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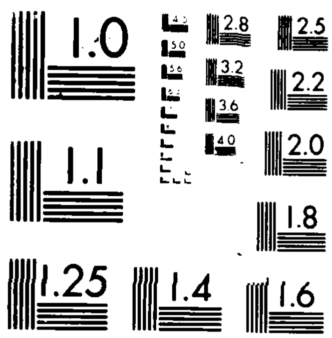

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ANNUAL REPORT ON ELECTRONICS RESEARCH
AT THE UNIVERSITY OF TEXAS AT AUSTIN

NO. 34

For the period April 1, 1986 through December 31, 1986

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract ~~AFOSR~~ F49620-86-C-0045

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December 31, 1986

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712-1084

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The Electronics Research Center at The University of Texas at Austin consists of interdisciplinary laboratories in which graduate faculty members, Master and PhD candidates from numerous academic disciplines conduct research. The disciplines represented in this report include information electronics, solid state electronics, quantum electronics, and electromagnetics.

The research summarized in this report was supported by the Department of Defense's JOINT SERVICES ELECTRONICS PROGRAM (U.S. Army, U.S. Navy and the U.S. Air Force) through the Research Contract AFOSR F49620-86-C-0045. This program is monitored by the Department of Defense's JSEP Technical Coordinating Committee consisting of representatives from the U.S. Army Research Office, Office of Naval Research and the U.S. Air Force Office of Scientific Research.

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This paper develops a systematic approach to select a time-dependent state transformation which can map a linear time-variant (LTV) digital filter to an equivalent filter having diagonal state-feedback matrices. Due to the structure simplicity of the diagonal systems, this time-dependent state transformation is a convenient tool for analyzing recursive LTV filters expressible in the state-variable form. In this paper, we discuss both the theoretical basis and the application of this diagonalization procedure. The properties of two types of recursive LTV filters are examined by using this state transformation technique. Based upon the separable properties of the impulse responses with major class of recursive LTV filters. This technique, through suboptimal can substantially reduce the computation required in the synthesis procedure.

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Research Contract F49620-86-C-0045

Submitted by Edward J. Powers

on behalf of the Faculty and Staff

of the Electronics Research Center

December 31, 1986

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712

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DIRECTOR'S OVERVIEW

This Annual Report covers the nine month period ranging from March 1, 1986 through December 31, 1986, in order to bring our reporting schedule into synchronization with the new DoD JSEP report cycle. The progress reported herein was accomplished during the first "year" of our current triennial technical program. Ten faculty members and approximately twenty graduate students from the Department of Electrical and Computer Engineering and the Department of Physics are conducting the research described in this report.

The University of Texas DoD JSEP program is a broad-based program with four research units in Solid State Electronics, two in Electromagnetics, two in Quantum Electronics, and two in Information Electronics. The Solid State Electronics program is a broad-based study of fundamental issues in semiconductor physics and technology and is designed to address basic problems which must be solved for the development of the next generation of electronic and optical devices. In the Electromagnetics area several novel monolithic millimeter-wave integrated circuit structures are being investigated for use as quasi-optical array elements. In addition, fundamental studies of nonlinear wave phenomena are being carried out. The Quantum Electronics research part of the program has as its overall theme the study of optical quantum effects with emphasis on nonlinear optical phenomena. Research in Information Electronics is concerned with both the theoretical and practical aspects of the analysis, implementation, and performance of information processing systems designed for the extraction of information from signals.

The scientific objective, recent progress, references, and related JSEP publications are given in this Annual Report for each of the ten Research Units. A synopsis of significant accomplishments and/or technology transfer immediately follow.

SIGNIFICANT ACCOMPLISHMENTS/TECHNOLOGY TRANSFER

Research Unit QE86-1, "Nonlinear Optical Interactions", H.J. Kimble, Principal Investigator: Observation of Squeezed States of Light. Squeezed states of light represent a manifestation of the nonclassical character of the electromagnetic field and hence are of great intrinsic interest in quantum optics. There are as well a number of applications in optical physics associated with the possibility of sensitivity beyond the standard quantum limit. Over the past six months, squeezing has been achieved in our laboratory in two distinct physical systems. The first is the optical parametric oscillator operated below threshold for degenerate oscillation. While we have observed noise reductions of 63% relative to the vacuum level, a quantitative comparison with theory indicates that the field would in fact be squeezed more than tenfold in the absence of avoidable linear losses in the current apparatus. The second experimental program investigates squeezing for two-level atoms coupled to a single mode of a high finesse cavity. For comparable atomic and cavity decay rate, there is a mode splitting in the eigenvalue structure of the system that persists for arbitrarily weak fields. Noise reductions of 10-15% relative to the vacuum level have been recorded.

Research Unit EM86-1, "Millimeter-Wave Monolithic Array Components", T. Itoh and D.P. Neikirk, Co-Principal Investigators: A prototype quasi-optical receiver front end which contains a coupled slot antenna, a balanced mixer and a Gunn oscillator in an integrated form has been successfully fabricated and tested for microwave and millimeter-wave applications. This novel device can be used for a number of applications including a millimeter-wave imaging array. Several industrial corporations have been contacted and informed of successful demonstration of this device.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE86-1 ELECTRONIC SIGNAL PROCESSING

Principal Investigator: Professor J.K. Aggarwal (471-1369)

Graduate Students: N. Nandhakumar and T.Z. Leou

A. SCIENTIFIC OBJECTIVES: The present research unit is addressing a number of problems in digital signal processing and extraction of information from signals. Briefly, the continuing objectives of the ongoing and proposed research are to investigate and establish algorithms for computerized analysis of information in signals and to apply Artificial Intelligence techniques and develop rule-based methods for the extraction of information from signals.

Digital signal processing and pattern analysis techniques have become important tools in a variety of fields such as communications, surveillance, geophysics, remote sensing, autonomous vehicle guidance, etc. Significant effort has been devoted to the selective extraction of information from single and multi-dimensional signals. The conventional approach has been to develop techniques for linear filtering, for statistical analysis and classification of signals, and for combining detected pieces of information in the signal via structural methods. In comparison, little effort has been expended on exploring more general methods of extracting information from signals. Adequate effort has not been directed twoards characterizing the signal's dependence on parameters which cannot be described by mathematically well founded formulations. Hence, there exists a need for the development of rule-based methods to model diverse mechanisms that generate and distort signals.

Our research has dealt with the extraction of meaningful information from signals. Recent research which was supported by this grant has yielded promising results and are discussed in the next section entitled "Progress." The preliminary results have opened several avenues for future research. The issues that our research has identified which we shall address in the near future are discussed in the section entitled "Follow-Up Statement." The rule-based approach to signal processing has been identified to be a powerful methodology for the analysis of signals. We have identified several topics in this area for future research. We plan to develop rule-based signal analysis systems for application in various domains and address issues such as improving communication between the different levels of analysis and the tightening of the coupling between front-end processing and the higher levels of analysis.

B. PROGRESS: We have developed a new approach to interpret signals obtained from different sensing modalities, viz. infrared sensors and visual (gray level) sensors [1,2]. The developed approach is seen as a way of resolving some of the ambiguities inherent in interpreting data sensed by thermal or visual cameras alone. We show that the resultant information, which cannot be obtained by processing the sensor outputs separately, is useful in describing intrinsic thermal behavior of objects imaged in outdoor scenes. Hence, this approach can be used for distinguishing between classes of objects based on perceived differences in thermal behavior and can be employed in applications such as autonomous vehicle navigation, surveillance,etc. The new approach developed overcomes many of the limitations of the conventional (statistical pattern recognition) approach to analyzing IR images which allows only minimal amounts of information to be extracted from the signals [3].

The approach developed by us consists of formulating a computational model for sensor integration that makes possible descriptions of thermal behavior of sensed objects. The model provides meaningful features based on estimates of surface heat fluxes. At the outset a model is established relating the exchange of heat fluxes between the environment and the object. Based on this model, heat fluxes are estimated at the surface of the imaged opbject. In estimating these heat fluxes, the thermal image is used to provide estimates of surface temperature, and the visual image is used to provide estimates of relative surface orientation and reflectivity. The model which relates irradiation at the thermal camera and temperature of the surface of the imaged object was based on several key observations such as emmisivity of commonly occuring surfaces in outdoor scenes are typically high, such surfaces are diffuse emitters, etc. Also the view-factor between imaged object and thermal sensor which was a heretofore unaddressed issue was incorporated into the model. The careful modelling of such mechanisms provided a convenient method for estimating object surface temperature using the thermal camera.

We have shown that the normalized value of the conduction heat flux at the surface of the object provides a great deal of information about the class to which the object belongs. We have shown that such features based on the estimated heat fluxes are specific in delineating broadly defined classes of objects such as vegetation, buildings and pavements, vehicles, etc. We have demonstrated the usefulness of the developed approach by using real data consisting of registered thermal and visual images of outdoor scenes.

In the next section we discuss future research which will augment the techniques developed for computerized analysis of signals. The ultimate objective is the development of general system for signal analysis that is based on both - analytical models of signal generation and distortion, and meaningful features and heuristic rules for information extraction.

C. FOLLOW-UP STATEMENT: The research above is being actively pursued towards its goal. The preliminary work reported above opens several avenues for further research. In the newly developed algorithms for scene analysis, the scenes were labelled with the values of one feature, i.e. the ratio between the conduction heat flux and the absorbed heat flux [1,2]. The variation, with the time of the day and with the season of the year, in the value of this ratio for a particular class of objects needs to be analyzed, and accounted for in the scheme for classification. Such research will allow for the design of a more general and robust system for signal interpretation. Other sources of information also need to be incorporated, e.g. color, position, size, etc. of the surfaces.

Experience gained in this project has also shown that in order to develop a robust system which employs multiple sensors it will be necessary to integrate information from the sensors at various levels of abstraction in the interpretation process. Suitable strategies and rules to achieve such information integration need to be devised. The use of other diverse sources of information obtained by different sensing modalities and/or interpretation strategies is also warranted. Future work will focus on the enhancement of the preliminary system discussed above by addressing these issues.

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J.K. Aggarwal, "3-D Structure from 2-D Images" presented at the Image Processing Workshop, Chitou, Taiwan (June 29, 1986).

J.K. Aggarwal, "Motion and Computer Vision Research", presented at Academia Sinica, Nankang, Taiwan (July 1, 1986).

J.K. Aggarwal, "Computer Vision and 3-D Object Recognition," presented at National Taiwan University, Taipei, Taiwan (June 30, 1986).

C.H. Chien and J.K. Aggarwal, "Computation of Volume/Surface Octrees from Contours and Silhouettes of Multiple Views," presented at the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Miami, Florida (June 1986).

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THE UNIVERSITY OF TEXAS AT AUSTIN — ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE86-2 NONLINEAR ESTIMATION AND DETECTION

Principal Investigator: Professor S. I. Marcus (471-3265)

Graduate Students: Hangju Cho, Emmanuel Fernandez-Gaucherand, and Hong Gi Lee

A. RESEARCH OBJECTIVES: The problems considered in this research unit involve estimation, detection, and control of systems involving noise and unknown parameters. The area of nonlinear state estimation is concerned with the extraction of information about the state of a nonlinear stochastic dynamical system from nonlinear noisy measurements. The state cannot be observed directly; instead, we have access to an observation or measurement process which is contaminated by noise and which is related to the state via a stochastic model. The objective is the calculation of either the entire conditional distribution of the state given the past measurements or some particular estimate, such as the conditional mean (which is the minimum mean square error estimator). In addition, it is desired that the state estimate or conditional distribution be calculated recursively; that is, the observations are being received continuously, and it is required that the estimate be continuously revised to take into account the new data. Thus the state estimate is generated by passing the measurements through a nonlinear system (also called a filter or estimator). The basic objective here is the study of the design, analysis, and implementation of high-performance optimal and suboptimal estimators which operate recursively in real time. A related approach to systems with unknown or changing parameters is that of adaptive estimation and control. Our objective in adaptive estimation and control is the study of recursive adaptive algorithms which simultaneously identify the unknown parameters and estimate the state or control the system.

B. PROGRESS: We have begun a major new direction of research involving adaptive estimation and control problems for stochastic systems with incomplete (or noisy) observations of the state. In [1], the adaptive estimation of the state of a finite state Markov process is investigated. In this context, the adaptive estimation problem is that of computing recursive estimates of the conditional probability distribution of the state given the past observations, when the state transition matrix (i.e., the model) depends on an unknown parameter. Such problems arise in computer communication networks and in other areas. A new adaptive estimation algorithm for such problems is developed; the algorithm combines a recursive parameter estimation algorithm of the type proposed by Kushner and Shwartz [2] and Ljung and Soderstrom [3] with a recursive state estimation algorithm. The algorithm is analyzed via the Ordinary Differential Equation (ODE) method. That is, it is shown that the convergence of the parameter estimation algorithm can be analyzed by studying an "averaged" ordinary differential equation. The most crucial and difficult aspect of the analysis is showing that, for each value of the unknown parameter, an augmented Markov process has a unique invariant (steady-state) probability measure. This was shown by a thorough study of the nonlinear recursive equations describing the process.

In [4], we consider the related adaptive stochastic control problem for discounted-reward, denumerable state space, Markov decision processes with incomplete state information and unknown parameters; this work generalizes our earlier results [5] on problems with complete state observations. It is shown that there exists a strongly consistent sequence of estimators which converge to the true values of the unknown parameters. In addition, an adaptive control law known as nonstationary value iteration (NVI) (originally proposed in [6]) is used and is shown to be optimal. Compared to other adaptive control schemes, NVI involves more on-line computation, but significantly less storage, thus representing an important and useful class of adaptive controllers.

We have studied in [7] problems in which, instead of there being a finite number of unknown parameters, the distribution of the disturbance is unknown. Three different adaptive policies (including the NVI policy) are shown to be asymptotically discount optimal in the sense of Schal [8], and for each of these we have obtained uniform approximations of the optimal reward function. These results extend recent work of Gordienko [9] on the average-reward case, as well as recent results by several authors on the adaptive control of Markov processes with unknown parameters.

In order to better understand the nonlinear systems which arise in nonlinear estimation, detection, and control, we have also studied related nonlinear deterministic control problems. In [10]-[12], we have solved a number of synthesis problems for discrete time nonlinear control systems. It is highly desirable to have available techniques which determine when a nonlinear system can be exactly or approximately transformed into a linear system, because well-known linear analysis and synthesis methods can then be employed. In [10] and [11], necessary and sufficient conditions are given for approximate linearization by state feedback and nonlinear change of coordinates. A sufficient condition for local linearizability is also given. In [12], necessary and sufficient conditions for local input-output linearizability are given. Also, it is shown that the zeros at infinity of the system can be obtained by a particular structure algorithm for locally input-output linearizable systems.

C. FOLLOW-UP STATEMENT: This work is continuing. Two particular directions are the following. In our work [1] on adaptive estimation of finite state Markov processes, the next step is to analyze the stability of the resulting ordinary differential equation in order to prove convergence of the parameter estimates to the true parameter value. Then we will work on showing that the adaptive state estimates are optimal. In addition, our results [7] on adaptive control of problems with unknown disturbance distribution will be generalized to the case of incomplete state observations. This will involve, in particular, a study of the resulting nonlinear estimation problem.

This research has been complemented by Grant AFOSR-86-0029 from the Air Force Office of Scientific Research and Grant ECS-8412100 from the National Science Foundation.

