (Grant PHY79-09739)

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

Robert E. Tench, Richard P. Hackel, John E. Thomas, Shaoul Ezekiel

We have performed very high resolution studies of Doppler-free resonances in folded three-level systems of I_2 vapor subject to intense monochromatic fields. Line shapes have been obtained for saturation parameters (I/I_{sat}) up to 10^4 .

Detailed studies of the interaction of intense monochromatic fields with two- and three-level systems¹ provide important tests of theoretical predictions and also are essential to a complete understanding of powerful new spectroscopic techniques. In comparing experimental line shapes for ultrahigh intensity fields with theoretical predictions, one must be certain that the experimental conditions are carefully matched to the theoretical assumptions. For example, due to extreme saturation effects, minor variations in shape and type of modulation can drastically alter signal form; long-lived three-level systems at low pressure may exhibit some transient response which will be detected in an experiment intended for comparison with a steady-state theory. In addition, such effects as spatial variation of the laser intensity, beam-transit time, and details of the level structure must be considered.

Using an argon ion laser pump beam at 5145 Å and a dye laser probe at 5828 Å, folded three-level Doppler-free resonances have been carefully studied over a wide range of pump intensities (7 mW/cm^2 - 70 W/cm^2). The co- or counter-propagating beams pass three times through an 80-cm-long cell containing I_2 at low pressure, after which the probe and pump are separated. The pump beam is amplitude-modulated and the change in the probe beam is synchronously demodulated after subtraction of the probe fluctuations yielding high signal-to-background ratio.

In the ac Stark effect studies using co-running waves, a spatially averaged line shape was obtained by observing the gain of the entire probe beam. The line shape in this case is roughly symmetrical and is in reasonable agreement with the steady-state theoretical predictions after averaging the theoretical line shape with

a Gaussian intensity distribution and summing the contributions of all the rotational M levels.

Critical to the shape of the signal at high-saturation parameters is the percentage of pump-amplitude modulation. This effect was studied with an electro-optic modulator at 2 kHz by varying the bias level and the depth of modulation. At high intensities, the line shape is dramatically altered for deviations of only 1% from full modulation. Line shape distortion due to pump modulation frequency and modulation rise time has also been investigated for various pressures and intensities.

Sensitivity of the high-intensity line shapes to the spatial variation of the pump laser field was studied by using a movable pinhole to sample the probe gain as a function of radial position. In the very uniform intensity region near the beam center, the ac Stark-effect signal was found to be highly asymmetric. The symmetry varies with radial position within the Gaussian beam, but it is independent of azimuthal angle. Further investigation of the possible causes for the asymmetric probe signal is under way. Variation of the signal asymmetry with pump intensity, beam size, and pressure is being studied, and a possible contribution to the signal from additional molecular levels is being considered.

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3. OBSERVATION OF ROTATIONAL DEPENDENCE IN COLLISIONAL SELF-BROADENING OF STIMULATED VIBRATIONAL RAMAN SPECTRA IN O_2

National Science Foundation (Grant PHY79-09739)

Bruce W. Peuse, John E. Thomas, Shaoul Ezekiel

We have utilized high-resolution stimulated Raman gain spectroscopy in O_2 to observe the rotational (N) dependence of the collisional self-broadening for

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transitions in the fundamental vibrational band.¹ In addition, polarization dependence of the line shapes was investigated. Pump-beam (argon-ion laser) modulation and synchronous detection of the probe beam (dye laser) gain at 8 MHz has enabled shot-noise-limited signal-to-background ratios to be obtained. At atmospheric pressure, the laser linewidth is negligible compared to the resonance full width at half maximum. For Q branch ($\Delta N=0$) resonances obtained with collinearly propagating $\pi^+ \pi^+$ polarized laser fields, the resonance full width is found to decrease from a maximum of ~ 3.1 GHz at $N = 9$ to ~ 2.1 GHz at $N = 23$.

Nonresonant stimulated Raman gain spectroscopy is particularly suited for studying collisional broadening of laser-induced nonlinear resonances, since the linewidth depends only on the initial-to-final state coherence decay rate. In this case, the effective transition operator can be represented as a sum of tensorial components, each of which contributes independently to the line shape. By selecting the relative polarizations of the pump and probe lasers, particular tensorial components of the signal can be enhanced or suppressed. Generally, these components are affected differently by the intermolecular forces and exhibit different decay rates.² A study of the effect of dephasing collisions on the linewidth of the individual tensorial components of the signal is of particular interest. Using widely tunable lasers as sources, dependence of the decay rates on rotational and vibrational quantum numbers can be established.

