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

NO. 37

For the period January 1, 1988 through December 31, 1988

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F49620-86-C-0045

December 31, 1988

ELECTRONICS RESEARCH CENTER

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

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.

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This Annual Report covers the twelve-month period ranging from January 1, 1988 through December 31, 1988. The progress reported herein was accomplished during the third 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.

Solid State Electronics includes work on implantation and annealing of InP and related compounds; molecular beam epitaxy with high-speed device applications; epitaxial growth, structure and electronic properties of silicides on silicon surfaces; and femtosecond processes in condensed matter. In Quantum Electronics, nonlinear optical interactions and nonlinear Raman scattering from molecular ions are being investigated. Work in Electromagnetics includes millimeter-wave monolithic array components and nonlinear wave phenomena, while electronic signal processing and nonlinear estimation and detection are being studied in Information Electronics.

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SIGNIFICANT ACCOMPLISHMENTS

DIRECTOR'S OVERVIEW

This Annual Report covers the twelve month period ranging from January 1, 1988 through December 31, 1988. The progress reported herein was accomplished during the third 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.

CURRENT STATUS

Solid State Electronics: We have developed extensive laboratory facilities for MBE growth and analysis of semiconductor materials, along with appropriate device fabrication capabilities. Using an extremely versatile computer-enhanced image processing system for reflection high energy electron diffraction (RHEED) on our Varian Gen II MBE machine, we are able to study the details of MBE growth at the submonolayer scale. We have also developed extensive analytical capabilities including temperature dependent Hall effect, low temperature photoluminescence, photoluminescence excitation spectroscopy, deep level transient spectroscopy, and other techniques for examination of MBE grown layers and structures. These capabilities allow us to not only examine details of MBE growth at the monolayer and submonolayer scale, but also to use the resulting controlled growth for device development and studies of transport properties in semiconductor multilayers.

We have applied the imaging RHEED system described above to study the effect of growth interruptions on interface quality, and also to accurately control the dimensions of resonant tunneling structures. This system is also used routinely as an in-situ measure of alloy composition. We have shown that significant changes in the principal RHEED streak intensity and shape are produced by very small changes in adatom coverage and that the profile is noticeably different for Ga and As stabilized surfaces.

In pursuing this work we have also studied MBE growth techniques and have made improvements in the system. We have shown that carbon compounds are produced by the substrate rotation mechanism, and the rate of evolution is proportional to the rotation speed. We have developed and installed a refractory, two-zone, large capacity arsenic cracking source for providing As2 for MBE growth. This system provides As2/As4 flux ratios of 6-8 over a wide range of cracking furnace temperature.

In device development, we have grown high quality normal and inverted AlGaAs/InGaAs High Electron Mobility Transistor (HEMT) structures on GaAs substrates by MBE, and studied the influence of rapid thermal annealing (RTA) on electrical conduction in the two-dimensional electron gas (2-DEG).

We have invented a new transit-time device in which electrons are injected into the drift region through a resonant tunneling structure rather than by avalanche injection as in a conventional IMPATT. This device, called the Quantum Well Injection Transit-Time (QWITT) diode, is an extremely promising extension of resonant tunneling structures for high-speed device applications. Simulations clearly indicate that significant improvements in output power over conventional quantum well oscilators will be achieved. We have grown high quality quantum well devices of this type by MBE, and are at present performing dc testing on prototype devices.

In addition, pseudomorphic growth such as that described above should allow us to fabricate new types of quantum well structures, providing improvements in QWITT diode performance.

In addition, femtosecond optical techniques have been developed and it is anticipated that this capability will be exploited to measure and understand the basic electron scattering and transport phenomena which underlie the electronic characteristics of III-V materials and devices.

Information Electronics: Our information electronics program rests upon recent progress in extracting information from signals that would otherwise not be obtainable if conventional algorithms were employed. We have begun to make important contributions in the development of novel methods of information extraction and processing. Our recent research in the analysis and processing of signals from different sensors has demonstrated that multisensor fusion is a powerful approach for signal processing and interpretation. We have recently developed a system for hierarchical integration of information extracted from thermal and visual sensors, which provides new information not available by processing either kind of image alone.

We have also developed and analyzed new adaptive nonlinear estimation algorithms for the extraction of information concerning the state of a nonlinear stochastic system with unknown parameters in the system model. The convergence and optimality of the algorithms has been analyzed completely; this is the first such analysis of an adaptive nonlinear estimation algorithm. As a first step toward the analysis and control of "hybrid" dynamical systems containing both discrete and continuous variables, we have made important contributions in the modeling and control of discrete event dynamical systems. These and our other efforts described in detail in this proposal have considerably advanced the state-of-the-art in the development of innovative techniques for information extraction and have enabled us to develop the expertise to make significant contributions during the next three years.

Electromagnetics: The current work in electromagnetics involves, in a general sense, wave interactions. For example, we note that most of the circuit configurations presently used in monolithic and millimeter-wave integrated circuits are not designed with the interaction of the electromagnetic wave and the devices (both active and passive) in mind. A number of new integrated circuit configurations for mixers and receivers for quasi-optical applications have been conceived, designed, and tested.

Three different quasi-optical planar circuits have been successfully developed for millimeter-wave receiver applications. They are: a balanced mixer with an integrated Gunn local oscillator, a balanced mixer with an integrated MESFET local oscillator and a self-oscillating HEMT receiver front end. All of them make use of the inherent electromagnetic isolation of the even and odd modes of a coupled slot antenna which is simultaneously used as a portion of the local oscillator circuits. They were designed based on the careful electromagnetic analysis and the solid state device characterizations of the constituent elements. This is the first time that all essential elements of millimeter-wave receiver front end are integrated coherently in a quasi-optical manner. On the other hand, the local oscillators used in these configurations are of a rather standard design. Thus our work for the current triennium will focus on integrated distributed oscillators for millimeter-wave applications.

With regard to the nonlinear wave research, we have succeeded, during the current triennium, in demonstrating an approach to measure complex three-wave coupling coefficients, and to the best of our knowledge, this is the first time that such measurements have been made for turbulent-like "incoherent" fluctuation data. Our approach to estimating the 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. Most work in nonlinear systems modeling assumes the "input" is Gaussian, an assumption that is clearly unacceptable here, since the fluctuation waveform is nonGaussian due to its past nonlinear history. Thus an important part of the current research program is to develop an approach valid for nonGaussian "inputs". The success of this later objective not only made it possible to make the first measurements of three-wave coupling coefficients and associated energy cascading but appears to have great "technology transfer" potential to other areas of science and engineering.

Quantum Electronics: In our research dealing with dynamical instabilities in optical systems extensive quantitative characterizations of time-dependent steady states have been made for a passive bistable system composed of fundamental elements (two-level atoms in an optical cavity). Our investigations have demonstrated the complete inadequacy of theoretical analysis based upon models that neglect the transverse structure of the electromagnetic field in the cavity. The findings are significant in that broad regions of stable operation are demonstrated in domains that were previously thought to lead exclusively to dynamic instability. Further, these measurements in optical bistability represent one of only a few examples in optical physics for which absolute comparisons with theory for dynamical instabilities have been made.