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12. H. G. Lee and S. I. Marcus, "On Input-Output Linearization of Discrete Time Nonlinear Systems," to appear in Systems and Control Letters.

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THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE86-1 IMPLANTATION AND ANNEALING OF INP AND RELATED COMPOUNDS

Principal Investigator: Professor Ben G. Streetman (471-1754)

Graduate Students: A. Campbell, A. Dodabalapur, C. Farley, T. Kim, S. Lester

A. SCIENTIFIC OBJECTIVES: Several important materials properties of InP make it particularly attractive for use in high-speed field effect transistors (FETs) and integrated circuits, as well as in optoelectronic systems. InP has excellent electron transport properties, very attractive surface electronic properties, and a higher thermal conductivity than GaAs. However, these inherent advantages cannot be exploited in electronic devices and systems without a considerable understanding of the effects occuring during processing. This information is currently unavailable, or is too incomplete to be useful for device fabrication. The objective of this research is to provide a better understanding of two of the most important issues facing a reliable InP FET technology: (a) impurity migration and activation during various implantation and annealing procedures, and (b) formation of a stable InP/insulator interface with a low density of interface states.

In the implantation and annealing studies, our objective is to develop procedures for obtaining controllable donor and acceptor distributions with good electrical activation. Studies will focus on the activation of low dose channel implants ($\sim 10^{12}$ ions/cm^2) and the activation of shallow (< 100keV) high dose source-drain implants ($\sim 10^{15}$ ions/cm^2), with high activation efficiency, high mobility, and minimal redistribution of other impurities. It is clear from the work done by our group over the last three years that rapid thermal annealing (RTA) using an incoherent light source or a strip heater will best address these issues. Surface protection methods including dielectric encapsulation, proximity techniques and column V overpressures have been studied. Impurity distributions, donor or acceptor activation, interactions with compensating impurities, and effects associated with dual implantation techniques have been examined. Since comparisons of these effects in GaAs and InP are important to the interpretation, implantation and annealing studies are made on both of these materials.

Research on InP surface properties include basic studies of ambient/InP interactions and studies of the properties of various interfaces between InP and deposited dielectrics. Investigations of InP surfaces include studies of the interaction of InP with chemical etching solutions, gas ambients, and vacuum environments [1]. Studies of dielectric interfaces include a number of SiO_2 and Si_3N_4 based dielectric systems. Also, the effects of surface preparation and post-dielectric deposition processing on the properties of InP/dielectric interfaces have been investigated. This work should improve the current understanding of InP interfaces and help to advance the state-of-the-art InP FET technology.

B. PROGRESS: We found that the temperature responses of different semiconductors in a Rapid Thermal Annealing (RTA) system vary widely. Much of this variation in temperature response can be correlated with free carrier concentrations in the materials, but other material properties also play a role [2,3].

The sheet carrier concentration and mobility profiles of epitaxial and implanted GaAs have been studied using a special four-terminal Hall effect MESFET (HFET). From the carrier concentration and mobility profiles, surface and bulk effects can be distinguished [4].

Out-diffusion of In, and in-diffusion of Si from from the Si_3N_4 and PSG caps, were found to play a significant role in the activation of low dose channel implants in InP, by encapsulated RTA [5]. Phosphorus vacancy complexes were detected for encapsulant deposition temperatures in excess of 300°C, and their concentration was found to increase with deposition temperature.

The close-contact annealing of high dose Si implants in InP was found to result in surface conversion to p-type material [6]. This converted layer extends to a depth of about 700 Å and was attributed to phosphorus vacancies. Phosphorus overpressure Rapid Thermal Annealing of low dose Si implants in InP, yield better and less anomalous activation efficiencies and mobilities than close contact annealing and Si_3N_4 encapsulated annealing [7]. Activation efficiencies and mobilities are dependent upon the phosphorus overpressure, anneal temperature, and anneal time.

Low temperature PL studies of encapsulated and moderate-temperature annealed InP indicate seven encapsulant dependent emmision lines [8]. We observe that dielectric capping with SiO_2 enhances the formation of several transitions, while phosphosilicate glass or Si_3N_4 effectively suppressed their formation.

Studies on the activation efficiencies and the mobilities of GaAs implanted with Si, Si+Al and Si+P , revealed a temperature dependent, arsenic vacancy related autocompensation process [9]. Co-implantation of column V elements reduces autocompensation of Si by offsetting arsenic loss, while co-implantation of column III elements increases autocompensation.

Gas ambient changes were found to affect the photoluminescence intensity of GaAs and InP [10]. This phenomenon appears to be related to the ambient-sensitive surface Fermi level position . Radiative surface recombination states were observed in InP after certain chemical treatments and annealing [11]. Photoluminescence studies and X-ray photoemmision studies of treated surfaces indicate that the recombination centers are related to near surface substrate stoichiometry and to the composition of native oxide layers.

Very shallow n^+ junctions and non-alloyed ohmic contacts to semi-insulating GaAs were made by the pulse diffusion of Ge from a thin elemental source [12]. A comparison of the secondary ion mass spectroscopy (SIMS) atomic Ge profiles, and the carrier concentration profiles by differential Hall effect measurements, showed that these layers are highly compensated [13].

Details of these results can be found in the referenced articles. A few salient details are presented below:

Rapid Thermal Annealing: An investigation of the heating behavior of GaAs and InP in a Rapid Thermal Annealing (RTA) system shows a significant variation in the temperature response of these materials. These compound semiconductors are heated with incoherent light in an RTA system where a Si sample is used for temperature feedback. The temperatures of GaAs and InP samples thermally isolated from the Si control sample during heating may overshoot or undershoot the desired temperature by hundreds of degrees. When the samples are thermally connected to the Si control sample by means of a susceptor, the temperatures of the III-V semiconductors follow the programmed temperature closely. Much of the variation in temperature response can be correlated with free carrier concentrations in the materials, but other material properties also play a role. This significant variation in temperature response has practical implications for the design and application of RTA systems.

Implant Characterization: Carrier concentration and mobility profiles are typically determined by differential Hall effect measurements, especially when the sheet charge densities are large (>10^{13} cm^{-2}). When the sheet charge density is small, profiling can be accomplished using depletion under a Schottky barrier. A special four-terminal MESFET (HFET)has been employed in a unique way to characterize carrier concentration and mobility profiles of epitaxial layers and channel implants into GaAs. This device allows measurement of carrier concentration and mobility under forward gate bias, so that the near surface region within the zero bias depletion width can be profiled. From the carrier concentration and mobility profiles, surface and bulk effects can be distinguished.This characterization method has been applied to the study of Si activity in GaAs and InP.

Indium Phosphide Implantation Studies: Photoluminescence (PL) spectroscopy, secondary ion mass spectrometry (SIMS), and Hall profiling measurements were used to study the effects of encapsulation and annealing on semi-insulating (SI) InP. Control of both In and P evaporation from the InP surface during annealing is necessary to prevent anomalous activation of shallow, low dose Si implants in SI InP. P vacancy-related complexes are detected for encapsulant deposition temperatures in excess of 300°C and their concentration increases with increased deposition temperatures. Indium outdiffusion is detected for 750°C , 30 minute furnace anneals of samples capped with oxygen-free silicon nitride (Si_3N_4) or phosphosilicate glass (PSG), but substantially more In is detected in the PSG film than in the Si_3N_4. Silicon indiffusion is greatest for PSG-capped LEC InP and least for Si_3N_4-capped LPE material. Conducting layers with sheet electron concentrations approaching 2×10^{12} cm^{-2} are always formed in PSG capped samples, but only occasionally in Si_3N_4-capped samples. Net doping is strongly correlated with In outdiffusion and Si indiffusion, suggesting that under the anneal conditions studied here, the supply of In vacancies limits Si indiffusion from the cap and also plays a significant role in determining the amount of doping produced from the indiffused Si. Iron was observed to getter to the encapsulant/substrate interface, and in some Si_3N_4 capped samples, deplete from the near-surface region. These results point out the need for low temperature dielectric deposition processes and rapid thermal annealing for controllable low dose implant activation in SI InP.

High dose Si implants into InP with potential application to source-drain contact regions have been studied. These implants have been activated using close contact rapid thermal annealing. Differential Hall effect profiles of these samples indicate that a conducting p-type layer ~700Å thick is formed during anneals at 800°C for 1 to 30 seconds. The remaining portion of the implanted region shows n-type conduction and exhibits the "net donor solubility limit" typically observed for high dose Si implants into GaAs and InP. The formation of the p-type layer can be attributed to the loss of P from the InP surface during annealing, which shows that the close contact method is not satisfactory for annealing Si implants in InP.

A rapid thermal annealing technique for InP has been developed, in which a controllable phosphorus overpressure generated by heating red phosphorus supresses the dissociation of InP at required annealing temperatures. Three different annealing configurations were used to independently study the effects of phosphorus overpressures, anneal temperatures and gas flow rates on the post-anneal electrical and morphological properties of low dose Si-implanted InP:Fe. Maximum activation of low dose Si implants occurs for an annealing temperature of 750°C. The maximum 77K mobility obtained was 8100 cm^2 volt^{-1}sec^{-1}or a Si implant dose of 4×10^{12} cm^{-2}. Phosphorus overpressure annealing was found to be superior to close-contact annealing. Gas flow velocities close to the sample were found to significantly affect the surface morphology. To preserve the surface morphology, it was found that a static layer immediately above the sample is beneficial.

Low temperature photoluminescence was used to study optical transitions in InP which arise from moderate-temperature annealing or dielectric encapsulation. A total of seven shallow emission lines appear in annealed or encapsulated InP that are not present in unprocessed material. These transitions are easily observed in undoped substrates. They are less intense or absent in Fe-doped material, and are not seen in p-type material. It was found that dielectric capping with SiO_2 enhances the formation of several transitions, while phosphosilicate glass or

Si_3N_4 effectively suppressed their formation. Surprisingly, some of these recombination centers were found to extend many microns into the substrate after SiO_2 deposition at 350°C or after annealing at temperatures as low as ~400°C. These centers appear to be related to previously observed processing-induced carrier concentration changes.

Indium Phosphide Surface Studies: We have observed radiative surface recombination centers on InP by low temperature photoluminescence. The luminescence band is observed only after etched or annealed surfaces are treated with HF, and is not found after rinsing in de-ionized water. These observations and X-ray photoemission studies of the treated surfaces indicate that the recombination centers are related to the near-surface substrate stoichiometry or to the composition of native oxide layers. The peak energy of the transition has been studied as a function of excitation power and is found to increase from 1.392 eV at low power densities to 1.404 eV at higher power densities.

The effects of gas ambient changes on the photoluminescence intensity and conductivity of chemically cleaned (100) InP and GaAs have been investigated. The room temperature PL intensity of n-type, p-type, and Fe-doped semi-insulating InP was found to be reversibly changed by the presence of various gases at the semiconductor surface. The resistivity of thin film InP resistors was also found to be affected by gas ambient changes, both under illumination and in the dark. These measurements show that the surface Fermi level of InP is unpinned and is reversibly changed by exposure to different ambients. The PL intensity and surface conductivity of GaAs were also found to be sensitive to the gas environment, though to a lesser degree than InP. The responses of InP and GaAs are of a different nature and suggest that the surface state densities of these materials are reversibly affected by the chemisorption of oxygen. This in turn suggests that there are adsorbate-induced surface states on InP and GaAs which arise as a result of the interaction of adsorbed oxygen with the semiconductor surface and that are not associated with intrinsic semiconductor defects.

Gallium Arsenide Implantation Studies: Close contact rapid thermal annealing of semi-insulating GaAs:Cr implanted with Si, Si+Al, and Si+P has been studied using variable temperature Hall effect measurements and low temperature (4.2K) photoluminescence (PL) spectroscopy. Isochronal (10 sec) and isothermal (1000°C) anneals indicate that As is lost from the surface during close contact annealing at high anneal temperatures and long anneal times. Samples which were implanted with Si alone show maximum activation at an annealing temperature of 900°C, above which activation efficiency decreases. Low temperature Hall and PL measurements indicate that this reduced activation is due to increasing autocompensation of Si donors by Si acceptors at higher anneal temperatures. However, co-implantation of column V elements can increase the activation of Si implants by reducing Si occupancy of As sites and increasing Si occupancy of Ga sites, and thereby offset the effects of As loss from the surface. For samples implanted with Si+P, activation increases continuously up to a maximum at an anneal temperature of 1050°C, and both low temperature Hall and PL measurements indicate that autocompensation does not increase in this case as the anneal temperature increases. In contrast, samples implanted with Si+Al show very low activation and very high compensation at all anneal temperatures, as expected. The use of column V co-implants in conjunction with close contact RTA can produce excellent donor activation of Si implanted GaAs.

Gallium Arsenide Diffusion Studies: The diffusion of Ge into GaAs from a thin elemental source using rapid thermal processing has been investigated. Several types of encapsulants and substrates have been examined. The diffusion and activation of Ge have been found to depend on both the encapsulant and substrate growth conditions. Photoluminescence (PL) spectroscopy indicates that Ga vacancies may control dopant diffusion and activation. Very shallow n^+ junctions and nonalloyed ohmic contacts to semi-insulating GaAs have been formed. A comparison of secondary ion mass spectrometry (SIMS) atomic Ge profiles and carrier concentration profiles determined by differential Hall effect measurements shows that these n^+ layers are highly compensated. In our study of Ge pulse diffused into GaAs, we observed no evidence of Ge_{As} acceptors in either electrical or PL data.

C. FOLLOW-UP STATEMENT: This work will be continued under JSEP sponsorship. The implantation studies will concentrate on two issues: the study of deep levels induced by ion-implantation and annealing using deep level transient spectroscopy (DLTS), and the effects of co-implantation on the activation of amphoteric dopants and mobility. Studies will also be made on the activation of dopants and carrier mobility, when overpressures of different column V sources (P for GaAs and As for InP) are used during annealing.

For surface studies, photoluminescence spectroscopy will be continued as a study-tool of the surface properties of chemically treated InP wafers. These studies will enable the use of PL as a process monitor during fabrication of MIS devices. Investigation of InP/insulator fabrication processes will be made.

D. REFERENCES

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13. C.W. Farley, T.S. Kim, S.D. Lester, B.G. Streetman, and J.M. Anthony, "Complex Compensation of Ge Pulse Diffused into GaAs," in preparation.

14. C.W. Farley and B.G. Streetman, "Simulation of Anomalous Acceptor Diffusion in Compound Semiconductors," to appear in J. Electrochemical Society.

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*T.R. Block, C.W. Farley, T.S. Kim, S.D. Lester and B.G. Streetman, "Heating of GaAs and InP by Incoherent Radiation," 157-162 in Advanced Processing and Characterization of Semiconductors III, D.K. Sadana and M.I. Current, eds. Proc. SPIE vol. 623.

III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

*C.W. Farley, T.S. Kim and B.G. Streetman, "Co-Implantation and Autocompensation in Close Contact Rapid Thermal Annealing of Si-Implanted GaAs," presented at the Electronic Materials Conference, Amherst, MA (June 1986).

*C.W. Farley, T.S. Kim, S.D. Lester, B.G. Streetman and J.M. Anthony, "Complex Compensation of Ge Pulse Diffused into GaAs," presented at the State of the Art Program on Compound Semiconductors V, 1986 Fall Meeting of the Electrochemical Society, San Diego, CA (October 1986).