Vibrational nonresonant stimulated Raman spectra in oxygen were obtained using an argon-ion pump (5145 Å) and a tunable ring dye laser (5592 Å). The beams copropagate through a ~ 200 -m path in oxygen at atmospheric pressure by multipass reflection between a pair of high-quality mirrors (88 passes). Various relative polarizations ($\pi^+ \pi^+$, $\pi^+ \pi^-$, $\sigma^+ \sigma^+$, $\sigma^+ \sigma^-$) were chosen for the argon-ion and dye laser, respectively.

It is well known³ that the probe gain signal consists generally of an isotropic part (rank 0 tensorial component) and an anisotropic part (rank 2 tensorial component). For π^+, π^+ (or σ^+, σ^+) relative polarizations of the argon-ion and dye laser fields, both components contribute to the Q-branch spectra. Choosing π^+, π^- (or σ^+, σ^-) relative polarization, however, allows only the anisotropic component to contribute.

The relative area under each Q-branch probe gain vs probe-frequency resonance was determined as a function of rotational quantum number (N). Results for the relative

areas are in good agreement with the theoretical predictions which are expected to be independent of collision parameters.⁴ The widths of the resonances varied significantly (about 50%) in going from $N = 7$ to $N = 23$. From signals obtained utilizing $\pi^+\pi^-$ or $\sigma^+\sigma^-$ relative polarizations for the lasers, the anisotropic contribution to the Q-branch intensities is found to be much smaller than the isotropic component. Hence, the variation in the widths of the resonances can be interpreted as the variation in the self-broadening of the isotropic component of the resonances with rotational quantum number N .

Since the laser linewidth is negligible compared to the Raman Doppler width, an interesting application of the stimulated Raman gain technique is to study vibrational Raman spectra at low enough pressure so that the Raman Doppler width limit is attained. In this limit, the vibrational dependence of the spin-spin coupling constant may be observable.

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4. MEASUREMENT OF INERTIAL ROTATION USING A PASSIVE RING RESONATOR

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

Glen A. Sanders, Robert P. Schloss, 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

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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. So far, we have reduced the fluctuation in our measurements to $5 \times 10^{-3} \Omega_E$ ($\tau=1$ second) where Ω_E is earth rotation. In contrast, the photon noise limit in our setup is $5 \times 10^{-4} \Omega_E$ ($\tau=1$ second).

Once we achieve the photon noise limit in the 70 cm x 70 cm cavity, we plan to set up a 30 m x 30 m cavity in an isolated area below ground. With a 3-watt argon ion laser and this larger cavity the photon noise limit should be a few parts in $10^{-11} \Omega_E$ for an averaging time of 1 hour.

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

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

James L. Davis, Shaoul Ezekiel

The objective of this program is an investigation into the use of a multiturn fiberoptic Sagnac interferometer for the measurement of inertial rotation.¹ When such an interferometer is subjected to inertial rotation perpendicular to the plane of the fiber ring, a nonreciprocal phase shift is induced for counterpropagating light beams which is proportional to inertial rotation.

We have set up such an interferometer using a 200-m single-mode fiber in order to study a number of techniques for the measurement of small nonreciprocal phase shift in the fiber. So far we have achieved a sensitivity close to that of earth rate, and we anticipate a substantial improvement in the near future.

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6. OBSERVATION OF NATURAL WIDTH DIFFERENCES IN I_2
HYPERFINE STRUCTURE USING HIGH-RESOLUTION
TWO-STEP SPECTROSCOPY

National Science Foundation (Grant PHY79-09739)

Richard P. Hackel, Shaoul Ezekiel

We report the observation of differences in the natural widths of I_2 hyperfine structure due to hyperfine predissociation^{1,2} in the $B^3\Pi_{0^+u}$ state. Because these linewidths are very narrow, in the 50-kHz range, we found it advantageous to use a Doppler-free stimulated-resonance Raman technique^{3,4} to perform these measurements.