RECENT DEVELOPMENTS RELATED TO JSEP PROGRAM AT U.T. AUSTIN

There have been several recent developments that will impact either directly or indirectly on the JSEP Program at The University of Texas at Austin.

New Building: The University of Texas at Austin has committed $20M for the construction of a new research facility for Microelectronics, Materials Science, and Manufacturing Engineering. Approximately 55,000 square feet of space in this new building has been designed specifically for research in microelectronics and materials science. JSEP research involving III-V compounds, MBE growth, and devices will make use of these new facilities, particularly those projects requiring clean rooms and toxic materials handling. The new building will include approximately 12,000 sq. ft. of clean space (including service aisles), approximately 15,000 sq. ft. of testing and evaluation laboratory space, and office space for 15 faculty and 120 graduate students involved in semiconductor research. The UT Board of Regents has approved the $20M appropriation for this new facility, and design work is underway. We expect to move into this new facility in 1990.

Texas Advanced Research Program: In 1987 the Texas Legislature appropriated $60 million dollars for research programs. A total of 3,223 proposals were received from researchers at 80 public and private institutions in Texas. The proposals underwent peer review by experts not connected with Texas higher education. The reviewers represented 57 institutions nationwide. Of the 3,223 proposals submitted, 345 were selected for funding, 101 of them being at U.T. Austin. Of the 101 proposals funded at U.T. Austin, 7 were submitted by faculty associated with the JSEP Program and are worth a total of $1.2 million dollars. Drs. Itoh, Keto, Neikirk, Powers, and Streetman are recipients of these grants with Itoh and Powers being PI or Co-PI on more than one grant.

SEMATECH: Recently it was announced that SEMATECH would locate in Austin, Texas. The mission of SEMATECH, which is supported by several leading U.S. companies, is to "insure the world manufacturing leadership of the U.S. semiconductor industry for the production of commercial and military products, ..." We anticipate that SEMATECH's choice of Austin will favorably impact The University of Texas programs in microelectronics and microelectronics manufacturing. It is difficult to predict the exact nature of the benefits at this stage, but we predict they will be substantial in both financial and intellectual terms.

In conclusion, the University and the State of Texas are committed to providing the type of environment where programs like JSEP can flourish.

Edward J. Powers
Director

Multisensor Signal Processing

J. K. Aggarwal

The objective of this research unit is to develop algorithms for multi-sensor signal processing and interpretation. In addition, in this research we apply Artificial Intelligence techniques and rule-based methods to combine information from multiple sensors. The sensors being used include visual, infrared, laser radar and millimeter wave radar sensors. Signal processing that integrates multisensory data can provide information that cannot be obtained by processing the data individually. We use these data to build a more powerful and robust system. We have approached the problem by (1) studying of the physical models of the imaged objects and individual sensors, and (2) integrating information derived from various sensors.

A unified approach to model thermal and visual image generation has been developed. The model we use is capable of synthesizing both infrared images and monochrome visual images under a variety of viewing and ambient scene conditions. A structure called the octree is used to organize data in these models. The developed model describes the thermal behavior of an entire object, rather than surface only. Therefore, it is much more accurate, and can be used to test thermal image interpretation systems. We have tested this model on laboratory scenes with success.

We have developed a method for image segmentation using thermal and visual images. This method partitions images into meaningful regions. This step is important because the segmented images can be understood more easily. This method exploits the different characteristics of the two imaging modalities to differentiate one region from its neighbors. It uses the pyramid structure to organize data. This structure allows us to work at different resolution levels. This helps to eliminate redundancy, helps to overcome problem of image misalignment, and allows more accurate classification.

We have built a system for integrated image analysis using infrared (thermal) and visual sensors. Information from thermal and visual imagery is fused for classifying objects in outdoor scenes. Pixel level information fusion yields a feature based on the lumped thermal capacitance of the objects. Region level fusion employing a decision tree classifier categorizes imaged objects as being either vegetation, building, pavement or a vehicle. This system has been tested on outdoor scenes with excellent results.

An image understanding system using multiple sensors, including laser radar, thermal, and other sensors is under development. Laser radar is a special type of radar that gives range, intensity and velocity images. Its images are extremely noisy and very difficult to work with. We want to separate man made objects from background and reason about what kind of objects they are by using a knowledge-based system. We use different methods to segment the images, then combine them to generate the best segmentation. This result is then used by a reasoning program to determine what each small piece is. A prototype scene interpretation system using laser radar has been built. Other signals, such as infra-red and millimeter wave radar signals, will be added into the system as additional knowledge sources to further enhance its performance. This system has been tested on laser radar data supplied by Night Vision Laboratory.

The research described above deals with combining information from different sensors. Signal interpretation systems based on this approach have better potential for detecting and recognizing objects. Both the scientific and the engineering/development aspects are considered in the research being pursued.

Molecular Beam Epitaxy for Ultra-High Speed Device Applications

Ben G. Streetman and Dean P. Neikirk

There is considerable interest in developing quantum well devices for high frequency analog applications. Quantum well oscillators have been shown to be capable of generating power at high millimeter wave frequencies, and there is great expectation that these devices will serve as a useful local oscillator at frequencies between 100-1000 GHz. However, there is considerable debate over the quantum well device structures that must be used to maximize the output power obtained from these devices.

During the 1987 contract year we proposed an improved quantum well oscillator, the quantum well injection transit time (QWITT) diode, consisting of a double barrier structure coupled with a depletion region which increases the specific negative resistance and impedance of the device so that higher output power can be obtained. We have also performed both small- and large-signal analyses of the QWITT diode in order to develop a model that relates physical device and material parameters to the output performance of the device. Based on these results we have recently begun fabrication of QWITT diodes using our molecular beam epitaxy facilities.

A schematic diagram of the device structures studied so far is shown in Fig. 1. Three structures, A, B, and C, consisting of identical quantum well regions but with three different drift region lengths of 500Å, 1000Å, and 2000Å respectively, have been examined. The heterolayers were grown in our Varian GEN II MBE system on n^+, (100) GaAs substrates, and device mesas were defined using conventional photolithographic techniques. Top ohmic contacts were formed using AuGe/Ni. Both dc and rf performance have now been measured. The rf measurements have been made using a rectangular waveguide post mount with a whisker-contact, as well as using a planar microstrip circuit. As expected, due to the asymmetric structure of the QWITT diode, the dc I-V characteristics for this device is also very asymmetric. In any negative resistance diode the voltage and current difference between peak and valley, ΔV_{pv} and ΔI_{pv}, must be as large as possible to increase the device output power; in a low frequency model power is directly proportional to $\Delta V_{pv} \cdot \Delta I_{pv}$. For the QWITT diode, ΔV_{pv} is increased through the use of a drift region, but ΔI_{pv} should remain virtually the same as the intrinsic quantum well. This results in an increase in the total output power that can be obtained from the QWITT diode compared to a bare resonant tunneling diode. For the three QWITTs fabricated so far, we find that while the variation in peak-to-valley current differences, ΔI_{pv}, for the devices is quite small, a large increase in ΔV_{pv} is observed, as predicted by the QWITT device models. For the QWITT bias mode (forward bias, substrate positive), as the length of the drift region is increased from 500Å to 2000Å, the voltage corresponding to the current peak, V_p, increases from 2.4V to 5.5V, and the voltage difference between peak and valley currents, ΔV_{pv}, also increases from 0.3V to 1.18V. The peak current density for the three devices is essentially constant at 3.0-3.5x10^4 A/cm^2.