*C.W. Farley and B.G. Streetman, "The Gated Hall Effect Transistor and Its Application to Carrier Concentration and Mobility Profiling in GaAs MESFETs," presented at the State of the Art Program on Compound Semiconductors V, 1986 Fall Meeting of the Electrochemical Society, San Diego, CA (October 1986).

(Page 7, Res. Unit SSE86-1, "Implantation and Annealing of InP and Related Compounds")

IV. LIST OF THESIS AND DISSERTATIONS (*JSEP supported in whole or in part)

*Thomas R. Block, MS, May 1986, "Rapid Thermal Annealing System for the Processing of III-V Compound Semiconductors".

*Scott Chalmers, MS, December 1986, "An In-Depth Analysis of the Kelvin Resistor Structure".

*Gentry E. Crook, MS, May 1986, "Rapid Thermal Annealing of Silicon Ion Implanted Semi-insulating Indium Phosphide".

*Craig W. Farley, Ph.D., December 1986, "The Influence of Stoichiometric Variations on the Site Selection and Electrical Activity of Amphoteric Dopants in Gallium Arsenide and Indium Phosphide".

V. CONTRACTS AND GRANTS

National Science Foundation Grant ECS 8420002, "Studies of Ion Implanted Multilayer Heterostructures," Professor Ben Streetman.

THE UNIVERSITY OF TEXAS AT AUSTIN — ELECTRONICS RESEARCH CENTER SOLID STATE ELECTRONICS

Research Unit SSE86-2 MOLECULAR BEAM EPITAXY WITH HIGH-SPEED DEVICE APPLICATIONS

Principal Investigators: Professor Ben G. Streetman (471-1754)
Professor Dean P. Neikirk (471-4669)

Graduate Students: G. Crook, V. Kesan, C. Farley

A. <u>SCIENTIFIC OBJECTIVES:</u> The objectives of this work are to explore new physical phenomena arising in multilayer semiconductors and to identify potential device applications. The areas to be examined include growth of GaAs/AlGaAs by molecular beam epitaxy (MBE), studies of defects arising during growth and processing, and characterization of multilayer structures which have potential for applications in high-speed devices. The emphasis in the crystal growth work will be on fundamental issues of materials quality, doping and composition control, interface smoothness, layer thickness uniformity, and heterojunction properties.

The work on multilayer structures will emphasize their use in devices for very high frequency applications, such as monolithic integration with millimeter-wave and submillimeter-wave circuits. The potential for control of both doping and composition at a monolayer scale provided by molecular beam epitaxy makes it uniquely suited for these applications. Two prototypical examples of such devices are the GaAs TUNNETT diode, which may provide a low noise alternative to the IMPATT diode, and the AlGaAs/GaAs/AlGaAs quantum well resonant tunneling device, which may be useful as either a mixer or an oscillator at very high frequencies. Both of these devices place very stringent requirements on the control of the epitaxial growth process. Each of the following issues of molecular beam epitaxial growth must be addressed and characterized in this study: the required interface smoothness (and the related question of layer thickness uniformity); the generation of appropriate abrupt and hyper-abrupt doping profiles; and the close compositional control necessary for the heterojunction structures. The objectives of this study are to understand these three interrelated aspects of molecular beam epitaxial growth, and to apply the resulting growth capabilities to appropriate test structures for a careful study of device mechanisms. Once these issues are understood, work on the application of these techniques to the fabrication of high frequency devices will be done in collaboration with the unit EM86-1, "Millilmeter Wave Monolithic Array Components."

B. <u>PROGRESS:</u> During the first eight months of this contract, substantial progress has been made in developing Molecular Beam Epitaxy (MBE) growth techniques and applying these methods to high speed electronic device structures. The MBE system has been installed and characterized. A new quantum well injection transit time device (QWITT) device structure has been proposed and a small signal analysis has been performed. Trial transit time structures have been grown in the MBE facility and are presently being characterized.

<u>Molecular Beam Epitaxy</u>: The Varian Gen II MBE machine used in this research has been installed and is now operational. Initial growth runs were made to calibrate behavior of dopants in GaAs and AlGaAs as well as preliminary GaAs/AlGaAs heterojunction structures. Characterization methods currently being used on MBE-grown layers include photoluminescence, Hall effect, and deep level transient spectroscopy (DLTS) measurements.

A vital component of the MBE facility is a new extension of the reflection high-energy electron diffraction (RHEED) system to include extensive data acquisition capability. We have installed a CCD camera and a computer system to continuously display and store the diffraction pattern. This system is comprised of a Panasonic CCD camera with a manual focus, manual iris lens and an Imaging Technology image processing system run by a PDP-11/73 computer. The University has recently purchased and installed a Cray X-MP/24 supercomputer which will be used in some of the diffraction calculations. Monitoring oscillations in the RHEED pattern provides in-situ determination of material growth rates; in addition, comparing GaAs to AlGaAs growth rates allows in-situ determination of the Al composition of the alloy $Al_xGa_{1-x}As$. We have verified this Al composition measurement by comparison to photoluminescence measurements of the alloy bandgap energy. We have also used RHEED oscillations to calibrate the growth rate and Al mole fraction of multiple quantum well structures. PL characterization of these quantum wells indicate good control over well thickness and alloy composition.

We have grown GaAs layers with very low oval defect densities ($<100/cm^2$). Modulation-doped heterojunction structures (MODFETs) with 77K electron mobilities greater than 105 $cm^2/V.s$ have also been grown.

Device Studies: A new transit time device which uses resonant tunneling through a quantum well has been proposed and analyzed. Depending on the bias level, this device permits injection of carriers into the drift region at more favorable phase angles (hence higher efficiencies) than other transit time devices. The device promises low noise performance and should be capable of operating at high millimeter wave frequencies with higher output power than other transit time devices or pure quantum well oscillators. Since the device uses quantum well injection and transit time effects, it is called a QWITT diode. Small signal analysis has been performed, and the device seems to possess self starting oscillations.

C. FOLLOW-UP STATEMENT: This work is continuing. The progress made in the first eight months of this contract will make this next year very productive.

MBE studies: Our MBE-related research is in its early stages and will be central to our research program in the future. We are in the process of incorporating a nitrogen-ambient glove box into the sample preparation and loading procedure. This will allow the final preparation and loading of the samples to be done in a dry nitrogen atmosphere, and should help us to realize grown layers with consistently low oval defect densities. A LEED/Auger system is also being installed in the preparation chamber of the MBE to allow additional surface analysis of the wafers before and after growth.

Immediate goals include determination of the optimum sample preparation procedure for achieving low oval defect densities and optimum dopant incorporation, and determination of optimum growth conditions for growing high-quality AlGaAs on GaAs and GaAs on AlGaAs interfaces. Heterojunction structures will also be grown to study the effects of ion implantation and annealing of these structures. The ability to grow high-quality layers and interfaces by MBE and to control implantation and annealing processes in these structures will lead to the application of MBE to fabrication of high-frequency device structures.

Device Studies: Large signal analysis of the QWITT device is presently being attempted. Fabrication using MBE, and testing of the microwave performance of this device is also currently under way. The effect of various physical parameters of the quantum well on the output characteristics of this device will be studied in detail.

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III. LIST OF THESIS AND DISSERTATIONS

V.P. Kesan, MS, December 1986,"Quantum Well Devices."

IV. CONTRACTS AND GRANTS

Texas Advanced Technology Research Program, "Integrated Millimeter Wave and Optoelectronic Components for Very High Speed Communications Applications," Professor D.P. Neikirk, Principal Investigator; Professors B.G. Streetman, T. Itoh and A.B. Buckman, Co-Principal Investigators.

Texas Advanced Technology Research Program, "Multilayer Heterojunctions in III-V Semiconductors," Professor B.G. Streetman, Principal Investigator; Professors D.P. Neikirk, J.L. Erskine, L. Kleinman, F. Matsen and J. Stark, Co-Principal Investigators.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE86-3 EPITAXIAL GROWTH, STRUCTURE AND ELECTRONIC PROPERTIES OF SILICIDES ON SILICON SURFACES

Principal Investigator: Professor J.L. Erskine (471-1464)

Graduate Students: Jose Araya, Craig Ballentine and Dave Anacker

A. SCIENTIFIC OBJECTIVES: The primary objectives of this research unit are to establish accurate interface models for selected metal-semiconductor interfaces, explore growth mechanisms and transport phenomena which lead to interface related compound formation, and establish the relationship between the interface structure and electronic properties of selected metal semiconductor contacts and their electrical characteristics such as the Schottky barrier height.

Silicide compounds comprise an important class of metallic contacts for semiconductor applications. Silicides are formed by mass transport at an interface that accompanies the selective growth process.[1] The resulting metal semiconductor interface exhibits useful electrical characteristics including good conductivity by the metal film, and Schottky barrier behavior associated with the silicide-silicon interface.

A considerable amount of effort has been directed towards understanding the growth processes which produce silicide compounds, and defining the interface properties which control the Schottky barrier height.[2,3] Nearly all of the silicide-silicon interfaces that have been studied, have been produced by thermal annealing of a vacuum deposited metal overlayer to form the silicide. It is not surprising that the electrical characteristics (Schottky barrier height) of contacts formed using this process are nearly the same value.

Recent work [4-5] has suggested that microstructure at the interface can affect the barrier height, although some of the results appear to be in conflict.[6] One of the specific objectives of our work is to explore the relationship between interface microstructures and impurities and the Schottky barrier height of silicide-silicon contacts. Our approach to this involves a novel use of molecular beam epitaxial growth. Our plan is to produce epitaxial silicides on silicon substrates by a deposition of metal and silicon in the correct stoichiometric ratio. This synthesis technique will permit the fabrication of metal semiconductor interfaces without mass transport (ie bypassing selective growth). In this way, perturbations of the silicon surface should be preserved at the interface, and it will be possible to explore how the Schottky barrier is affected by various impurities and lattice imperfections at the interface.

B. PROGRESS: New experimental capabilities are required to carry out this work, and since our request for supplemental funding to purchase the equipment (MBE cells) was declined, we are constructing the required sources. This will cause a one year delay in beginning our proposed work.

Good progress has been made in related areas using existing instrumentation. In collaboration with colleagues at the University of Wisconsin, Milwaukee,[7] we have carried out an extensive investigation of the properties of Pb on Ge(111) surfaces. The Pb overlayer stabilizes a new crystal structure characterizing monolayer coverage which produces a $\sqrt{3} \times \sqrt{3}$ R30° unit cell. Valance band dispersion of electronic states of this metal-semiconductor interface system were determined by angle-resolved photoemission spectroscopy using synchrotron radiation as a source. The experimental data suggests that the overlayer remains semiconducting. Two Pb induced surface states were identified and characterized and are found to be related to intrinsic surface states associated with the Ge(111) c(2x8) surface. The Pb Ge system appears to be an interesting candidate for studies at greater coverages, especially if the interface states persist.

Some JSEP resources are being directed towards setting up an ultra-high precision optical/magneto-optical ellipsometer for thin film analysis using the magneto-optic Kerr effect and ellipsometry. This facility will be used primarily to investigate monolayer and multilayer epitaxial magnetic films, but should also have application to some of our proposed work on semiconductor surfaces and interfaces. We have completed the construction of the ellipsometer, and have bench tested it. The new instrument achieves stability sufficient to detect one arc second changes in polarization.

Additional JSEP sponsored work has been done in collaboration with Mike Downer (JSEP Research Unit SSE86-4). The objective of this joint effort is to combine femptosecond pulse excitation of a semiconductor with surface science preparation techniques and angle-resolved photoelectron emission, spectroscopy to study the momentum distribution (transport dynamics) of hot electrons injected into the conduction band across the band gap by a fast optical pulse. Present efforts are directed towards demonstrating feasibility of the technique. The experiment is based on a pump-probe concept in which two very short pulses are used to first create electron hole pairs in the semiconductor by optical excitation (pump pulse), and then probe the electron (probe pulse) in the conduction band by photoemission before relaxation (to k=0) or recombination occurs.

C. FOLLOW UP STATEMENT: The projects described above represent new approaches which are only beginning to be explored. The effort in which MBE will be used to bypass selective growth will be pursued to a point where the concept is either shown to be feasible or impractical. Feasibility of growing epitaxial silicides and bypassing selecting growth will result in a new method for fabricating silicide based Schottky barriers which will permit parameter variation of interface composition and structure. This capability is likely to lead to a more thorough understanding of interface parameters that determine the Schottky barrier, and experimental tests of several models of the barrier height.[8-11]

Precise optical measurements of thin films and interfaces can in principle provide information which is not available from electron spectroscopy because the penetration depthof electrons is limited to a few angstroms. Magneto-optical measurements of epitaxial magnetic films offers unique new opportunities for probing the relationship between structure and magnetism. This effort will be continued until the sensitivity of the technique to monolayer magnetic structures has been clearly established. This project is partially supported by NSF.

The joint effort to combine femptosecond excitation with angle-resolved photoemission offers unique opportunities for probing dynamical effects in solids.[12] Our crude attempts to detect signals can be refined in a number of ways before limits of detection are reached, and until it is clear that a fundamental detection limit has been achieved in the experiments, these experiments will be continued under JSEP support.

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III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

Colloquium "Thin Film Magnetism: New Interest in an Old Topic", J. L. Erskine, Department of Physics, University of Florida, Gainesville, Florida, March 2, 1986.

Invited Talk "Hydrogen Interactions at Niobium and Niobium Based Alloy Surfaces", J. L. Erskine, Symposium of the American Chemical Soc., Denver, Colorado, June 8-12, 1986.

Invited Talk "Photoemission Studies of Surface Magnetism", J. L. Erskine, Bull. Am. Phys. Soc. 31, 1004 (1986).

Invited Talk "Photoemission Studies of Magnetic Thin Films", J. L. Erskine, Atlanta Synchrotron Radiation Conference (Sponsored by Southeastern Universities Research Association) Georgia Institute of Technology, Atlanta, GA, May 8-9, 1986.

Workshop "Entrance Mirror Figure Error Effects on Flux and Resolution for a Six-Meter TGM", D. C. Anacker, L. H. Breaux and J. L. Erskine, Brookhaven Workshop on X-ray Optics: Problems in Materials, Manufacturers and Performance, Upton, Long Island, N.Y., May 28-30, 1986.

Invited Talk "Electron Energy Loss Studies of Chemisorbed Underlayers at Metal Surfaces", J. L. Erskine, Department of Chemistry, University of Wisconsin, Madison, Wisconsin, Oct. 23, 1986.

Workshop/Invited Talk "Magnetic Materials Research Using Synchrotron Radiation", J. L. Erskine, Waterfall Glen Conference Series, Argonne National Lab, Argonne, Illinois, Oct. 8-10, 1986.

Conference "High Resolution Low Energy Electron Diffraction Studies of W Using an Electron Energy Loss Spectrometer", J. P. Woods and J. L. Erskine, 33rd National Symposium of the American Vacuum Society, Boston, Massachusetts, Oct.27-31,1986.

Invited Talk "Exploring Magnetic Properties of Surfaces, Epitaxial Films and Interfaces", M. A. Thompson, M. F. Onellion and J. L. Erskine, Annual Meeting of the Materials Research Society, Boston, Massachusetts, Dec. 2-5, 1986.