The natural predissociation of the $B^3\Pi_{0^+u}$ state of I_2 due to the presence of the dissociative $1^1\Pi_{1u}$ state produces different lifetimes for different hyperfine sub-levels within a given rovibrational level.^{1,2} Therefore the natural width of an individual hyperfine component is comprised of contributions from radiative as well as predissociative processes.

For the $v' = 43$, $J' = 12$ level in the $B^3\Pi_{0^+u}$ state in I_2 , calculations indicate³ that the natural widths of individual hyperfine components can vary in the range of 40-120 kHz depending on the nuclear spin for each component. To directly observe such narrow linewidths in a single step, molecular beam or saturation spectroscopy is difficult because of the extremely high resolution that is required. However, by using a resonant two-step excitation scheme in a folded Doppler-broadened system, it is possible to achieve an almost doubling of the upper-level linewidth. This comes about from Doppler averaging in a folded three-level system that is subjected to very weak but counterpropagating pump and probe fields. For such a case, the probed linewidth Γ_s is given by⁴

$$\Gamma_s = \frac{\Omega_s}{\Omega_p} \Gamma_1 + \left(1 + \frac{\Omega_s}{\Omega_p}\right) \Gamma_2 + \Gamma_3, \quad (1)$$

where Γ_1 , Γ_2 , Γ_3 are the relaxation rates of the initial, intermediate, and final levels, respectively, and Ω_s, Ω_p are the frequencies of the probe and the pump. If

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the initial and final levels are metastable, as in the case of I_2 , the probed linewidth is approximately $(1 + \frac{\Omega_s}{\Omega_p}) \Gamma_2$. If $\Omega_s \approx \Omega_p$, we can get an almost doubling of the upper-level linewidth.

Our experimental setup² consists of an 80-cm-long, low-pressure I_2 vapor cell subjected to an argon laser pump and a counterpropagating dye laser probe. Both pump and probe lasers are single-frequency and short-term-stabilized. The pump is held fixed within the Doppler-broadened B-X(43,0), P(13), and R(15) transitions at 5145 Å. The dye laser is scanned over the B-X(43,11), P(13), and R(15) transitions at 5828 Å. The pump is amplitude-modulated at 2 kHz, and the probe is synchronously demodulated in a lock-in amplifier. The $(1 + \frac{\Omega_s}{\Omega_p})$ enhancement factor according to Eq. 1 is 1.88 for this setup.

Using this technique, we were successful in observing variations in the linewidths for various hyperfine-structure transitions. For example, the largest difference in width, 57 kHz, occurs for the lines terminating on $|J''I''F''\rangle = |15,1,15\rangle$ and $|15,5,20\rangle$ (similarly for $J'' = 13$). The measured differences in natural widths were used to obtain a direct estimate for the dominant predissociation constants. In addition, we showed that the differences in natural widths were independent of pressure.

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VIII. QUANTUM ELECTRONICS

B. Nonlinear Phenomena

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1. PICOSECOND OPTO-ELECTRONICS

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

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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. This is the motivation for the mode-locking work on semiconductor laser diodes initiated in our laboratory over the past several years. The shortest pulses achieved by active mode locking (modulation of the bias current) with uncoated diodes were 16 psec in duration at repetition rates of 2-4 GHz.¹⁻⁵ In order to keep the frequency of modulation low, so as to obtain both a satisfactory depth of modulation and high peak power of the mode-locked pulses, external mirrors are used to form a "long" resonator (5-cm spacing for 3 GHz).

Analytic work has shown that the pulse width is limited by the composite Fabry-Perot resonator effect; the uncoated diode in the external resonator acts as an etalon that causes the gain of axial modes to vary periodically with frequency.^{6,7} The mode-locked pulses consist of axial-mode clusters, each cluster coherent within itself. The spectral width of the clusters is proportional to the inverse time duration of the pulses. The clusters are incoherent with each other with the result that the mode-locked pulses (of 16-psec duration) contain subpicosecond substructure. Analysis shows that the suppression of the etalon effect requires an antireflection