The microwave performance of the three QWITT structures is summarized in Table I. Two rf circuits have been tested: a whisker-contacted post mount in a WR-90 waveguide backed by a sliding short, and a planar circuit consisting of a microstrip line with a dielectric resonator, using a long wire whisker to make contact between microstrip and the QWITT diode. A coaxial triple stub tuner was also used to improve matching between the diode circuits and 50Ω characteristic impedance measurement instruments. The oscillation frequency in the waveguide circuit could be varied from 8 to 12 GHz by changing the dc bias and the position of the sliding short. With the microstrip circuit oscillations in the frequency range of 2-8 GHz were detected, with a peak output power of ~ 1 mW from the QWITT with the longest drift region. For the different devices, as the length of the drift region is increased from 500Å to 2000Å, the output power increases dramatically in both oscillator circuits (Table I). No attempt was made to optimize the microwave resonant cavity and improve the output power by using either reduced height waveguide or improving the circuit impedance match in the planar circuit. In addition, the device areas used in this study were not optimized, and intentionally kept small to avoid excessive heating and consequent heat sinking problems. However, the dramatic increase in output power obtained in devices B and C compared to device A clearly suggests that, as predicted by previous analyses, the intrinsic device characteristics have been improved through an appropriate choice of drift region length. These are the first dc and rf results measured for the QWITT diode. The peak output power of ~ 1 mW in the frequency range of 2-8 GHz obtained here is the highest output power ever achieved from any quantum well oscillator at any frequency. Since no attempt has yet been made to optimize either the microwave resonant cavity or the area of the diode the performance achieved here suggests that further improvements should make higher power output possible. It seems clear that the actual power limitations of quantum well oscillators have not yet been determined, and that through the use of QWITT design principles useful power levels may be achieved at high millimeter wave frequencies.

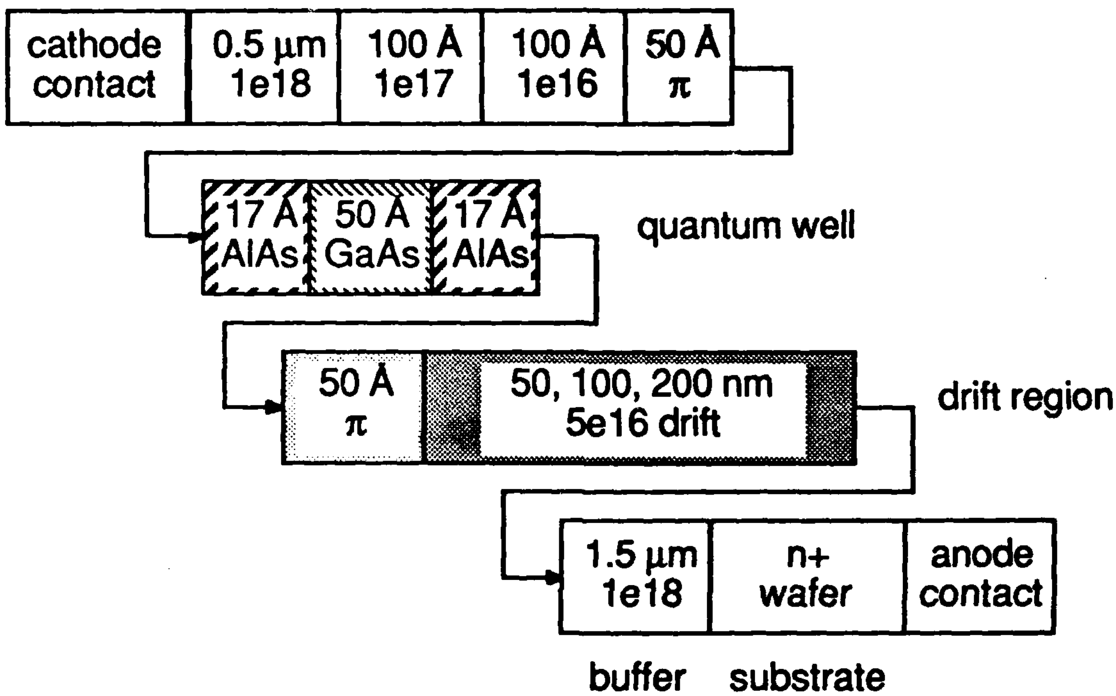

Figure 1: A schematic cross section of the QWITT structures examined to date.

Drift Region Length	dc Negative Resistance	Output Power (µW)	Oscillation Frequency (GHz)
500 Å	64 Ω	3 240 (planar) 275 (planar)	8-12 6-8 6-8
1000 Å	120 Ω	10	8-12
2000 Å	380 Ω	30 910 (planar)	8-12 2-8

Table I: Microwave frequency performance of the three QWITT oscillators in both waveguide and planar circuits.

Planar Quasi-Optical Receiver for Millimeter-Wave Array Components

Tatsuo Itoh and D. P. Neikirk

With the advent of improved metal semiconductor field effect transistors (MESFET) and of new devices such as high electron mobility transistors (HEMT), the circuit environment in which these devices are implemented becomes very crucial for the optimum use of device capability. It is well recognized that the availability of these devices alone does not guarantee high performance communication and radar components at high frequencies such as those for millimeter-waves. To rectify this problem, several novel circuit configurations have been investigatged for planar quasi-optical receivers.

The latest effort that has led to a significant development is a quasi-optical balanced self-oscillating mixer. Figure1 shows the top view of the prototype configuration that was designed and tested at X band frequencies (around 10 GHz). The essential element in this circuit is a coupled slot (CSL) which is used simultaneously as a half-wave resonant antenna for receiving the RF signal in the even mode and as an embedding circuit for the local oscillator (LO) in the odd mode. Due to the orthogonality of the even and odd modes, the RF signal and the LO signal are intrinsically isolated, which in turn prevents the LO signal from being injection locked to the RF signal. Either two MESFET's or HEMT's are placed in the slots and their drain terminals are connected to the two output microstrip lines. The gate and the source leads are connected to the center conductor of CSL and the edges of the CSL ground planes, respectively.