IV. LIST OF THESIS AND DISSERTATIONS

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(Page 6, Res. Unit SSE86-3, "Epitaxial Growth, Structure and Electronic Properties of Silicides on Silicon Surfaces")

V. CONTRACTS AND GRANTS

The Robert A. Welch Foundation Welch F-1015, " Electron Scattering Studies of H/Nb(100)," Dr. J.L. Erskine, Principal Investigator, 1985-1988.

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Joint Services Electronic Program, "Epitaxial Growth, Structure and Electronic Properties," Dr. J.L. Erskine, Principal Investigator, 1986-1988.

Research Unit SSE86-4: FEMTOSECOND PROCESSES IN CONDENSED MATTER

Principal Investigator: Professor M. C. Downer (471-6054)

Graduate Students: Glenn Focht and David H. Reitze

A. SCIENTIFIC OBJECTIVES: We seek new insight into the physics of ultrafast fundamental processes in technologically important solids using the techniques of femtosecond laser spectroscopy. We focus, first of all, on the direct observation of those microscopic femtosecond carrier relaxation channels, in particular those mediated by carrier-carrier, carrier-phonon, and carrier - plasmon interactions, which ultimately determine the important macroscopic electronic and transport properties of materials. Secondly, we seek to study carrier transport directly in microelectronic device structures using femtosecond laser techniques. Finally we seek to improve and develop femtosecond optical measurement techniques and sources in new directions which will optimize our capability for experimental study of ultrafast processes.

B. PROGRESS: During the first year of JSEP funding, progress has centered on construction of a femtosecond laser laboratory, and initial efforts on several experiments, as summarized below.

Instrumentation: Since this was a new research unit based on a new laboratory, much of the effort during the first year of JSEP funding was devoted to building up an appropriate experimental system. A state-of-the-art femtosecond dye laser, based on the cw pumped colliding pulse mode locking concept [1], was completed by December 1985. With the aid of intracavity dispersion control using Brewster angle prisms [2], pulse durations of 50 fsec. are now achieved routinely. We also have a cavity dumping capability [3], which permits higher pulse energy output along with variable repetition rate, which is especially valuable for pulse injection into an amplifier system.

Construction of a 5 KHz repetition rate amplifier system based on a copper vapor laser pump source [4] is also nearing completion. Pulse energies of 0.5 microjoule have been obtained, and several fold improvement is anticipated shortly. Efficient frequency conversion by white light continuum generation has been demonstrated. Since this amplifier system will be the mainstay of much of the experimental work, efforts are concentrated on making it totally reliable.

Construction of a second amplifier system for achieving millijoule pulse energies at a 10 Hz repetition rate, based on a frequency doubled Nd: YAG laser pump source [5], has just begun. All parts have now been procured for this system, which will complement the lower power system in applications requiring highly energetic pulses. We have designed and procured a novel gain cell for this amplifier based on an "axicon" geometry proposed by Schafer [6]. The expected advantages of the new design over conventional gain cells [7] are more efficient amplification and improved cross sectional beam profile, allowing tighter focussing and thus higher peak intensity.

Femtosecond Angle-Resolved Ultraviolet Photoemission Spectroscopy: With collaboration from Professor J. L. Erskine (Research Unit SSE86-3), we are developing a powerful new technique for directly measuring *momentum* , as well as energy, relaxation of hot carriers on a subpicosecond time scale. This experiment builds upon several years of success of angle-resolved ultraviolet photoemission spectroscopy (ARUPS), performed largely with synchrotron-based light sources, in directly mapping $E(\underline{k})$ band structures of unexcited solids through analysis of the angular distribution of photo-emitted electrons [8]. Recent work at AT&T Bell Laboratories [9] has shown that, using picosecond laser sources, one can apply ARUPS to the study of photo-excited transient electron populations in solids and their dynamics. Our extension to femtosecond laser sources adds a powerful new dimension, since photo-excited hot carriers can be probed (i.e. photo-emitted) in the course of subpicosecond relaxation processes such as intravalley and intervalley electron-phonon scattering. With the angle-resolved photoemission technique, we will have the capability to determine the momentum change $\Delta\underline{k}$ as well as the energy change ΔE which accompanies such an electron-phonon scattering event. This overcomes a major limitation of femtosecond spectroscopy, and permits much more direct testing of theories of electron-phonon coupling than has been previously possible.

Preliminary measurements have begun with the intention of demonstrating the long term feasibility of this experiment. Professor Erskine has provided high vacuum, electron detection and analysis, and surface preparation and diagnostic equipment, as well as previous experience with ARUPS methods. We have been working so far with an unamplified femtosecond laser source. We have developed an effective new ultraviolet probe source for this experiment, described in more detail below, by using intracavity second harmonic generation in the femtosecond laser. Using this source we have detected substantial (signal to noise ~ 100) single beam photoemission signals from a low work function sample (gadolinium, ϕ = 3.1 eV.) using a primitive angle-resolved electron detector of the cylindrical mirror analyzer (CMA) design and a minimum of signal averaging. By upgrading to a multichannel hemispherical detector, which Erskine has already ordered, improvement of two to three orders of magnitude in detector sensitivity is anticipated. The eventual time-resolved experiment will employ a pump and probe method, in which the ultraviolet probe pulse will photo-emit electrons from the transiently excited population, which will typically be three to five orders of magnitude less dense than the ground state electron population. With the improved detector, however, and with the additional advantages of signal averaging, lock in detection, and amplified laser pulses are taken into account, the preliminary results show that available detection sensitivity for time-resolved photoemission will be adequate. Photo-emitted electrons from the transient population will be easily distinguishable from background electrons emitted from below the Fermi level, since they will have higher energy. Preliminary testing will continue in an effort to detect actual time-resolved photoemission signals, even with the present crude detection scheme. As the amplifier systems come on line, their applicability to the experiment will also be investigated. Probe pulse energy will have to be kept low enough to avoid distortion of the energy and angular distribution of the photo-emitted electrons by space charge effects.

It is anticipated that our first time-resolved experiments will be performed on silicon, for which the surface photoemission has been well characterized. Theoretical work in the Microelectronics Research Center is being carried out to model electron-phonon scattering processes in $Al_xGa_{1-x}As$ using Monte Carlo methods. Femtosecond ARUPS will be an ideal tool for testing these calculations. Extension to time-resolved surface adsorbate spectroscopy should be possible.

<u>Femtosecond Intracavity Harmonic Generation</u>: Although numerous femtosecond dye laser sources have recently been developed which operate over a wide spectral range [10], high repetition rate sources of *synchronized* femtosecond pulses in widely separated spectral regions are still lacking. We have developed an unamplified source of synchronized red and ultraviolet pulses at 100 MHz repetition rate by intracavity frequency doubling in our passively

mode-locked femtosecond laser [11]. While intracavity frequency doubling has been demonstrated in other types of lasers, the primary novelty in the femtosecond laser is the avoidance of the otherwise prohibitive dispersive broadening effect of the intracavity crystal by using intracavity Brewster angle prisms for dispersion compensation [2]. We have thereby generated 310 nm. pulses of nearly a picojoule energy, and 100 fs. duration, while maintaining a red pulse width of 50 fs. This is a factor of 10^4 higher conversion efficiency than can be achieved by extracavity frequency doubling, because of the hundredfold higher energy of the intracavity pulses. This UV source can serve as seed pulses for injection into a recently developed XeCl subpicosecond pulse amplifier at 308 nm.[12]. It also provides a suitable probe pulse for our photoemission experiment described above. An interesting extension will be intracavity *third* harmonic generation by juxtaposing a second intracavity crystal with the first to mix the fundamental with the second harmonic. Availability of both second and third harmonic probe pulses will greatly increase the flexibility of the photoemission experiment.

<u>Solid State Carrier Dynamics</u>: Work is progressing on our investigation of time-resolved photo - displacement spectroscopy described in the original proposal. The position sensitive detector used in this experiment has been procured and equipped with sensitive signal processing electronics with the assistance of the Physics Department electronics shop. As a preliminary test, we have detected photothermal displacement signals resulting from cw laser heating of various solid surfaces. These results were consistent with literature values [13] for detector sensitivity. Initial attempts to detect time resolved displacement signals using unamplified femtosecond excite and probe pulses have been made, but so far only a DC background has been observed. We have determined that the high repetition rate (100 MHz) of the unamplified source leaves the sample insufficient time to cool in between pulses, resulting in cumulative heating of the semiconductor and metallic surfaces by successive pulses. The resulting DC signal dominates the transient heating effect. As our next step, therefore, we will excite the samples with amplified pulses at a much lower repetition rate, using our 5 KHz amplifier which is just now coming on line. Besides transient thermal effects, we are investigating the use of time-resolved photo-displacement spectroscopy to study nonthermal effects such as photostriction at semiconductor samples caused by dense transient electron-hole plasmas [14], or probe deflection caused by transient refractive index gradients in a sample [15]. In these latter applications we expect photodisplacement spectroscopy to be more sensitive than conventional optical measurement techniques such as reflectivity, absorbance, or ellipsometry.

<u>Picosecond Pulse Propagation on Transmission Lines</u>: With collaboration from Professor D.P. Neikirk (Research Unit EM86-1), we are using the femtosecond laser as an electro-optic sampler (16) to investigate picosecond electrical pulse propagation on transmission lines mounted on unique multilayer AlGaAs/GaAs substrates. Such structures are being developed by Professors Neikirk and Itoh (17) as millimeter wave phase shifters. The high frequency behavior of such structures are difficult to study electrically because of the parasitic capacitance introduced by electrical contacts. Our experiment, by contrast launches the picosecond electrical pulse by optically shorting the biased waveguide, then probing electro-optic effects downstream, thus avoiding parasitic effects altogether. The phase shifter furthermore provides a unique opportunity to study the effect of a lossy substrate on picosecond pulse propagation, since the multilayer substrate contains a precisely located GaAs loss layer in which electron-hole plasma density is externally controlled by cw optical illumination. Substrate loss, which is typically an unknown and uncontrolled parameter, introduces frequency dependent slow wave phenomena, which can strongly disperse propagating picosecond pulses. Our structure has the advantage of precisely known and controllable substrate loss, thus allowing detailed study of picosecond pulse dispersion under well known experimental conditions.

Our preliminary theoretical modelling (18) of picosecond pulse propagation in such a structure predicts strong effects due to varying the electron-hole pair density in the substrate layer. Surprisingly such calculations have shown that relatively high substrate carrier densities (10^{17} cm^{-3}) disperse a propagating picosecond pulse substantially less than lower densities (~ 10^{15} cm^{-3}). Experimental data will be essential, however, because of theoretical and numerical complications in the analysis.

Experimentally, our frequency doubled femtosecond pulses, described above, will serve as pump (shorting) pulses, while electro-optic probing will be done with the fundamental red pulses. The multilayer substrate structure is currently being grown in the MBE system in the Electrical and Computer Engineering Department (see Research Unit SSE86-2).

<u>Femtosecond Transport Processes in Microelectronic Device Structures</u>: A new generation of microelectronic devices and circuits will be based on transport processes, such as ballistic transport and quantum tunneling, which involve transit times on a femtosecond scale across submicron semiconductor layers. While extensive theoretical treatments of such phenomena have appeared, experimental studies on a femtosecond time scale are nearly totally lacking. We have begun detailed theoretical modelling and planning of experiments which will make use of femtosecond optical pulses to inject and probe carriers locally in order to study the physics of femtosecond transport while avoiding the parasitic influence of electrical contacts. A major problem which must be addressed in such experiments is the need for high spatial resolution, since optical absorption (and therefore carrier injection) depths at near band gap wavelengths (typically ~ 1 μm.) greatly exceed the thickness of the semiconductor layers in which many femtosecond transport phenomena occur (typically ~ 0.1 μm. or less).

We have theoretically investigated (19) attenuated total reflection as a means of collapsing optical absorption to as little as 200 Å. In this method, a light pulse passes through a high index (n) dielectric medium to the interface with a lower index (n') lossy semiconductor layer at an incident angle greater than the critical angle $\sin^{-1}(n'/n)$. Energy is absorbed from the evanescent wave, which has a penetration depth of approximately 200 Å, in the form of photo-excited carriers. This constitutes a thirty-fold reduction in absorption depth over normal incidence absorption. Trigonal selenium is a possible candidate for the internal reflection element for coupling to GaAs, although good optical quality samples have proven difficult to find.

We are also planning a femtosecond optical experiment to resolve temporally the evolution of carrier flow through a resonant tunneling structure. A recent calculation using a Wigner function model [20] predicts a transient response over a time scale of a few hunred femtoseconds. It is desirable to localize carrier injection as close as possible to the first barrier layer so that carrier drift within the contact region does not become a major parameter in the experiment. We believe this can be achieved by appropriate compositional grading of the injection contact region, so that absorption occurs only in the lowest gap part of the contact, near the first AlAs barrier. Plans for the growth of a resonant tunneling structure appropriate for this experiment have been discussed with Professor B.G. Streetman (Research Unit SSE86-2) and with M.R. Reed of Texas Instruments, Inc. Optical experiments are anticipated during the second or third years of the funding period.

C. <u>FOLLOW-UP STATEMENT</u>: Work will continue on further development of our experimental system, as well as its application in the experiments outlined above. Construction of the high power amplifier pumped by a frequency doubled Nd: YAG laser is expected during the second year. We will continue our efforts to measure time-resolved photoemission signals with our current prototype detection system, and will explore various excitation and probe schemes, most likely incorporating the new amplifier systems. Perfection of our intracavity harmonic generation technique is expected to play an important role in this experiment. Sometime during the second year we anticipate installing a hemispherical analyzer which will allow full angular resolution of photoemitted electrons. Our newly operational 5 KHz amplifier system will be put to additional use in the photo-displacement experiment. We also expect to initiate work on plasmon- aided recombination processes in germanium with this system, as described in the original proposal. We expect growth of at least a prototype millimeter wave phase shifter to be completed shortly, which will allow experimental work on the picosecond electricalpulse propagation problem to get underway during the second year. Work will continue on design and growth of samples for the femtosecond transport studies, although the actual experiments are not expected to begin until the third year.

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18. C. K. Tzuang, D. Miller, T. H. Wang, T. Itoh, D. P. Neikirk, P. Williams, and M. C. Downer, to be presented at Optical Society of America Topical Meeting on Picosecond Electronics and Optoelectronics, Lake Tahoe, Nevada, January, 1987.

19. M. C. Downer, D. H. Reitze, and T. R. Zhang, to be presented at Optical Society of America Topical Meeting on Picosecond Electronics and Optoelectronics, Lake Tahoe, Nevada, January, 1987.

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I. LIST OF PUBLICATIONS

NONE

II. LIST OF CONFERENCE PROCEEDINGS

M. C. Downer, D. H. Reitze, and T. R. Zhang, "Longitudinally Localized Optical Carrier Injection for Femtosecond Transport Studies", Optical Society of America, Topical Meeting on Picosecond Electronics and Optoelectronics, Lake Tahoe, Nevada, January 1987.

C. K. Tzuang, D. Miller, T. H. Wang, T. Itoh, D. P. Neikirk, P. Williams, and M. C. Downer, "Picosecond Response of an Optically Controlled Millimeter Wave Phase Shifter", Optical Society of America, Topical Meeting on Picosecond Electronics and Optoelectronics, Lake Tahoe, Nevada, January 1987.