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coating of the diode end face internal to the resonator of very high quality. E.P. Ippen experimented at Bell Laboratories with A.R.-coated diodes in an external resonator⁸ (before joining M.I.T. in January 1980) and achieved Fourier Transform-limited pulses of 5-ps duration. He also observed that the mode locking is most effective when it is passive; no μ -wave drive is applied for the shortest pulses achieved. The diodes were self-pulsing when placed in the external resonator due to the unavoidable saturable loss intrinsic to the diodes.^{8,9}

We are currently engaged in an effort to integrate the laser diode and external resonator into a compact structure. Our first experiments are centered around a "long" laser structure of 8-mm overall length with divided electrodes that can be separately excited. J. Carney has successfully operated a shorter version of such a structure at room temperature.¹⁰ The electrodes will be excited so as to produce a standing-wave bias-current pattern, with a phase velocity equal to the group velocity of the optical radiation. This form of "integration" obviates the need for a passive waveguide coupled to an active lasing region, a system that would most closely duplicate the diode-external resonator geometry but is more difficult to construct.

In an effort to learn whether mode locking at higher frequencies may produce satisfactory pulses, we are investigating a system designed for 10-GHz mode-locking drive. If mode-locked lasers are to be used for transmission and processing of signals on a picosecond time scale, we must have means for multiplexing and demultiplexing pulse trains containing such pulses. Work is proceeding on the construction of an integrated optical multiplexer in InGaAsP. As a first step toward developing the technology, semi-insulating epilayers are being grown and a coupled waveguide switch is being constructed by Marjorie Johnson. The transverse optical confinement is accomplished by a metallic overlay. The same construction will be used in the multiplexer.

Pulses may be used to sample waveforms; indeed, this is one of several applications envisaged for the mode-locked pulse trains. High-speed sampling may be achieved by other means provided the system is broadband. Optical systems have broad absolute bandwidths and thus may be employed in various ways for this purpose. We are currently developing an integrated optical sampler that consists of four waveguide interferometers¹¹ in cascade. With cw μ -wave drives of 10, 20, 40, and

80 GHz, respectively, sampling functions with a half-power width of 2 psec can be achieved theoretically. The sampler is envisaged as the central component of a picosecond sampling oscilloscope.

With the aim of developing picosecond pulse-processing systems we are investigating various nonlinear optical processes in order to determine their relative merits for this purpose.

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C. Distributed Feedback Structures

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1. SURFACE ACOUSTIC WAVE GRATINGS

National Science Foundation (Grant ENG79-09980)

Hermann A. Haus

The impetus for our research in gratings derives from their potential use in integrated optics. Present-day technology is not yet at a state where gratings with periods of the order of 2000 \AA 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 outstanding in its own right. The realization of new SAW structures with interesting characteristics and the analysis of existing structures pose challenging problems.

We have investigated theoretically a filter structure that utilizes coupling of surface acoustic waves to bulk waves to achieve narrow-passband transfer characteristics.^{1,2} The structure was proposed originally by Melngailis and Williamson.³ It has the advantage of utilizing efficient coupling of surface waves to bulk waves that have lower loss and are insensitive to surface aging.

Another investigation focuses on higher order effects (in h/λ_r , where h is the groove depth and λ_r the Rayleigh wavelength) in SAW gratings. The Bragg frequency is a function of $(h/\lambda_r)^2$. Also, the groove reflection is a function of all powers of (h/λ_r) and, in fact, the second-order term can be as large as the first-order term for $(h/\lambda_r) \approx 0.02$ for trapezoidal grooves of 60° inclination. We have developed a variational principle in support of the analysis with the result that closed-form

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expressions have been obtained for all parameters of interest.⁴ Because the analysis is simple, it is less error-prone. The only previous publication on the subject was found to be in error.⁵

We hope that a detailed understanding of the effect of groove shape upon the reflection and frequency shift will provide a means for "trimming" of fabricated filters. The lack of the ability to trim SAW grating filters after manufacture has prevented thus far their acceptance in place of bulk wave resonators.

Another project recently initiated is the analysis of diffraction effects in metal-strip grating couplers⁶ and RAC devices. The former problem is a natural extension of the work on groove gratings. The latter problem is of great practical importance but has not been analyzed to a degree that is helpful to the RAC designer in suppression of spurious responses produced by diffraction effects.

Experimental work is planned to provide tests for the theories in cooperation with Dr. J. Melngailis of the Materials Science and Engineering Center.

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