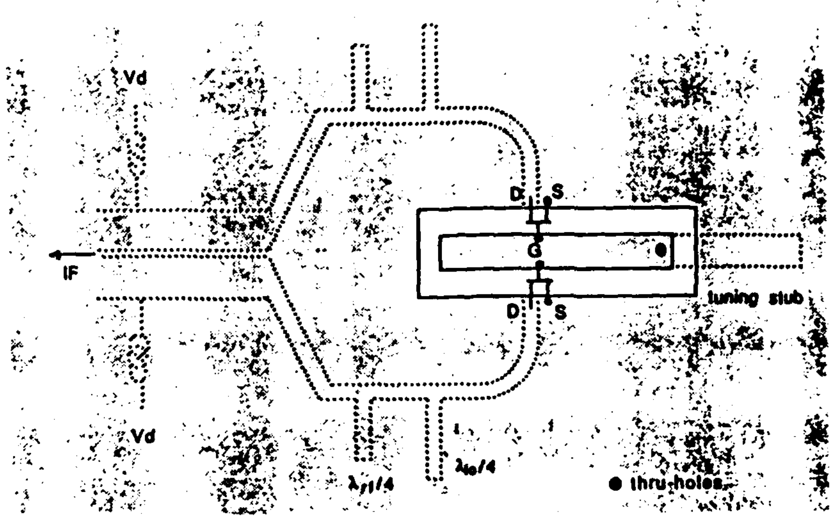

Fig.1 Quasi-optical planar self-oscillating HEMT (or MESFET) mixer

The circuit operates in the following manner. An LO signal is generated by the two transistors which are coupled to the high Q odd mode in the CSL. At the same time, the nonlinearity of these transistors is used for mixing the generated LO signal with the RF signal captured by the even mode of the CSL antenna. The downconverted IF (intermediate frequency) signals from two transistors are 180° out of phase. Hence, as the two output microstrip lines are coupled by the proximity effects, they are combined in the output port (identified with IF in Fig.1) as the odd mode of the coupled microstrip line.

The circuit developed here has a number of advantages. First, it is suited for monolithic integration, because only one type of device (MESFET or FEMT) is used. These devices are currently the workhorse of the microwave and millimeter-wave monolithic integrated circuits (MMIC and MIMIC) and hence the processing technology is well established. Second, the circuit is extremely simple. Its simplicity is almost to the level of a much less sophisticated detector/antenna combination. This feature is extremely important when an imaging array or a phase array using many receiver elements is formed. Third, unlike other quasi-optical receivers, the present structure provides a conversion gain instead of a conversion loss in a resistive mixer. Finally, the quasi-optical design allows a lower insertion loss in the system as no transmission line exists between the antenna and the mixer.

Figure 2 shows the measured isotropic conversion gain and noise figure versus bias voltage for the HEMT circuit. The maxium isotropic converstion gain was 4.5 dB and the best noise figure was 6.5 dB. These numbers are better than the corrsponding data for the MESFET circuit by 1.5 dB and 2.5 dB, respectively. This fact demonstrates that the HEMT is a low noise and high gain device useful for quasi-optical circuit applications.

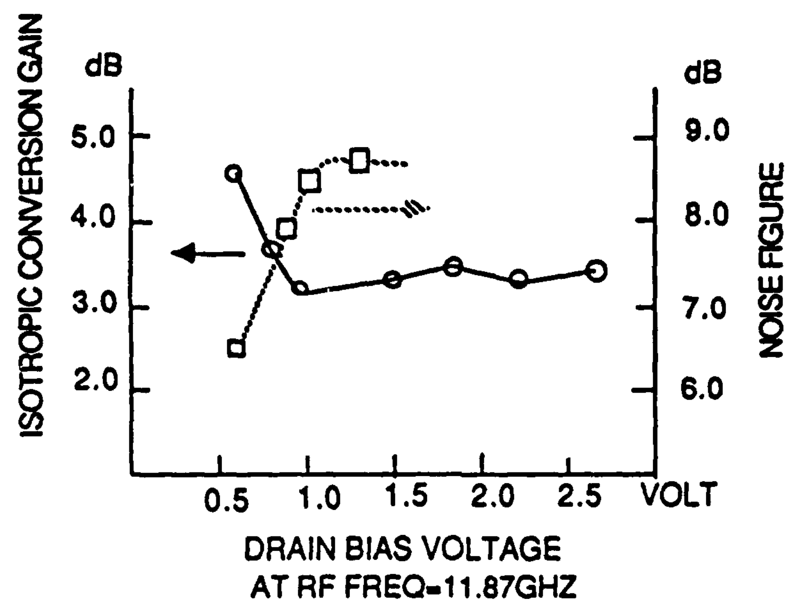

Fig.2 Conversion gain and noise figure of an HEMT self-oscillating mixer

As a new millimeter-wave source, an oscillator based on the QWITT diode was obtained with the highest RF power ever reported. This is a microstrip planar circuit with a wisker contact connecting the microstrip resonator with the diode. The output of 910 μW was realized at 4.2 GHz. This planar oscillator is the first step for integration with other circuits such as a planar mixer. More recently, a millimeter-wave oscillation in the 26 ~ 35 GHz range was observed by using a waveguide cavity.

I. INFORMATION ELECTRONICS

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

Research Unit IE88-1: Multisensor Signal Processing

Principal Investigator: Professor J. K. Aggarwal (512) 471-1369

Graduate Students: C. Oh and C. C. Chu

A. SCIENTIFIC OBJECTIVES:

The overall scientific objective of this research unit is to develop algorithms for multi-sensor signal processing. Further, accurate sensor-scene and sensor-sensor relationship will be established based on the physical principles of signal generation, detection and interactions. We shall develop computer methods for concomitant analysis of information in signals from different sensors, and develop efficient and accurate techniques for signal processing and interpretation. In this research, the extraction of information from signals is to be accomplished by using Artificial Intelligence techniques and rule-based methods, so that information gathered from multiple sensors may be easily combined. The sensors to be used in the system will include visual, infrared, laser radar and millimeter wave radar sensors.

Signal processing that integrates multisensory data can provide information that cannot be obtained by processing the data individually. By integrating information from different sensors, a more powerful and robust system can be built to interpret the scenes of interest. On one nand, rule-based methods can better implement the integration task among signal systems that do not have well-understood mathematical models. On the other hand, detailed analysis of signal generation process, transmission environment and data acquisition models should be thoroughly investigated to find out the physical significance of the sensed signals. Thus more meaningful processing techniques can be designed based upon such knowledge.

There are a number of issues to be studied for a multi-sensor system, such as, relationship between different sensors, sensor behavior difference under different weather conditions, spatial and temporal correspondence between signals, calibration and registration problem between various sensors, and the strategies for synergistically integrating the extracted information. The drastic differences between the principles of how these sensor devices work require that individual sensor system be analyzed, and accurate models be established for sensed signals. The strategies to combine the extracted information and to interpret them in a consistent way is critical to multi-sensor signal processing, and is a research area that has not yet been fully explored.

Traditionally, the extraction of information from single and multi-dimensional signals are done by filtering, statistical analysis and classification, and structural methods. In comparison, little effort has been devoted to more general methods of extracting information from signals. In particular, adequate attention has not been given to problems where the relationships between the signals and the system parameters cannot be described in terms of mathematically well-understood formulations. Hence, there exists a need for the development of rule-based methods to model diverse mechanisms that generate and distort signals. We plan to develop rule-based signal analysis systems for application in various domains and address issues such as improving communication between different levels of analysis and tightening the coupling between front-end processing and the higher levels of analysis.