III. LIST OF PRESENTATIONS

NONE

IV. LIST OF THESES AND DISSERTATIONS

NONE

V. CONTRACTS AND GRANTS

Texas Advanced Technology Research Program, "Femtosecond Optical Probing of Ultrafast Electronics and Surface Processes", Professor M. C. Downer, Principal Investigator.

Robert W. Welch Foundation, "Femtosecond Spectroscopy of Biological Molecules," Professor M.C. Downer, Principal Investigator.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE86-1 NONLINEAR OPTICAL INTERACTIONS

Principal Investigator: Professor H. J. Kimble (471-1668)

Visiting Scientist: Dr. Huifa Wu

Graduate Students: T. L. Boyd, R. J. Brecha, L. A. Orozco, L. A. Wu

A. SCIENTIFIC OBJECTIVES: With the support of the Joint Services Electronics Program we have undertaken a research program in the field of quantum optics with the objective of investigating the dynamical instabilities that result from the nonlinear coupling of a collection of atoms to the electromagnetic field. In general terms the systems that we are attempting to understand can undergo rather dramatic changes in their physical characteristics as a result of only minor changes in certain control parameters. We wish to characterize the various possible "phases" or operating states of these systems, including the stability of states to perturbations, the transitions between states, and perhaps most importantly the manner in which these systems are unique because of the quantum nature of the atom-field coupling. Towards this end two experiments are underway in the Quantum Optics Laboratory in Austin. One is the study of the phenomenon of optical bistability; the other is an investigation of the harmonic/subharmonic conversion of light in the presence of an optical resonator. While a range of interesting phenomena are expected and observed in each experiment (optical hysteresis, transverse spatial switching, ...), the principal focus of the current research program is the investigation of oscillatory instabilities exhibited by these two systems. The term "instability" is perhaps misleading, since it implies that the oscillations that we observe are unstable. This is of course not the case, but rather steady states that are time independent become unstable and give rise to stable time dependent states which exhibit complex, high frequency oscillations that persist indefinitely.

With regard to the specific objectives of the work, a quantitative comparison between theory and experiment is stressed in both the optical bistability and frequency doubling experiments. The experiments are in a sense prototypes for a large class of nonlinear systems. The frequency doubling experiment involves the simplest parametric coupling, namely an E^2 (E=electric field) term through the second order nonlinear susceptibility. The self-pulsing behavior in optical bistability is due to the nonlinearity $1/(1+E^2)$, which describes the most fundamental saturation behavior in nonlinear optics.

It is our objective to explore the characteristics of these new oscillatory states in quantitative detail. Questions being addressed include the stability to perturbations, both externally produced and as a result of the system's own internal (intrinsic) noise. We are extending our current work in optical bistability to yet higher atomic density to search for yet more complex dynamical states. The spectral characteristics of the oscillations are currently being analyzed by radio frequency techniques, and further information about their dynamical character will be obtained by digital time series techniques in future experiments.

B. PROGRESS: In recent years optical bistability has been the subject of intense investigation both for its significance in fundamental studies in optical physics and for its potential applications to optical signal processing. Within the context of the understanding of nonequilibrium processes, it is important to obtain a precise characterization of the dynamic behavior in optical bistability in terms of the relevant control parameters and their effect on the stability of the system. Given the complexity of many optical systems such a characterization is often possible only if one examines a situation in the simplest conceptual setting. We have worked towards this end experimentally with a system of two state atoms interacting with a single mode of a high Q optical interferometer. Our investigation is thus one of optical bistability with two level atoms [1-8].

The actual appartus consists of 10 well-collimated, optically prepumped beams of atomic sodium intersecting at 90°the axis of a high finesse interferometer, which may be operated in either a confocal (mode-degenerate) or nonconfocal (non-degenerate) configuration. In the ring configuration and with optical prepumping we have reached values of the effective cooperativity parameter, Ce, as high as 30 times the value for the critical onset of bistability (Ce is defined as one half the ratio of atomic losses to cavity losses and is a central control parameter). The dominant atomic relaxation process in our system is purely radiative although other broadening mechanisms are also present. The transit of the atoms through the interaction region effectively changes the transverse relaxation rate from 5 MHz (its natural value) to 6.25 MHz and hence alters $\gamma_{11}/\gamma_{\perp}$ from 2.0 to 1.6. Absolute calibrations of input and output detectors, atomic absorption and empty cavity characteristics enable absolute determination of the scaled input and output intensities (Y,X) and of the cooperativity Ce so that we are able to make contact with theoretical prediction free from any adjustable parameters. Over the past several years this work has produced a detailed quantitative characterization of the steady states in absorptive bistability [1-5]

Our present investigation is directed toward dispersive bistability. In the parameter space of cavity and atomic detunings (denoted θ, Δ in units of cavity and atomic decay rates, respectively) we have observed regions of dynamic instability characterized by self pulsing states at frequencies 20-150 MHz together with dramatic changes of the time averaged input-output characteristics [7-8]. This instability shares its physical origin with many of the instabilities observed in optical bistability and in the laser. The strong field driving the atoms inside the cavity radically alters their absorption profile inducing gain at frequencies away from the driving field. By detuning the cavity to such a frequency while keeping the intracavity field constant one can enhance the region of gain and obtain a beat note between the intense driving field and the new frequency that arises if the roundtrip gain exceeds the losses. However, relative to multimode instabilities such as the Ikeda instability [9], the intracavity field must satisfy a rather stringent condition associated with nonlinear dispersion in the single-mode cavity. Thus this simple picture must be complemented by a careful analysis of both gain and dispersion in the single-mode cavity in a fashion similar to that in the analysis of the single-mode laser instability.

For fixed values of Ce and of the cavity linewidth we have attempted to construct absolute, quantitative maps of the instability boundaries in the parameter space θ-Δ. In Figure 1 such a map is shown, together with a comparison with the theoretical results of a linear stability analysis [10] carried out with the mean-field and single-mode approximations. In view of the absolute nature of the comparison, the agreement is quite reasonable.

A further exploration of the role of transverse structure in the single-mode instability in optical bistability is provided by full numerical solutions of the Maxwell-Bloch equations in both the plane-wave and Gaussian-beam approximations and by comparisons of these results with each other and with experiment. A treatment employing the plane-wave and mean-field limits of the Maxwell-Bloch equations predicts a rich variety of higher order bifurcations including period doublings and intermittency [11]. An extension of this work to include the transverse dependence of the intracavity field reveals no significant qualitative differences between the plane-wave theory and the Gaussian beam theory as regards the stability boundaries obtained from a linearied analysis [10]. The instability persists in the presence of a Gaussian transverse profile and the boundaries are not radically modified compared to those obtained from the plane wave theory. However, numerical integration of the Maxwell-Bloch equations in the single transverse-mode approximation does not show the wealth of higher order dynamical states present in the plane-wave case. Our experimental investigation of optical bistability for two-level atoms in a single-transverse, single-longitudinal mode cavity exhibits limit cycle oscillation with stability boundaries that agree well with the boundaries obtained from the work in Ref. [10]. However, for the range of values $C<300$, $|\Delta|<5$, $|\theta|<50$, $X \approx 10^2$ the experimental results do not show the diversity of higher dynamical states expected from the plane-wave theory, in agreement with the numerical results. As well the measurements support the existence of a single transverse mode oscillation. The sum of the theoretical and experimental work indicates that, while limit cycle instabilities persist when one moves from a plane-wave to a spatially varying field mode, higher order dynamical states are suppressed if not lost altogether. In a single-mode cavity the Gaussian profile has a profound effect. This detailed comparison of theory and experiment is being undertaken in collaboration with L. M. Narducci at Drexel University and with L. A. Lugiato at The University of Milan.

The second experiment in our laboratory studying dynamic instabilities involves harmonic/subharmonic conversion. The basic apparatus consists of a nonlinear crystal inside an optical resonator in which both the fundamental frequency ω_1 and the second harmonic frequency $\omega_2 = 2\omega_1$ are resonant. The interferometer is driven by an external frequency stabilized source. At sufficiently high levels of excitation, the competition between the fundamental and harmonic modes for the available energy can lead to spontaneous pulsations, which are predicted to be quite regular over indefinite intervals. Further increase in driving power produces bifurcations to even more complex oscillatory states [12].

We have investigated a variety of nonlinear crystals for use in these experiments. Samples of barium sodium niobate and of lithium niobate doped with magnesium oxide look promising. The actual interferometer is somewhat complicated since the conditions which optimize the frequency doubling are incommensurate with the cavity boundary conditions. Xenon gas is used between the crystal and cavity mirrors to adjust the phases of fundamental and harmonic fields in order to optimize conversion efficiency. This circumstance is not peculiar to our experiment but is a feature of nonlinear processes in general. We have addressed the question of interference effects in second harmonic generation in a recent publication [13].

With the current experiment, we have observed signatures of dispersive bistability as the detuning of the cavity is swept for a constant injected field. There is clearly an appreciable conversion of the intracavity field at frequency $\omega_1$to the harmonic field at frequencey $2\omega_1$. Indeed this conversion should result in the appearance of instability. The difficulty that we encounter is that the ratio R of loss rates of the harmonic field (γ_2) to that for the fundamental field (γ_1) is too large. While for both frequencies the finesse is quite high, we have essentially constructed a cavity of too high a quality at the fundamental . Since the threshold power for selfoscillation scales as R^3 for $R > 1$, the high finesse at ω_1 relative to that at $2\omega_1$ means that our current pump power is insufficient to reach threshold. The solution to this problem should be straightforward. We need to slightly degrade the cavity quality at ω_1 by increasing the transmission coefficient of the cavity input coupler, while at the same time improving the quality of the dual band antireflection coating on the intracavity crystal. We have been dealing with several vendors and seem to have finally found a source for low loss dual band coatings that meet our specifications. With these modifications, I believe that the instability should be readily observed.

C. FOLLOW-UP STATEMENT: At present it is not clear whether the transverse profile of the intracavity field results in a complete elimination of higher order dynamical states. Both Narducci at Drexel and Lugiato at Milan are making extensive numerical investigations of the Maxwell-Bloch equations to answer this question. Experimentally we follow a course suggested by Figures 2 and 3. These figures show the stability boundaries predicted from our implementation of the linear stability analysis given in Ref. 10. Figure 2 demonstrates the rapid growth of the domain of instability (the regions inside the full curves are unstable) with increasing cooperativity parameter C. The plot is in the plane of atomic detuning Δ and cavity detuning $\kappa\theta$, both in units of the polarization decay rate $\gamma_{\perp}$, for fixed KAPPA = (cavity decay rate)/$\gamma_{\perp}$ and GAMMA = (energy decay rate)/$\gamma_{\perp}$. To access the larger instability domain indicated, we have successfully optically prepumped the sodium beam with a second laser to transfer population from the normally unused F=1 hyperfine ground state to the active F=2 ground state, resulting in a 60% increase in C. We are also considering a new array source for our source oven to increase C still further.

Perhaps the most important research direction that we have identified with our numerical analysis is indicated in Figure 3, which shows the domain of instability in the ($\Delta,\kappa\theta$) plane at fixed C and GAMMA, but for increasing values of KAPPA. By increasing KAPPA we are effectively moving to the situation of a large cavity damping rate relative to the atomic time scale. Note that the stability boundaries are relatively insensitive to the value of KAPPA for small KAPPA < 1 (our previous experimental work was for KAPPA $\approx$ 0.6). However, for large KAPPA $\approx$ 10 there is a dramatic increase in the size of the instability domain, suggesting the possibility of higher order dynamical states. We plan to explore this potentially exciting regime by employing a short cavity (0.9mm length) with KAPPA $\approx$ 8. The new cavity has been installed in the vacuum chamber and a new set of experiments is being undertaken.

In parallel with our effort to reduce the ratio of loss rates γ_2/γ_1, we have investigated the operation of our system as an optical parametric oscillator. In this configuration, the cavity is driven at the second harmonic frequency 2ω rather than at the fundamental frequency ω. We have observed both degenerate and nondegenerate operation, and have made an investigation of the deterministic phase space of the system. With new dielectric coatings for both the cavity mirrors and the frequency doubling crystal, we will return to the investigation of dynamical instability with a pump field at the fundamental frequency.

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III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

M. Xiao, R.J. Brecha, L.A. Orozco, M.G. Raizen, and H.J. Kimble, "Oscillatory Energy Exchange Between a Set of Two-Level Atoms and Cavity Field," paper presented APS Conference, Dallas, Texas (April 5, 1986).

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R.J. Brecha, L.A. Orozco, M.G. Raizen, M. Xiao, and H.J. Kimble, "Mode Splitting for Two-Level Atoms Inside an Optical Resonator," paper presented at the XIV International Quantum Electronics Conference, San Francisco, California (June 9-13, 1986).

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IV. LIST OF THESIS AND DISSERTATIONS

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V. CONTRACTS AND GRANTS

National Science Foundation, PHY 8211194, "Cooperant Atomic Activity in Optical Bistability (Physics)," Professor H.J. Kimble, Principal Investigator, January 1983-June 30-1986.

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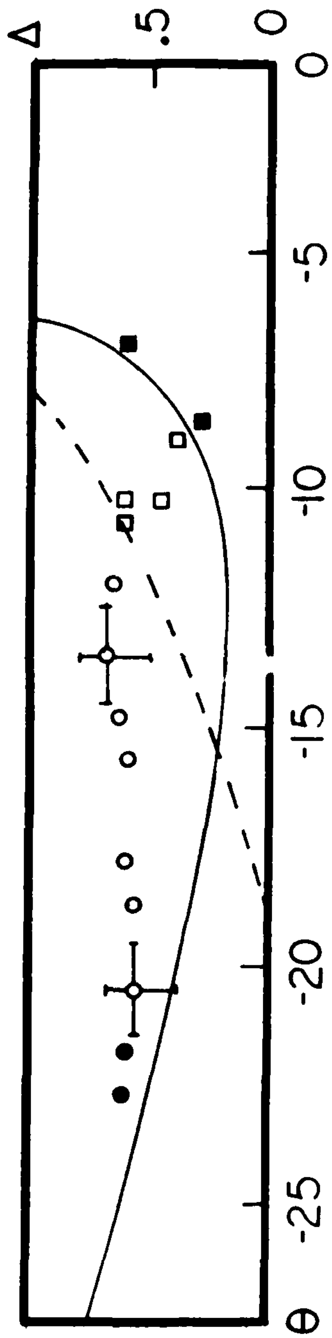

Figure 1. Domain of instability in the detuning space (Δ = atomic detuning, θ = cavity detuning) for a confocal, standing wave cavity and Ce = 95 ± 5. Filled dots and squares indicate stability, empty ones instability. Squares imply bistability while dots are for no bistability. To the right of the dashed line is the predicted bistable region and above the continuous line is the predicted unstable region.

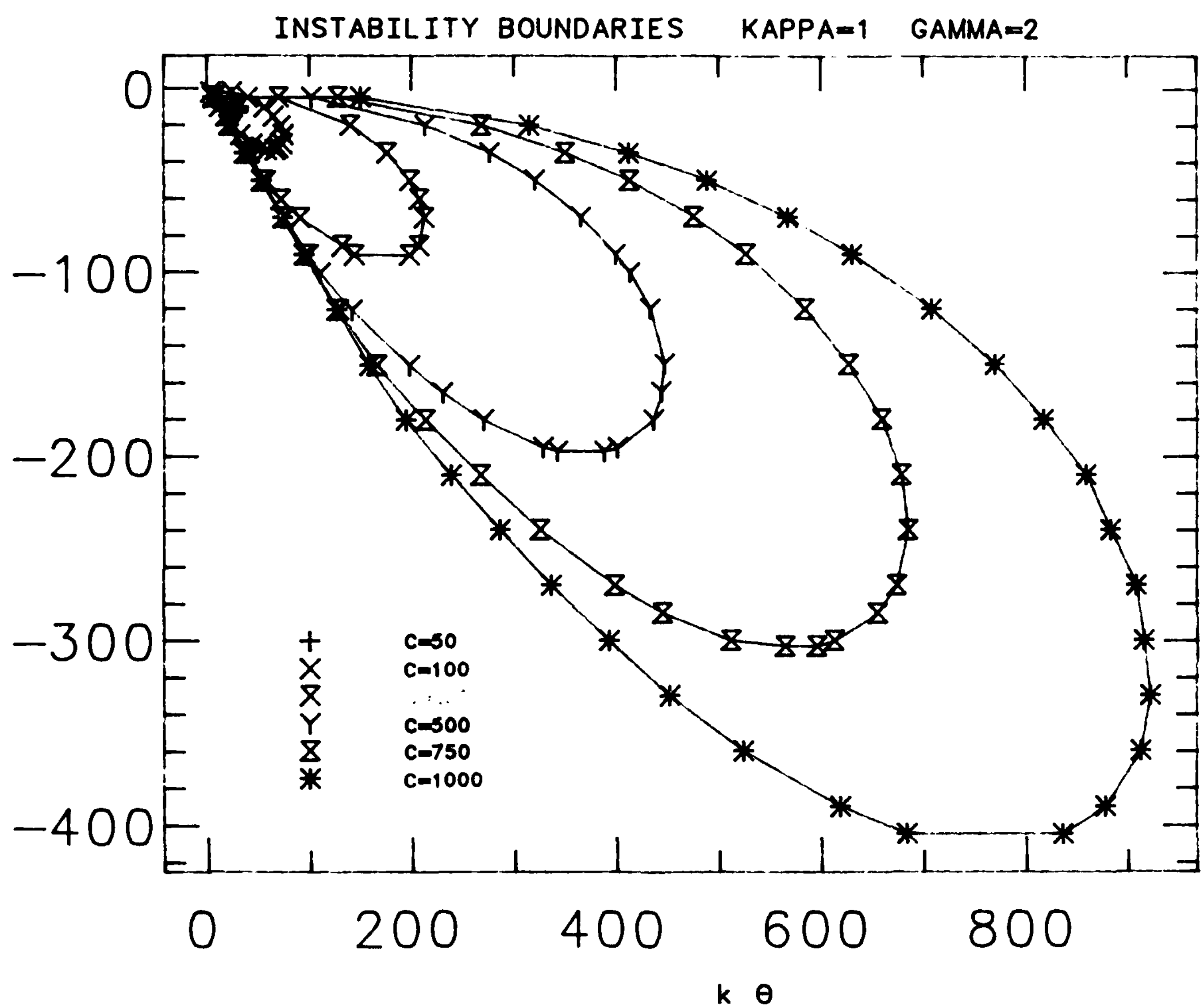

Figure 2. Boundaries separating domains of stable (time-independent) operation from the domain of dynamical instability. The regions enclosed by each full curve are unstable. The curves are drawn in the plane of atomic detuning Δ and cavity detuning $\kappa\theta$ for increasing values of the atomic cooperativity parameter C, as indicated. The ratio KAPPA of cavity decay rate to atomic polarization decay rate equals 1, and the ratio GAMMA of atomic energy decay rate to atomic polarization decay rate equals 2 (radiative broadening). Note the rapid increase in the domain of instability with increasing C.

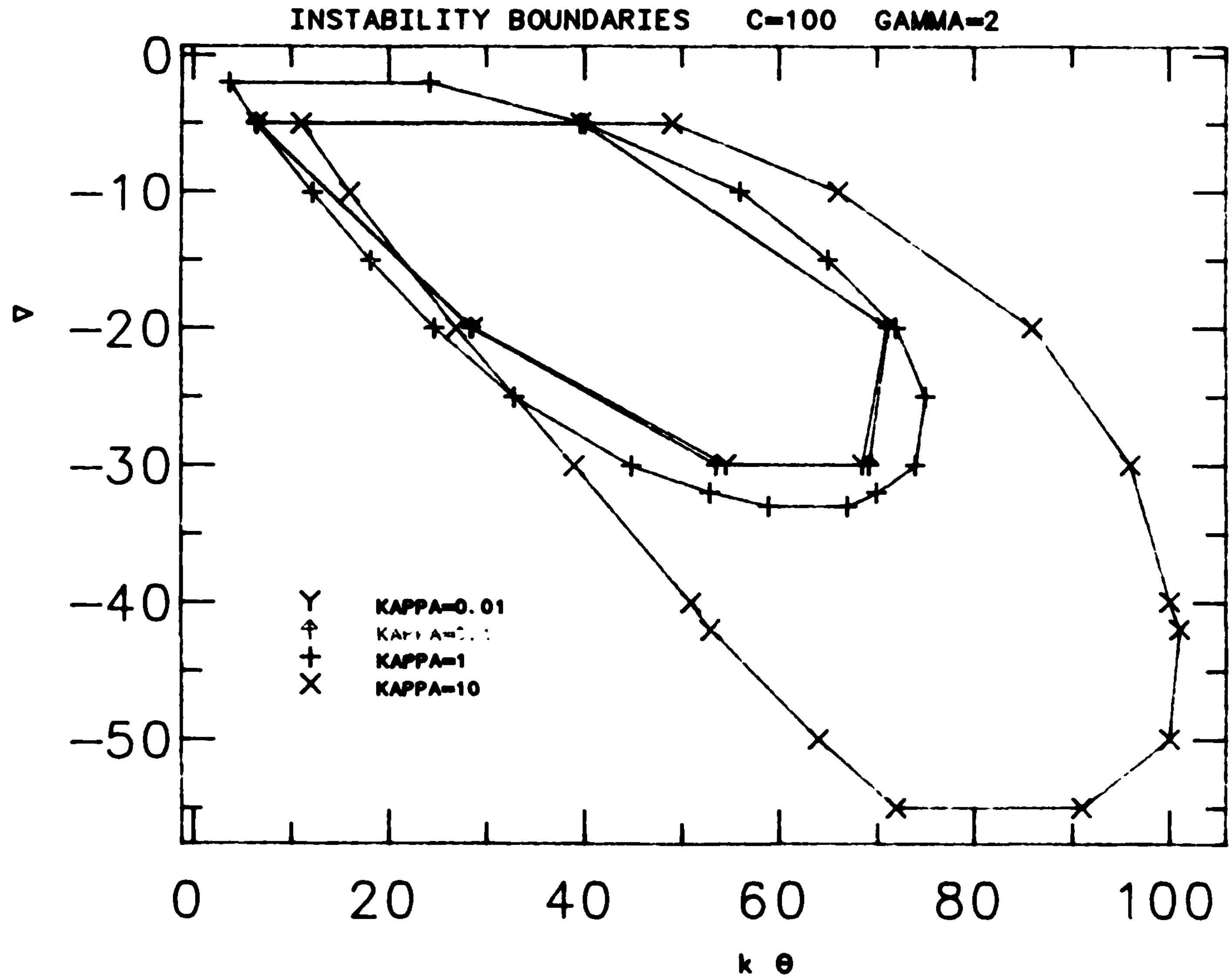

Figure 3. As in Figure 2, but for increasing values of KAPPA at fixed atomic cooperativity C=100. The regions enclosed by the full curves are unstable. As Kappa increases, the cavity damping rate becomes increasingly large relative to the rate of atomic decay. Note the insensitivity on KAPPA of the instability domain for KAPPA small. For KAPPA large there is a sudden dramatic growth in the predicted domain of instability.

THE UNIVERSITY OF TEXAS AT AUSTIN — ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE86-2 NONLINEAR RAMAN SCATTERING FROM MOLECULAR IONS

Principal Investigator: Professor J.W. Keto (471-4151)

Graduate Students: Mike Bruce, Winston Layne and Roger Taylor

A. SCIENTIFIC OBJECTIVES: A continuing problem in high pressure discharges is the understanding of the reactions of ions. At high pressures new ions in the form of clusters are formed and reactions of all forms of ions are complicated by the possibility of termolecular reactions. Few accurate experiments investigating ion reactions exist at high densities because of the lack of a suitable probe for studying ions immersed in a high pressure gas. The lack of a suitable diagnostic has effectively prevented an accurate understanding of the ion processes in high-pressure, gas-dynamic lasers such as the rare gas halogen lasers.

The probes for such studies must have high sensitivity, and good spectral and temporal resolution. Temporal resolution is required so that the decay rates can be used to measure reaction rates. We are interested in reactions such as association, recombination, and charge transfer. Nonlinear optical probes based on coherent Raman scattering processes when used in conjunction with high power pulsed lasers potentially meet all these criteria.

Research on the reactions and structure of ions at pressures near or above atmosphere is new. Such studies are motivated by electron beam driven or preionized lasers [1,2], particle beam weapons [3] and plasma chemistry [4]. In general it is thought that when fundamental two-body interactions are understood, they can be used to model the more complicated systems; however, at higher pressures the interaction of ions is known to become nonlinear. In estimating the formation rates of cluster ions, Smirnov [5] has described several models for estimating three-body (termolecular) reaction rates. Though the importance of termolecular reactions for formation of molecules has long been known, large termolecular reactions rates for molecular ions have only recently been discovered [6].

Polyatomic ions of interest include Xe_3^+, Ar_3^+ and Xe_nCl^+ which are relevant to excimer lasers. Other molecular ions for which there exists a need for experimental analysis include those formed in atmospheric discharges; H_3^+, N_3^+, N_4^+, O_3^+ and O_4^+ all fall into this category. The results from such studies will be applicable to the problem of particle beam transport in the atmosphere. Of partiuclar fundamental interest is H_3 which is the simplest nonlinear polyatomic molecule. Data obtained for H_3^+ may be compared directly to ab initio calculations.

B. PROGRESS: In nonlinear Raman spectroscopy, two lasers - often named the pump and probe laser - are focussed either colinearly or counter propagating onto a gas target. The third order susceptibility induced by the pump laser produces gain of the probe laser. In CARS, two waves from the pump beam combine with the probe to generate gain at the antistokes frequency. Both techniques have sufficient sensitivity to observe scattering from ion densities of 10^{13} cm^{-3}; but experimentally require all aspects to be optimized.

Many of the important developments in the study of high resolution Raman spectra of gases have originated from Owyoung's [7] group at Sandia Research Laboratories. He has developed the most sensitive spectrometer to date. In his experiments, Owyoung used a quasi-c.w. laser as the probe laser. Gain was then induced on the probe laser beam by a 10 nsec, high power dye laser. The quasi-c.w. probe power is limited by the c.w. saturation current of the photodetector to approximately 100 mW. The signal-to-noise is then limited by fluctuations in the number of photons incident on the detector during the 10 nsec gain pulse.

The difficulty in Raman gain spectroscopy is trying to measure a small change in the large probe laser intensity. This problem is reminiscent of early experiments in saturation spectroscopy by Hansch; he solved the problem by using polarization techniques [8]. A highly polarized probe laser is crossed with a high power pump laser in the sample and then procedes through a crossed polarizer onto the detector. When the pump and probe lasers are in resonance with the sample, induced birefringence generates a component in the probe of opposite polarization which is transmitted by the polarizer at the detector. The birefringence signal is then observed on a "black" background by the detector.

In the field of Raman gain spectroscopy this technique has been named RIKES (Raman induced Kerr effect spectroscopy) by Levenson [9]. The intensity observed at the detector is

$$I = I_B + (E_{LO} + E_R)^2 = I_B + (E_{LO} + g\,E_o)^2 \qquad (1)$$

$$I = I_B + \theta^2 I_o + 2\theta g I_o + g^2 I_o \qquad (2)$$

where $I_B = \beta I_o$ represents the residual background due to birefringence of the probe laser (power I_o) in the sample windows, etc., $E_{LO} = \theta\, E_o$ represents a local oscillator field obtained by uncrossing the polarizers an angle θ, and g represents the Raman gain induced by the pump laser. For small gains, the largest signal comes from the heterodyne of the probe laser with the Raman field. This signal which is the third term of Eq. 2 must be observed in a "not-so-black" background represented by the first two terms of Eq. 2. Levenson has described the expected signal to noise ratio in detail [9]. Under ideal experimental conditions one can ignor shot noise, thermal detector noise, and electrical noise compared to noise caused by fluctuations in the lasers' intensities. An optimum signal-to-noise ratio requires a local oscillator intensity

$$\theta I_o = (2)^{1/2} \beta I_o (F_b/F_o) \qquad (3)$$

where F_b and F_o are the fractional fluctuations in the intensity for the background and probe laser. At this probe power we obtain the ratio of signal to noise off resonance

$$S/N = \frac{g}{(F_o F_b \beta)^{1/2}} \qquad (4)$$

Levenson subtracted the background signal in Eq. (2), $(\beta + 2\,\theta\, g)I_0$ by using heterodyne detection of modulated c.w. lasers. For the smallest obtainable values of $\beta = 10^{-6}$, the optimum local oscillator powers obtained from Eq. 3 again limits the signal-to-noise by the shot noise in the light incident on the detector, unless very large probe powers I_0 can be obtained. For reasonable laboratory c.w. lasers, large values of θ are required. We propose to use high power pulsed probe lasers in order to obtain the maximum signal-to-noise ratio obtained by Eq. 4 and not be limited by shot noise of the detector [10].

The difficulty is that small changes in the intensity of a short (10nsec), pulsed power probe laser must be measured. We have devised an elegant technique which uses a single diode to sample the beam before and after gain [10]. This experimental approach is illustrated in Fig. 1. The basic idea is to delay one of the optical signals relative to the other using a low loss optical fiber. The two light signals are then combined onto a single diode. If the second pulse is delayed sufficiently to allow the diode to recover, both light pulses are processed by an identical transfer function. The signal is then split and one half delayed (with cables) so as to bring the two signals into time coincidence again. The clipping cable in Fig. 1 delays, inverts, and sums the signals at the intersection of the tee. The resulting error is approximately 1% of the optical pulse; and fluctuations in the integrated error signals is reduced to 1 part in 10^4 for a single pulse. With this technique we are able to obtain high quality stimulated Raman gain spectra (SRGS) as reported in the last progress report.

We know of three general improvements which can increase the sensitivity of our apparatus. The most obvious is to increase the Raman gain that can be produced by a molecule. It is known that for laser linewidths larger than the pressured broadened Raman linewidth the gain increases linearly with decreasing laser linewidth. To continue increasing the gain for laser linewidths less than the doppler broadening of the transition will require colinear focussing of the pump and probe lasers. This requires a different optical configuration from Fig. 1 in order to separate the probe laser from the pump laser. The gain also increases linearly with pump power up to intensities of 5 GW cm^{-2}. In our current experiments we obtain intensities comparable to this value by focussing our low power pump laser very tightly. If we had available a higher power laser, we could obtain this same intensity over a larger target volume by focussing to a larger diameter. This increases both the target area and interaction length. The last improvement is to reduce the noise in the subtraction process. In previous experiments using cw lasers, the subtraction was accomplished by a heterodyne technique, limited either by the shot noise of the laser or by the stability of the laser. In our experiments we found that we were limited by fluctuations of the pulse propagating in the optical fiber used as a delay. These fluctuations appeared to be fluctuations in the growth of higher order transfer modes in a multimode fiber. Because of the different group velocities for these modes, we reported observing a fluctuation in the pulse shape at the end of the fiber. We proposed eliminating these fluctuations by using a multi-pass cell as a delay.