B. PROGRESS

A significant amount of research has been conducted by this research unit in the analysis and interpretation of signals, including both mono-sensory and multi-sensory signals. The latter category includes signals sensed by diverse sensors and analyzed concomitantly to provide useful information regarding the sensed scene and its characteristics. Currently the major effort at this unit is being directed at various aspects of the problem of processing and interpreting signals from multiple information sources. Strategies at higher levels of analysis for robust interpretation of signals are being developed to integrate signals from different sensors. In our research program, we are developing knowledge-based systems for object detection and image interpretation in various domains of applications, with emphasis on information integration from multiple sensors. In this unit, we have four projects under development. They are the integrated analysis of signals from infrared and visual sensors, pyramid-based image segmentation system using multi-sensor data, thermal and visual image synthesis, and intelligent integration of information from laser radar and other special sensors.

We have approached the problem as follows. The ideas common to all projects in this unit are: (1) study of the physical models of the imaged objects and individual sensors, and (2) integration of information derived from various sensors. First, physical models for signal generation, transmission, and acquisition are studied, leading to a better understanding of fundamental properties of images and development of effective algorithms. Second, information integration is used to resolve ambiguities that cannot be dealt with in mono-sensor operation. This integration is not a simple concatenation of sets of data, but rather a synergistic integration.

The approaches and results of individual projects are outlined here. For the scene analysis project using infrared and visual imagery, our approach is to estimate surface heat-flux so as to evaluate intrinsic thermal properties of imaged objects. For the image segmentation project which uses multisensory data, we use pyramid data structure to alleviate both the image registration problem and excessive fragmentation. Neighborhood statistics from both thermal and visual images are used to segment the scene. For the thermal and visual image simulation project, the octree data structure is used to model 3D objects. Heat flows within the object are simulated. The resulting surface temperature variation is used to create the thermal image. The octree structure also facilitates generation of the visual images. For the LADAR project, surface fitting and image statistics are used to segment images. Knowledge-based system is used to achieve object classification and scene interpretation. A brief discussion of each project is presented below.

Integrated Analysis of Signals from Infrared and Visual Sensors

A new approach has been developed for computer perception of outdoor scenes [1]-[5]. The approach is based on the integration of information extracted from thermal (infra-red) images and visual images, which provides new information not available by processing either kind of image alone. The thermal behavior of scene objects has been studied in terms of surface heat fluxes. The thermal image is used to estimate surface temperature, and the visual image provides information about surface absorptivity and relative surface orientation. These parameters, when used together, provide estimates of surface heat fluxes which cannot be obtained by processing either the thermal or the visual image alone. Features based on estimated heat fluxes are shown to be more meaningful in characterizing the thermal behavior of scene objects. They are also more specific in distinguishing scene components.

Most earlier work in automated scene analysis using thermal images has been of limited scope and has been directed at identifying one among a set of vehicles in a scene. It has dealt mainly with the use of statistical pattern recognition techniques and with features that are computed directly from the image pixel values. Such an approach suffers from many limitations, a major factor being the minimal amount of knowledge that can be extracted from the image. Our study of the various approaches to signal analysis and interpretation [6] revealed that the fusion of data from different sources and a more general knowledge-based approach are warranted for wider and more robust applications of thermal image analysis.

The new approach developed synergistically combines information in thermal and visual data. Also, the application of principles of heat transfer yield meaningful descriptions of thermal behavior of scene objects, thus meeting the above requirements. Several observations are made which are unique to the situation where outdoor scenes are imaged in daylight [5]. These observations allow the formulation of a simple analytical model which relates surface temperature of the viewed object to the thermal irradiation at the camera, thus providing a simple algorithm for estimating surface temperature [4,5]. In the visual domain, approximating surface reflectivity by opaque, Lambertian behavior allows us to compute relative surface orientation from the apparent brightness.

At the surface of the imaged object, the absorbed heat flux is computed using estimates of surface reflectivity and relative orientation as described above, and also using estimates of intensity and direction of solar irradiation which are obtained from available empirical models. The convection heat flux is obtained by applying available empirical correlations which were developed for engineering applications of principles of heat transfer. The radiation heat loss from the surface is computed using the Stefan-Boltzmann law. Subtracting the convected and radiated heat fluxes from the absorbed heat flux gives us the "conducted" heat flux. The ratio of conducted heat flux to absorbed heat flux has been shown to describe the imaged objects' relative ability to sink or source heat radiation. The value of this ratio depends largely on the imaged objects' normalized lumped thermal capacitance. Thus, features based on these estimates of heat fluxes serve as meaningful and specific descriptions of imaged objects. The approach has been successfully tested on real data obtained from outdoor scenes and its usefulness in interpreting images of outdoor scenes has been demonstrated [3-5].

The integration of thermal and visual information at the pixel level allows for the evaluation of a useful feature, viz. the ratio between the conducted and absorbed heat fluxes. Although useful, this feature lacks the specificity to unambiguously delineate between the different classes of objects in the scene. Hence, interpretation at a higher level of abstraction is warranted via integration of thermal and visual imagery at the symbolic/region levels. A decision tree classifier was developed for this purpose [2]. The classifier employed aggregate features computed for each region, using both the thermal and visual images. The features included the mode of the heat flux ratio, average region temperature and surface reflectivity. These parameters allowed for an unambiguous classification of image regions as 'Road', 'Building', 'Vegetation', and 'Vehicle'.

Pyramid-based image segmentation system using multi-sensor data

This research aims at developing an automated system for segmenting scenes using multi-sensor data. The immediate objective of this project is to develop techniques to segment scenes using thermal images and visual images. This automatic segmentation system is designed to serve as the low-end processing module for the above mentioned system which interprets thermal and visual images. As shown by experimental results, the quality of segmentation obtained by using multi-sensor data is better than that obtained by using just the thermal data or just the visual data.

The concomitant use of thermal and visual data is designed to exploit the different characteristics of the two imaging modalities. Areas in the thermal image may be similar in pixel values but may have distinctly different intensities in the visual image. To separate such regions in the thermal image, data from the visual images may be used to determine a threshold, by looking at the corresponding regions in the visual image. For such regions a lower threshold value would be chosen, hence making it possible to separate the regions in the thermal domain. Similarly, there may be regions in the thermal image which are clearly separable, but not so in the visual domain. In such cases the thermal data alone should be able to label these regions as separate ones, regardless of threshold calculated from the visual domain. When the regions are distinctly different in both the domains, they can easily be segmented separately. When regions are very close in both the domains, then they may be merged together. Images segmented in this manner, i.e. using multi-sensor data, when used in the interpretation of multi-sensor signals, helps to provide a less ambiguous classification.

Pyramid data structure is known to be useful in dealing with multi-level control structure and complicated image processing tasks. In our pyramid-based scene segmentation system, image pyramids of reduced resolution versions, of both the thermal and visual data are generated. Links are adjusted between adjacent levels, based on proximity and similarity. The pixel values at coarser resolution levels are recomputed based on the new links formed. This process of relinking and recalculating the pixel values is carried out iteratively, until the links stabilize. Then the pixels at intermediate levels in each of the pyramids define homogeneous regions in the images. Before the pixel values are propagated down, region-growing is carried out at one of the intermediate levels of the thermal pyramid. Standard region growing techniques use a predefined threshold to merge two adjacent pixels into a common region. For our purposes, a new technique is developed, which selects the threshold based on a function of the values of corresponding adjacent regions in the visual domain. The threshold calculated from the visual domain is mapped to the thermal domain. This threshold is then used in the thermal domain in forming regions. After forming the regions at an intermediate level in the thermal pyramid, these regions are propagated down to the lowest level of the pyramid through the links to determine the segmentations.

The pyramid allows us to work at different resolution levels. This helps to eliminate a large number of redundant and fragmented segments in the process and allows more accurate classification at later stages. Also the criteria for exact registration of data from different sensors may be relaxed to some extent, by working at reduced resolution. At present, research is being carried out in devising more accurate functions to determine the thresholds from the visual domain and map these onto the thermal domain, for a better segmentation of the thermal image. Images segmented in this manner would enable higher level processes to classify the imaged scene more accurately.

Thermal and Visual Image Synthesis

We have developed a unified approach for modelling objects which are imaged by thermal (infrared) and visual cameras. The model supports the generation of both infrared (8μm - 12μm wavelength) images and monochrome visual images under a variety of viewing and ambient scene conditions. An octree data structure is used for object modelling. The octree serves two different purposes - (1) surface information encoded in boundary nodes and efficient tree traversal algorithms facilitate the generation of monochrome visual images, and (2) the compact volumetric representation facilitates simulation of heat flow in the object which gives rise to surface temperature variation, which in turn is used to synthesize the thermal (IR) image. The modelling techniques developed may be used in a model-based scene interpretation system which analyzes concomitantly thermal and visual images of scenes.

Thermal behavior of an object is estimated by using a model which is based on the thermal characteristics of the object itself (e.g., absorptivity, convection heat transfer coefficient and thermal conductivity) and the thermal parameters of the surroundings(e.g., wind speed, the direction of solar irradiation, the ambient temperature, etc.) which are obtained from empirical data. Surface temperature of an object is calculated for each node of the octree under the assumption that an equilibrium exists (1) between the heat flux flowing into the surface of the object and those flowing out from the surface, and (2) between the adjacent nodes. For the simulation of heat flows between a node and the surroundings and/or its adjoining nodes, first, the octree structure is modified to represent thermal characteristics of each node and to encode explicit adjacency information in each node. For each node of the octree, three modalities of possible heat flow (i.e., conduction, convection and radiation) and solar irradiation are calculated. The balance between these heat flows and the internal energy variation of the node is described quantitatively so as to form a set of equation which can be calculated using numerical techniques.

The resulting variation of the surface temperature is mapped into different intensity values and each node is projected onto the image plane (or view port) with the corresponding intensity value. This simulates the imaging processes of thermal (infrared) images. Also, the ratio of conducted heat flux to absorbed flux , which has been shown to facilitate the identification of different classes of objects in outdoor scenes, is computed at the surface nodes of the modelled object. Our implementation of the proposed technique shows reasonable results which are comparable to the information obtained from experiments [1]. Even though the effect due to atmospheric attenuation is not considered in our model, it is justified for imaging distances of a few hundred meters and sensing wavelength band of 8μm-12μm. Currently, no internal heat generation is assumed in the model. However, given quantitative information on the internal heat source, it will be easily incorporate into the model due to the inherent characteristics of the octree structure used in our system.

Since the proposed system is based on actual thermal behavior of an object rather than heuristics, it offers several advantages over surface facet based approaches for modelling thermal image generation. This system allows for effects of lateral heat flow in the surface, and also heat flow into the object. And this system does not require large data files of geometric and thermal parameters which need to be input to a facet based system.

This system will be used in a model-based vision system which interprets thermal and visual images. Each class of objects to be classified will be represented by distinct octree models.

The specification of a unique model for each class of objects to be recognized in the scene allows for more accurate prediction of thermal images of objects and also allows for the prediction of the values of discriminatory features which can be used in classification. Simulations of heat flows on this model yields thermal images specific to scene conditions. These generated images and the discriminatory features calculated in the simulation will be used in a Hypothesis and Verify scheme to identify objects belonging to that particular class.

Intelligent Integration of Information from Laser Radar and Other Special Sensors

Laser radar (LADAR) systems have received much attention in recent years. LADAR gives range and intensity (reflected signal) image pairs simultaneously. Some systems even provide velocity image by using Doppler Effect. The LADAR image data is extremely noisy and very difficult to extract information. Therefore, we integrate information from multiple sources to improve segmentation. In the past year, we have acquired two sets of LADAR data (one with range and intensity, the other also with velocity) and one set of FLIR data from the Army Night Vision Laboratory. Currently we are working on both sets of LADAR data and already have preliminary results that demonstrate improved scene segmentation by integrating multiple components of LADAR data [7]. In the future, we will also incorporate millimeter-wave radar (MMW) and passive Infra-red sensor data (FLIR). A knowledge-based system is being developed using KEE, an expert system shell, for intelligent system development.

We have studied LADAR images of man-made objects in outdoor scenes. Our first objective is to find image segmentation to separate objects from background. The second objective is to interpret the segmented scene by using a knowledge-based system. Our approach is to segment individual LADAR image components first, then we integrate the results from multiple segmentation maps. The final integrated segmentation provides feedback to previous signal processing stages to refine the results.

For the range data, we segment the image by using geometric fitting to explore the geometric characteristics of object surface. The range segmentation module tends to find smooth fits around man-made objects. Because of the noise and irregularities of shapes of objects in the background, e.g., trees, shrubs, the background usually cannot be fitted with planar surfaces. The intensity data is segmented based on the mean and SD of the image *busyness*. For objects with same surface characteristics (say, metallic body), the areas occupied by the object on the intensity image are likely to present approximately the same degree of busyness. However, experimental results showed that this technique only works well for less noisy images. We also found that the statistics method, if applied to the range data, can also provide good segmentation cues that are not readily available from the surface fitting method. The velocity component, if available, is useful when the object is moving. But in some cases, even when the object is not moving, both surface fitting and statistics method can still offer some cues in segmentation. The segmentation information from velocity data is combined with segmentation results from range and intensity images to get the integrated results.

Next, we combine various segmentation maps from different data channels and processed by different methods to produce a single integrated segmentation map. A segment is established with high credit, if both segmentation maps on range image and intensity image generate about the same segmentation. Otherwise, the segment is either cancelled or degraded to a lower credit, if the two segmentation maps contradict each other. The integrated segmentation results are compared with those obtained by human interaction. The two segmentation maps show strong resemblance to each other and share nearly coincident contours. By examining the computed means and SD's guided by the segmentation, we find that: (1) in the intensity data, different types of targets generate different statistics; and (2) in the range data, the background segments, if any, have much larger SD than those of the objects. Thus it is possible to use the statistics on the range data to separate background from possible objects/targets in the scene [16]. In the next stage, statistics and other information from the intensity data can be used to distinguish between different types of targets. After the segmentation maps are effectively integrated, the new map can be used to verify old individual segmentation maps, generate cues for each low level process to refine its work, if necessary, but with high level knowledge guidance.