We have made significant progress in all three of these areas in the past six months. Using funds provided by the University of Texas, we purchased a YAG laser which is frequency doubled and tripled to use as a pump laser for our dye lasers. This laser has an order of magnitude greater energy output than our N_2 laser at the doubled wavelength and simultaneously 6 times the energy of our N_2 laser at the tripled wavelength. We have designed new dye lasers that will use the tripled light to pump the probe laser and the oscillator and preamplifier of the pump laser. All of the doubled light will be used to pump the Rd6G laser's final amplifier. We expect this dye laser to produce 60 times the intensity due to increased efficiency (x3) and pump intensity (x20 over our previous lasers). We will decrease the bandwidth to 200 MHz in the first construction phase of these lasers [11] and later decrease the bandwidth to 50 MHz by the insertion of additional etalons in each laser. In the first phase, which will be operational by February, we will gain a factor of 40 in sensitivity by the decrease in linewidths alone. With projected increases in laser power we should observe an increased sensitivity factor of 2400. In phase II we hope for an increase of nearly 10^4.

Future improvements in laser intensity can be obtained by injection-locking the YAG oscillator so as to run in single mode and to add an amplifier rod. In this configuration the doubled light of the laser would be used as the Raman pump laser rather than a dye laser. These improvements will increase the laser power by approximately an order of magnitude, but would cost an additional $40,000.

During the last few years, 'his lab has worked on the design of a novel monochromator. As designed, this device will act so as to both separate the probe laser beam from the pump beam and to act as the optical delay in place of the optical fiber in Fig. 1. For the experiments proposed one must remove the pump laser from the probe laser with a rejection ratio of 10^{10}! A large rejection can be obtained by maintaining a small crossing angle (~ 2 mRad) between the pump and probe lasers. This provides a significant geometric separation of the beams and at the same time gives a large interaction length in the Raman process. The rejection is limited by scattering of the pump laser from the sample chamber windows into the solid angle of the probe laser detector. Specifically, the monochromator must be able to separate the scattered laser light whose frequency differs from the probe laser by as few as 10 cm^{-1} with as large an attenuation as possible. The design and construction of the device has been completed for some time, but final assembly and testing was delayed until recently when the dispersive elements - two, high quality, Brewster angle prisms - finally were ground and polished to the required specifications.

The principle of the monochromator is simple - use Brewster prisms to disperse the light and to maintain low losses. As reflection losses at Brewster's angle are limited to less than 1%, the number of laser passes through the prisms may be increased with negligible loss so as to increase the dispersion. The monochromator has been designed with essentially one large prism through which the laser beams travel as many as twenty times. The folding of the beam back through the prism is accomplished by high quality dielectric mirrors. A schematic view of the device from the vertical direction is shown in Fig. 2. The beams travel in a zig-zag pattern vertically at each pass. To obtain the full resolution of the monochromator, the beam is expanded to provide minimal angular divergence over the optical path. Each pass through the prism requires a 1 meter path so that 20 passes provides approximately 60 nsec delay for the subtraction technique. The mirrors are computer controlled to tune the monochromator to the desired wavelength.

Tests of the monochromator confirm its high transmission. A beam which makes ten passes through the prism is attenuated by only 10%, which implies an average transmission per pass of 97%. The resolution of the device was measured with a tunable dye laser whose linewidth is 0.44 cm^{-1} (FWHM). Scans were performed for 10, 12 and 14 passes through the prism (Fig. 3). The total rejection far from line center is limited by the signal-to-noise of the dye laser used for these tests and not the monochromator. We are now continuing measurements of the monochromator's rejection using a He-Cd laser spectrally filtered with etalons.

C. FOLLOW-UP STATEMENT: This work is continuing under Joint Services support. We propose to continue to investigate the use of coherent Raman scattering as a probe of molecular ions in high pressure discharges. As described in the progress section, we have developed technology for measuring small gains in a pulsed probe laser. This technique has been combined with polarization techniques to obtain improved sensitivity for Raman gain spectroscopy. It is now feasible to obtain Raman spectra for particle densities as low as 10^{13} cm^{-3}.

(Page 5, Res. Unit QE86-2, "Nonlinear Raman Scattering from Molecular Ions")

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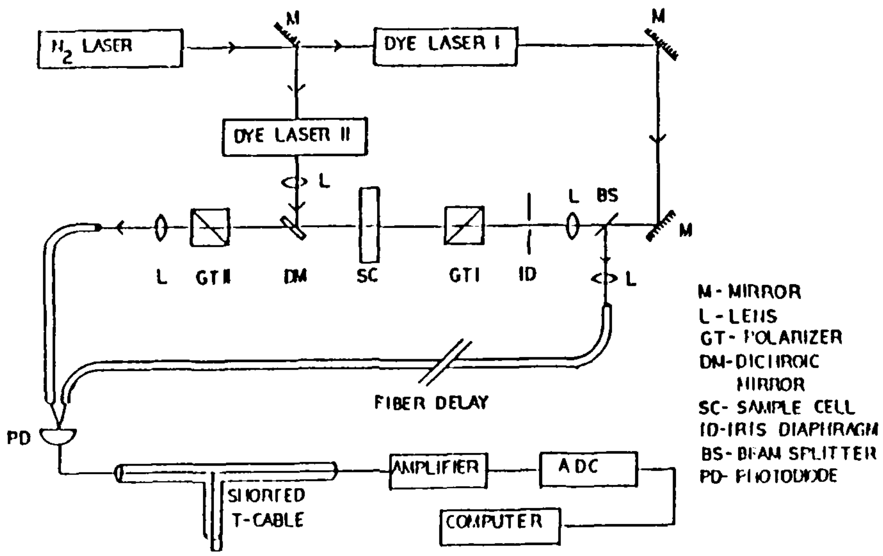

Figure 1. Raman gain apparatus with polarizers using a single photodetector to measure the depolarized probe laser gain.

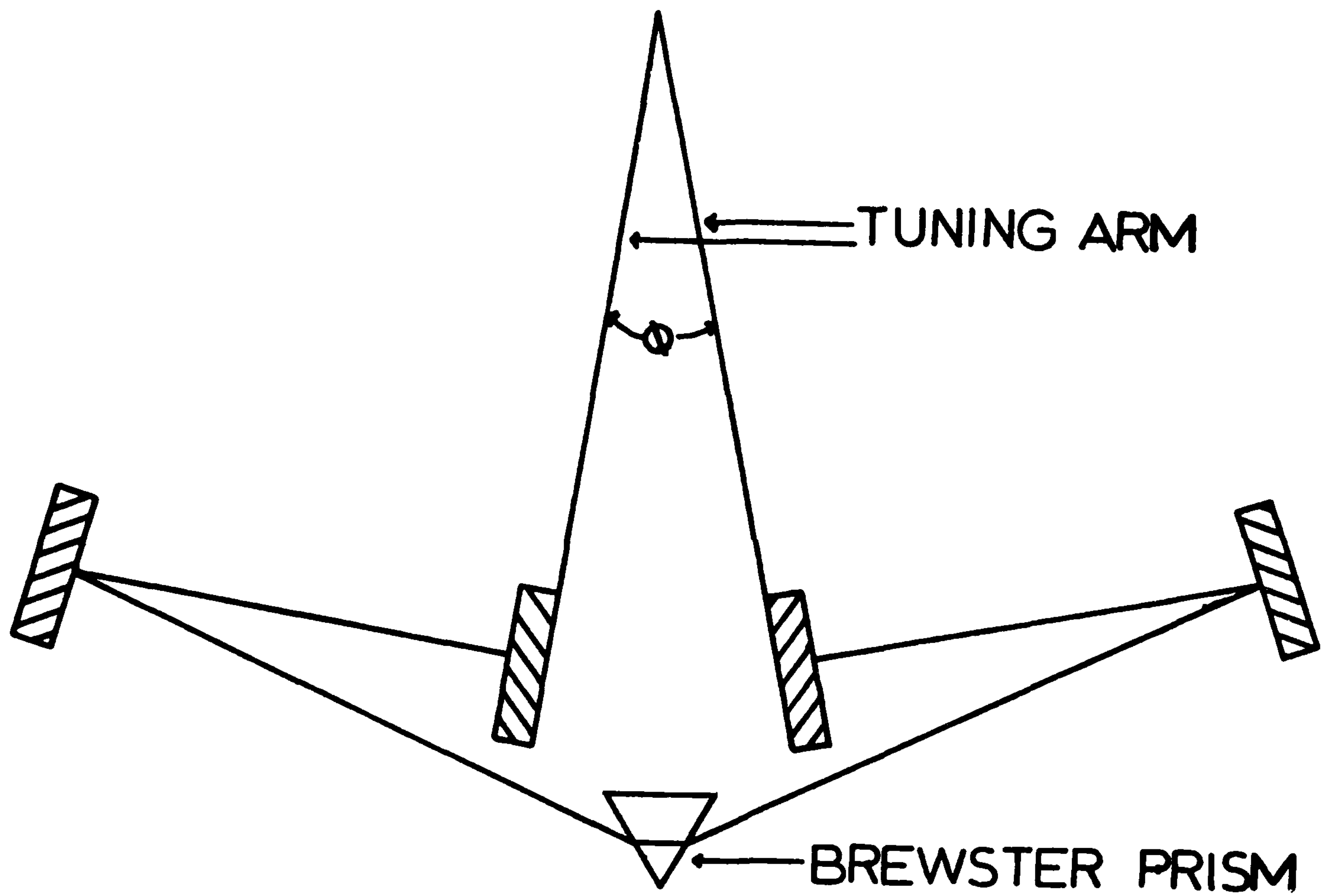

Figure 2. Monochromater schematic. The diagram presents a top view. The Brewster prisms and mirrors are six inches tall to allow multiple passes through the prism. The laser beam is coupled in and out of the device with Littrow prisms (not shown). The angle Π of the tuning arm can be computer controlled.

(Page 9, Res. Unit QE86-2, "Nonlinear Raman Scattering from Molecular Ions")

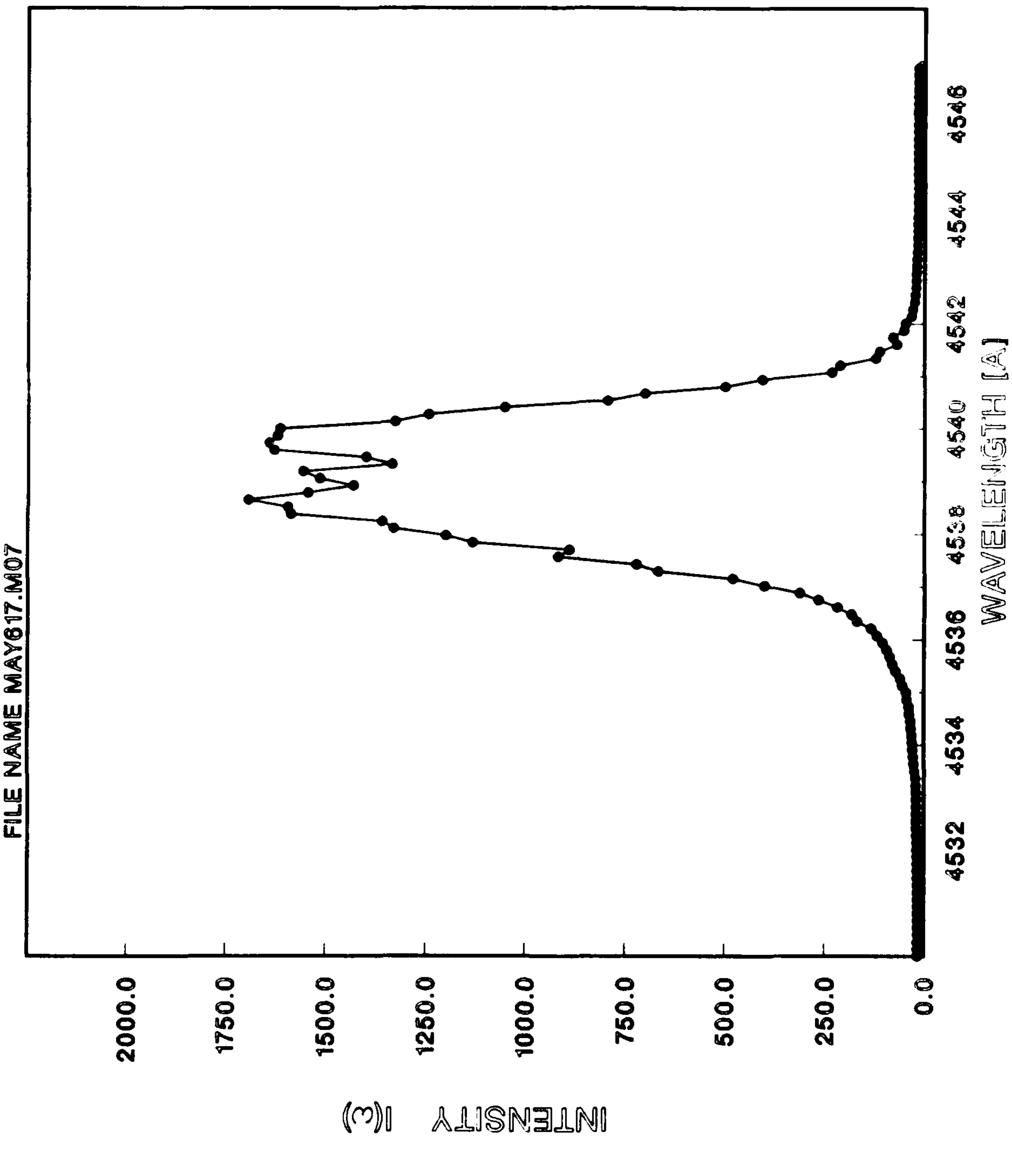

Figure 3. Laser scan using ten passes through the monochromator.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit EM-86-1 MILLIMETER-WAVE MONOLITHIC ARRAY COMPONENTS

Principle Investigators: Professor T. Itoh (471-1072)
Professor D. P. Neikirk (471-4669)

Graduate Students: N. U. Song, V. D. Hwang, Y-D Lin, R. Rogers, V. Kesan

A. RESEARCH OBJECTIVES: Planar millimeter-wave structures are investigated that would be useful for active, monolithically integrated quasi-optical receiver arrays. The objective is to advance the state-of-the art by way of fundamental understanding of circuit characteristics, wave interactions with monolithic solid state devices, and quasi-optical measurement and coupling techniques.