Currently effort is being devoted to the development of a prototype scene interpretation system. The knowledge-based system incorporates intelligent reasoning. Each region in the segmented scene will be analyzed and given a label. The interpretation system will postulate a hypothesis about the scene and use available data to verify or reject the hypothesis. Other signals, such as FLIR and MMW, can also be incorporated into the system as independent knowledge source modules.

This project is expected to achieve better understanding of the sensor/scene physical models and signal transmission models for thermal, LADAR and other types of images. We expect to develop algorithms that can integrate information from multiple types of sensors and detect objects in difficult imaging conditions. With (1) better understanding of sensor physics, (2) different signal processing and segmentation techniques applied on different information sources, and (3) effective methods of information integration, we expect to achieve better scene analysis and object classification than conventional algorithms. The final scene interpretation is aimed to (1) classify segments as different types of objects, (2) generate a complete interpretation of the scene, and (3) pinpoint a *most interesting region* to human operator or other control systems. In particular, segmentation and recognition of objects of relevance and interests to the Department of Defense in thermal, visual, and radar images are the ultimate goals for all projects of this unit.

C. FOLLOW-UP STATEMENT:

Past research conducted by this research unit in the analysis and processing of signals from different sensors has demonstrated that multi-sensor fusion is a powerful approach for signal processing and interpretation. Detailed signal modeling based on physical principles and field observations will be undertaken to derive more effective signal processing techniques. Research is being directed at the formulation of accurate models of the scene-sensor interactions based on a detailed study of the physical phenomena that generate and distort the signals. Various issues, such as relationship between different sensors, spatial and temporal correspondence between signals, and strategies for synergistically integrating sensed information, are being investigated. This unit will pursue both the investigation of scientific issues and the development of engineering solutions to the practical problems. A study into the details of signal generation, transmission, and acquisition is essential to the design of satisfactory signal processing and interpretation algorithms. This research will allow for the design of general, robust systems for signal interpretation that can take the advantage of multiple information sources.

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V. List of Grants and Contracts

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

Research Unit IE88-2 — NONLINEAR ESTIMATION AND DETECTION

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

Graduate Students: Hangju Cho, Emmanuel Fernandez-Gaucherand and Enrique Sernik

A. RESEARCH OBJECTIVES: This research unit is concerned with novel methods of extracting information from noisy measurements of the state of a nonlinear stochastic system, for the purpose of real time estimation or control. The problem 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. 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 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 undertaken an in-depth investigation of adaptive nonlinear estimation problems for stochastic systems involving incomplete (or noisy) observations of the state and unknown parameters. In [1], [2], and [8], the adaptive estimation of the state x_t of a finite state Markov chain with incomplete state observations y_t taking values in a finite set, and in which the state transition probabilities depend on unknown parameters, is studied. Such problems arise in systems such as computer communication networks. In general, the adaptive estimation problem involves the computation of estimates (e.g., state estimates) in the presence of unknown parameters; in addition, estimates of the parameters are computed simultaneously. In the present context, the adaptive estimation problem is that of computing recursive estimates of the conditional probability vector of the state x_t given the past observations $\{y_0,\dots,y_t\}$, when the state transition matrix Q is not completely known (i.e., it depends on a vector of unknown parameters θ — this dependence is expressed as $Q(\theta)$).

The approach to this problem which we have investigated has been widely used in linear filtering: we use our previously derived recursive filter [3] for the conditional probabilities with known parameters, and we simultaneously recursively estimate the parameters, plugging the parameter estimates into the filter. This adaptive estimation algorithm is then analyzed via the Ordinary Differential Equation Method [4], [5]. 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 proof is that of showing that, for each value of the unknown parameter, an augmented Markov process has a unique invariant measure. New techniques for the analysis of the ergodicity of time-varying Markov chains are utilized. The convergence of the recursive parameter estimates is studied, and the optimality of the adaptive state estimator is proved. This is the first such analysis of an adaptive nonlinear estimation problem in the literature.

In a natural extension of our work in [1],[2],[8], we have begun to apply similar techniques to some interesting stochastic control problems involving finite state Markov processes with incomplete observations and unknown parameters. One intriguing set of problems for which some results are available when the parameters are known are those involving quality control and machine replacement; we study the properties of these problems in the papers [6],[7], with the eventual aim of developing optimal adaptive stochastic controllers. However, the presence of feedback makes this stochastic adaptive control problem much more difficult than the adaptive estimation problem of [1],[2],[8]. We concentrate in [6] and [7] on the adaptive control of a problem with simple structure: the two-state binary replacement problem. An adaptive control algorithm is defined, and it is shown that the relevant augmented closed-loop Markov process is ergodic. This represents a crucial step toward the application of the ODE method and the solution of the adaptive control problem.

In related work on adaptive Markov decision processes, the important issue of implementation has been addressed in [9], which presents finite-state discretization procedures for discrete-time, infinite horizon, adaptive Markov control processes which depend on unknown parameters. The discretizations are combined with a consistent parameter estimation scheme to obtain uniform approximations to the optimal value function and asymptotically optimal adaptive control policies. The adaptive control of systems with unknown disturbance distribution has been addressed in [10], in which we have extended the nonparametric results of [11] to problems with incomplete state observations. Our approach combines convergence results for empirical processes and recent results on parameter-adaptive stochastic control problems.

In order to deepen our insight into the types of nonlinear systems which occur in problems of nonlinear estimation and adaptive control, we have also investigated and solved a number of problems in the linearization of discrete-time and discretized nonlinear systems. In [12], necessary and sufficient conditions for local input-output linearizability are given. We also show that the zeros at infinity of the system can be obtained by a particular structure algorithm for locally input-output linearizable systems. Whereas the objective of input-output linearizability is to make the input-dependent part of the output sequence linear in the new input, that of immersion by nonsingular feedback into a linear system (solved in [13]) is to make the output sequence jointly linear in the new input and some analytic function of the initial state. Necessary and sufficient conditions for such immersion are given in [13].

Feedback linearization is a very effective control technique, when applicable. However, a digital feedback law is inevitable in practice, and discretization can destroy linearizability [14]. This is because the control input is constant between the sampling times. The method which is usually employed is that of neglecting the error due to sampling by increasing the sampling frequency. However, increasing the sampling frequency is not always possible or desirable. Furthermore, it is shown in [15] and [16] that this method is equivalent to the classical Euler method, which is known to be lacking in accuracy. This problem is studied further in [15] and [16], in which we develop a new digital control technique which approximately linearizes a system (by using a state coordinate change and digital feedback) up to a higher order power of the sampling interval.

Adaptive control refers to the control or regulation of a system in the presence of parameters which are unknown or which vary with time. Systems in which changes can occur which are more drastic than relatively slow parameter variations are exemplified by systems with failure modes which significantly alter the structure of the system. Reconfigurable aircraft represent one such type of system. In this case, there is a "hybrid" situation in which the state of the system consists of a set of real numbers (the usual "state") together with a set of discrete or Boolean variables (describing, for example, the structure of the system). One eventual result of research on this class of systems will be higher level symbolic modules which will work with lower level adaptive controllers to form a more intelligent multi-level control system.