B. PROGRESS: The basic building block in this project is a half wavelength coplanar waveguide (CPW) resonator on a GaAs substrate. The local oscillator (LO) signal is to be generated in this structure using a resonant excitation of a CPW mode by a built-in active device such as a Gunn diode. As a receiving antenna, the incoming RF signal is to be coupled into the structure by way of the coupled slot line (CSL) mode of the resonator. A pair of mixer diodes is then installed in an appropriate location in the resonator, with the polarities of the diodes in the same direction. Since the CPW mode is a balance mode, its radiation loss is small and presents a high Q resonator to the local oscillator diode. The CSL mode, on the other hand, is an unbalanced mode, and hence its radiation and coupling to free space are efficient. The two mixer diodes receive the RF signal in phase and the LO signal out of phase. Hence, a balanced mixing operation results which has the advantage that the noise contained in the LO signal should not appear in the IF (intermediate frequence) signal output of the mixer. The present structure therefore contains an antenna, a balanced mixer, and a local oscillator as an integrated single element, and may be called an integrated quasi-optical receiver.

During this reporting period, we first characterized the electromagnetic properties of a coupled pair of slots. Based on the spectral domain technique, the propagation constant and the characteristic impedance have been calculated for both the CPW mode and the CSL mode. From this information, the resonant frequencies of the two modes and the radiation characteristics of the coupled slot as an antenna can be determined. The results will be reported at an upcoming scientific meeting[1].

Next, we have built an X-band scale model of the receiver on a soft substrate. As the first step, we experimentally characterized the antenna radiation patterns of the CSL resonator. Then, we installed only the mixer diodes and into which an LO signal is fed externally. After confirming mixing operation, we constructed a hybrid Gunn oscillator in microstrip form on the same substrate, but at a distance somewhat away from the CPW resonator containing the mixer diodes. After observing promising results, we proceeded to install a Gunn diode at one end of the CPW resonator. The measured results of the integrated X-band mixer show good characteristics with an estimated conversion loss of about 8 dB. This is an excellent performance for this type of mixer. The radiation patterns of the structure measured at the IF frequency are somewhat distorted as compared to the previous RF characterization. This is because of the additional complexity of the circuit, such as the heat sink plate located near the resonator and the change of antenna impedance due to mixer diodes. The schematic top view of the developed circuit is shown in Fig. 1. The findings will be reported at a scientific meeting [2].

This circuit will eventually be used for a planar array on a high permittivity substrate such as GaAs. In such a structure, excitation of surface waves should be avoided. Otherwise, unwanted effects such as cross talk between the receiver elements can occur. As a possible remedy, we have also initiated a simulation study for a multilayered "lens" on which the GaAs substrate with an array of receivers could be placed. Such a system utilizes the properties of an antenna on an electrically thick substrate, in contrast to the studies performed to date on electrically thin substrates. Past research has shown these systems can be fairly efficient [3], but the use of non-planar lens surfaces can introduce some difficulties in monolithically fabricated antenna arrays. We have begun calculations that should allow us to estimate the efficiency of various multilayer substrate combinations. Preliminary results indicate a simple l/4 matching layer may be sufficient to allow reasonable coupling to the antennas. The direct effect of surface waves on efficiency will be included as the simulation is developed. In conjunction with this numerical effort, a development of a more accurate antenna measurement setup is underway.

C. FOLLOW-UP STATEMENT: The work reported above will be continued in the subsequent periods. The immediate plan is to complete more accurate antenna characterization, followed by further modeling of the receiver structure on a high permittivity substrate such as Epsilam-10 or alumina so that the results will provide more accurate information for the forthcoming monolithic integration on GaAs material. Next, we plan to increase the operating frequency. Multilayered structures for antenna characterizations will move into the experimental phase shortly. The receiver measurements will be based on the results of this new platform configuration. In addition, in conjunction with Unit SSE86-2, a new transit time oscillator [4] will be integrated with the resonant cavity structures developed here.

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Texas Advanced Technology Research Program, "Multilayer Heterojunctions in III-V Semiconductors," Professor B. G. Streetman, Principal Investigator, Professors D. P. Neikirk, J. L. Erskine, L. Kleinman, F. Matsen and J. Stark, Co-Principal Investigators.

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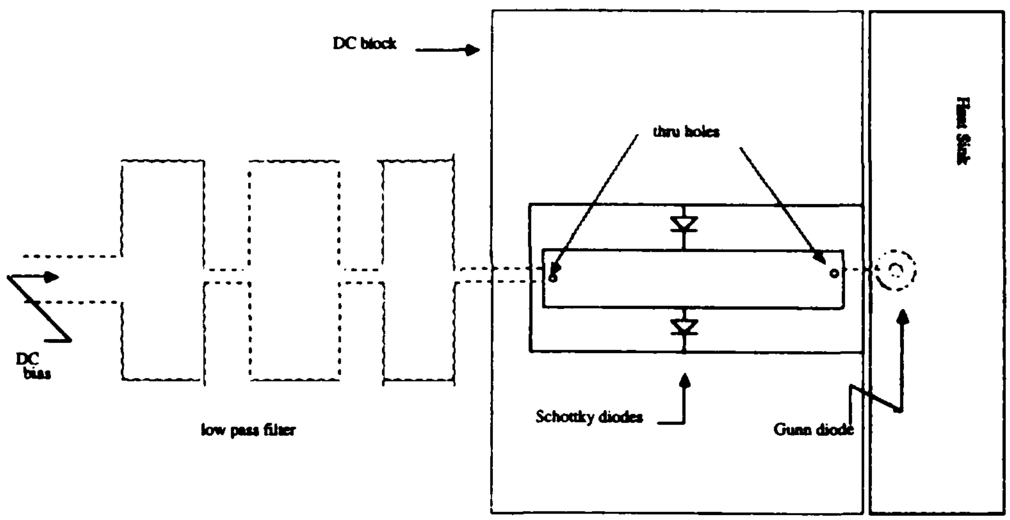

Fig. 1 Schematic top view of integrated quasi-optical receiver front-end

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM86-2 NONLINEAR WAVE PHENOMENA

Principal Investigators: Professor Edward J. Powers (471-3954)
Dr. Christoph P. Ritz (471-4507)

Graduate Student: K.I. Kim

A. SCIENTIFIC OBJECTIVE: The overall scientific objective of this research unit is to conceive and implement novel digital time series analysis techniques that may be used to analyze nonlinear wave fluctuation data associated with noise and turbulence phenomena in a wide variety of different physical media. In particular, we concentrate on those canonical questions that are relevant to many areas of science and technology. The specific objective of this proposal is to measure three-wave coupling coefficients from the raw fluctuation data. Although quantitative measurements of such complex coupling coefficients have been made for interacting coherent modes, to the best of our knowledge, no such measurements have been made for incoherent fluctuation data characteristic of noise or turbulence spectra.

From a scientific viewpoint, experimental determination of the coupling coefficient is of fundamental importance since the "strength" of the nonlinear interaction is imbedded in this term. The complex coupling coefficients describing quadratic three-wave interactions are two dimensional functions of temporal and/or spatial frequency, thereby suggesting that a higher-order spectral density must be used to estimate such coupling coefficients. The appropriate higher-order spectrum is the bispectrum, a two-dimensional function of frequency. Our approach to estimating complex three-wave coupling coefficients is based upon measurement of a quadratic transfer function, given two channels of raw time series data representing the fluctuation field observed at two spatial points. We have previously developed techniques, based on digital implementation of higher-order spectra, to determine quadratic, cubic, etc. transfer functions. The approach developed is valid, and is shown to work well, for "inputs" that are Gaussian. However, to determine the quadratic transfer function of a self-excited noise/turbulence system, the assumption of a Gaussian "input" signal usually does not hold because of the nonlinear history of the signal. Thus an important part of our proposed research program is to develop an approach valid for non-Gaussian inputs as well.

To summarize, the specific scientific objectives of this research unit are: (1) the development of a method to measure quadratic transfer functions for non-Gaussian inputs, (2) the determination of complex three-wave coupling coefficients from the measured quadratic transfer functions, and (3) development of a method which quantifies the energy cascading between modes as a result of three-wave coupling. To demonstrate the validity, relevance, and practicality of this approach, it shall be applied to both simulation data and real noise/turbulence data available to us as a result of research projects sponsored by other agencies.

B. PROGRESS: During the nine month period covered by this report we have focussed on the first sub-objective mentioned in the preceding paragraph, namely, the development of an approach to measure linear and quadratic transfer functions for non-Gaussian inputs. Since demonstrating the validity and relevance of our approach is an important aspect of this project, we also report on applications of the nonlinear transfer function approach, and other digital approaches developed earlier, to a variety of scientific and engineering fields. The application fields and the principal sponsors of that work are: fluctuations and transport in plasmas (DoE), transition to turbulence in neutral fluids (NSF), and nonlinear and parametric structural vibrations

(McDonnell Douglas). In the publications cited at the end of this report and which deal with such applications, it is acknowledged that the digital signal processing approach was originally developed under JSEP sponsorship.

Quadratic Transfer Functions for Non-Gaussian Inputs. As mentioned previously, the procedure for estimating linear and quadratic transfer functions for Gaussian inputs is reasonably well established. Simply speaking, the linear transfer function (LTF) is computed in terms of the cross-power spectrum between input and output, and the quadratic transfer function (QTF) from the cross-bispectrum between input and output. When the input is non-Gaussian it is not possible to solve for the LTF and QTF separately, rather, it is necessary to simultaneously solve two equations for the two desired transfer functions. The non-Gaussianity significantly increases the computational complexity (with resulting cost in computer time) as well as necessitates the revision of such concepts as linear and quadratic coherency and the introduction of new concepts such as a hybrid (i.e., a mixed linear and quadratic) coherency. We have undertaken two approaches in estimating the LTF and QTF for non-Gaussian inputs. The first approach reported in [2] utilizes an interactive scheme where one neglects the QTF and solves the LTF. This value of the LTF is then substituted into the appropriate equation to solve for the QTF and so on. Initial results, using simulation and actual data, indicate that the convergence and accuracy of the approach are quite encouraging. The second approach described in [7] is a somewhat more exact approach in that the relevant equations are written in matrix form and solved accordingly. We are currently improving our understanding of the merits and limitations of each approach.

We have made two initial attempts in applying our nonlinear transfer function estimation techniques for non-Gaussian inputs. In the first case, the technique was used to model the nonlinear response of moored vessels to random sea wave excitation [6]. Considerable improvement in modelling the nonlinear dynamics was achieved with our new non-Gaussian approach relative to the more classical Gaussian one. In the second case, the linear and quadratic transfer functions characterizing nonlinear wave interactions were measured at several spatial points in a wake undergoing transition to turbulence [16]. This measurement is a first step in eventually measuring the complex nonlinear three-wave coupling coefficient which governs the rate and direction of energy cascading in the turbulent fluctuation spectrum.

At this point we also mention a result based on earlier JSEP work and published in August 1986 [3]. In that paper we report on a procedure for measuring transfer functions for nonlinear dyadic-invariant systems. Expressions for transfer functions up to third order are developed and it is demonstrated that such transfer functions can be obtained from the raw input and output data by computing the appropriate Walsh sequency power spectra.

Other Applications: During this reporting period various digital time series analysis techniques developed under previous JSEP sponsorship (either sole or partial) were utilized in a variety of investigations principally supported by other agencies (DoE, NSF, McDonnell Douglas). These applications are briefly mentioned here since they substantiate the validity and practicality of this previous work.

Specifically, unique and innovative use of digital classical and bispectral spectral analysis techniques have been used to study the space-time statistics and to detect and quantify the presence of nonlinear wave (or mode) interactions in fluid turbulence [8,10,12,13] and nonlinear vibrations in structures [14]. Similar applications, including the role of fluctuations on particle and energy transport, have been carried out for plasmas [9,11]. Lastly, we mention four publications [1,4,5,15] where digital signal processing and laser scattering techniques have been combined to yield great insight into a variety of nonlinear wave and fluctuation phenomena in turbulent plasmas. This latter work represents a powerful union of digital signal processing on the one hand and classical electromagnetic (interferometry and scattering) techniques on the other hand. Specifically, in refs. [1,5] a new homodyne scattering technique is described which enables one to recover both the upper and lower doppler sidebands and, hence, recover directions of propagation. Normally, a more expensive and complicated heterodyne system is required to make such a velocity direction discrimination. In effect, our new homodyne approach utilizes innovative signal processing in lieu of the more complex heterodyne apparatus. In ref. [16] the wavenumber resolving capability of electromagnetic scattering systems and the temporal frequency resolving power of digital spectral analysis are combined to experimentally determine the bispectrum $B(k_1,\omega_1,k_2,\omega_2)$. The bispectrum is useful for detecting and quantifying nonlinear three-wave interactions since it is sensitive to the phase coherence existing between the primary waves (ω_1,k_1) and (ω_2,k_2) and the resulting sum (or difference) frequency wave ($\omega_3 = \omega_1+\omega_2$, $k_3=k_1+k_2$). Finally, we mention that a new improved digital complex demodulation algorithm is described in ref [4]. The corresponding digital signal processing program is utilized to demodulate the output of a far-infrared interferometer. The superiority of the digital demodulator relative to the classical electronic analog demodulator is described with special emphasis on time response and insensitivity to noise.

C. FOLLOW-UP STATEMENT: This work is continuing. The primary focus in the next year will deal with sub-objective (2) mentioned in Sec. A., namely, the experimental determination of complex three-wave coupling coefficients from the QTF's determined for non-Gaussian inputs.

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12. *E.J. Powers, Ch.P. Ritz, R.W. Miksad and R.S. Solis, "Novel Digital Signal Processing of Transition-To-Turbulence Data," presented at the 10th U.S. National Congress of Applied Mechanics, Austin, Texas (June 1986).

13. *R.S. Solis, R.W. Miksad, E.J. Powers and Ch.P. Ritz, "Parametric Modulations Due to an Unsteady Mean Flow During Transition to Turbulence," presented at the 10th U.S. National Congress of Applied Mechanics, Austin, Texas (June 1986).

14. *E.J. Powers and R.O. Stearman, "The Application of Higher Order Spectra to Experimentally Identify Responses of Nonlinear and Autoparametric Dynamical Systems," presented at the 10th U.S. National Congress of Applied Mechanics, Austin, Texas (June 1986).

15. *E.J. Powers, Ch.P. Ritz, D.L. Brower, W.A. Peebles, and N.C. Luhmann, Jr., "Studies of Three-Wave Coupling Phenomena in the Interior Plasma of TEXT," presented at the 28th Annual Meeting of the Division of Plasma Physics, American Physical Society, Baltimore, Maryland (November 1986). Abstract published in the Bull. Am. Phys. Soc. 31, 1573 (October 1986).

16. *Ch.P. Ritz, E.J. Powers, F.L. Jones, R.W. Miksad and R.S. Solis, "Experimental Measurement of Nonlinear Transfer Functions Characterizing Transition to Turbulence," presented at the 39th Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Columbus, Ohio (November 1986). Abstract published in Bull. Am. Phys. Soc. 31, 1727 (November 1986).

IV. LIST OF THESIS AND DISSERTATIONS

K.I. Kim, Ph.D., May 1986, "Frequency Domain Modeling of Quadratic Systems with Random Inputs."

V. CONTRACTS AND GRANTS

E.J. Powers and R.W. Miksad, "Experiments on Spectral Energy Redistribution During Transition to Turbulence," National Science Foundation, NSF Grant MSM-8211205, February 1983-September 1987.

R.O. Stearman and E.J. Powers, "Identification of Aeroelastic Wing Store Oscillations Employing Spectral Analysis Techniques," McDonnell Douglas, April 1986-December 1986.

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