There has recently been considerable research concentrating on the higher level of discrete or symbolic variables in the hybrid dynamical system. Systems described only by such variables are also important in their own right, and have been called discrete event dynamical systems. In such systems, examples of which include flexible manufacturing systems and computer networks, the state of the system changes at asynchronous discrete instants of time instead of continuously and is governed by the intricate interaction of discrete events. Models and control algorithms have begun to be developed by modeling the discrete event dynamical system (or plant) as a finite automaton with certain controllable events, the occurrence of which can be disabled by means of a control action. A number of such problems are understood and have been solved in the case that the supervisor can perfectly observe the occurrence of events in the plant [17], but the more interesting case of the supervisor receiving incomplete information is less well understood. In many cases, this can be modeled by constructing a mask, or observation function, M, through which the supervisor observes the occurrence of events; hence, certain events cannot be distinguished from each other or cannot be seen by supervisors. In this case, necessary and sufficient conditions for the closed-loop behavior or language L to be realized by the construction of a suitable supervisor are known for some problems of interest [18]. As opposed to the much simpler case of perfect information, it turns out that the class of sublanguages $\underline{I}$(L) of a given language L which satisfy the necessary and sufficient conditions do not necessarily possess supremal elements; thus, minimally restrictive solutions may not exist. Therefore we are forced to resort to a solution that is minimally restrictive in some narrower sense. On the other hand, there is a smaller class of sublanguages $\underline{D}$(L) which is algebraically well-behaved and does possess a supremal element. In [19] and [20], we show that the supremal element of this class can be computed via an algorithm which has a simple graphical structure and is well suited to computer implementation; this algorithm recursively removes edges and nodes from the graph of an automaton which generates a particular language. These algorithms provide a good suboptimal solution to the problem; in addition, they involve new classes of automata which are of interest in their own right.

C. <u>FOLLOW-UP STATEMENT:</u> The research described above will be actively continued under JSEP sponsorship. Some particular directions are the following. Our work [1],[2],[8] on adaptive estimation of Markov chains with incomplete observations will be extended to include rate of convergence results and the tracking of time-varying parameters, as well as to include other types of observations. The stochastic adaptive control problem of [6],[7] will be further analyzed to establish convergence of the parameter estimates and average cost optimality. Also, our work [19],[20] on discrete event dynamical systems will be pursued further.

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IV. LIST OF THESES AND DISSERTATIONS

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V. CONTRACTS AND GRANTS

Air Force Office of Scientific Research, Grant AFOSR-86-0029, "Research in Adaptive and Decentralized Stochastic Control," S.I. Marcus, Principal Investigator, November 15, 1985-November 14, 1988.

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II. SOLID STATE ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE88-1 IMPLANTATION AND ANNEALING OF InP AND RELATED COMPOUNDS

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

Graduate Students: A. Campbell, A. Dodabalapur, T. Rogers, K. Sadra

A. SCIENTIFIC OBJECTIVES: Our goal in this research is to understand the surface and bulk properties of InP and related compounds, and the effects of ion-implantation and rapid thermal annealing on these properties. The reasons for interest in these issues are the recent advances in device development using InP-based materials (including InGaAs and InGaAsP grown epitaxially on InP).

InP is a promising III-V material for a variety of semiconductor device applications. It has several potential advantages over GaAs, including a higher peak and saturation velocity [1]. These advantages are expected to result in faster switching devices, and in microwave devices which operate at a higher frequency [2]. Important ternary and quaternary alloys can be grown lattice-matched to InP; such heterojunction systems have important applications in fabricating optoelectronic integrated circuits [3], heterojunction bipolar transistors [4], and modulation-doped field effect transistors [5]. Using suitable deposited dielectrics, the InP-dielectric interface can be processed to have a fast interface state density as low as $6\times10^{10}cm^{-2}eV^{-1}$ [6], which is lower than the density obtainable with GaAs. Such a low density of surface states enables the fabrication of promising metal-insulator-semiconductor field effect transistors (MISFETs) [7,8]. One of the major objectives of this research is to provide a better understanding of two of the most important issues facing InP FET technology: (a) impurity activation during various implantation and annealing procedures, and (b) formation of a stable InP/insulator interface with a low density of interface states.

B. PROGRESS: The research can be generally divided into three areas: (a) bulk properties, (b) implantation and annealing studies, and (c) surface studies. Various characterizing techniques such as Hall effect measurements, DLTS etc. were employed in these studies. The use of rapid thermal annealing in controlled ambients for thermal treatment and remote plasma deposition of dielectric films provide us with considerable flexibility in processing these materials. We published the first report of dual implantation involving a donor ion in InP [9]. Our work on the use of ion implantation and rapid thermal annealing to study the DX center in AlGaAs [10] led to the development of a model to describe the capture and emission kinetics of the DX center [11]. The results of our work in the past year have been reported in journal and conference publications, as listed below.

Bulk Properties of InP and Related Compounds: We have studied the electron-hole scattering and minority-electron transport in $In_{0.53}Ga_{0.47}As$, InAs, and InP, including the role of the split-off band. Experimental velocity-field characteristics of minority electrons in p-$In_{0.53}Ga_{0.47}As$ exhibit a monotonic increase in the drift velocity to 2.8×10^7cm/sec at 7.5kV/cm. However, Monte-Carlo calculations including intraband electron-hole scattering with heavy holes indicate that the onset of negative differential conductivity (NDC) should occur at 5kV/cm, at a peak velocity below 2×10^7cm/sec. We have performed Monte-Carlo calculations of velocity-field characteristics in $In_{0.53}Ga_{0.47}As$, InAs, and InP, including intra-and inter-band electron-hole scattering with both electron and hole overlap factors. In addition, we have treated the role of scattering processes in which heavy or light holes are excited into the split-off band. Our results indicate that, due in part to the small value of hole overlap factors involving the split-off band, such processes do not significantly affect the minority-electron energy loss rate in $In_{0.53}Ga_{0.47}As$ or InAs. In InP, however, hole overlap factors are larger and a larger number of electrons have sufficient energy to excite holes into the split-off band.

Implantation and Annealing: The effects of dual implantation with different doses of Si and P on dopant activation efficiency and carrier mobility in InP:Fe were examined. The implants were activated by a rapid thermal annealing step carried out in an optimized phosphorus-containing ambient [12]. For high dose implants (10^{14} - 10^{15} cm^{-2}), which are typically employed for source/drain regions in FETs, dual implantation of equal doses of Si and P results in a higher sheet carrier concentration and lower sheet resistance. For 10^{14} cm^{-2} Si implants at 150 keV, the optimal P co-implant dose is equal to the Si dose for most anneal temperatures. We obtain an activation efficiency of ~ 70% for dual implanted samples annealed at 850 °C for 10 seconds. The high activation efficiencies and low sheet resistances obtained in this study emphasize the importance of stoichiometry control through the use of P co-implants and a phosphorus-containing ambient during the thermal processing of InP.

Dual implantation of Si and different doses of P in GaAs was also studied. For a Si implant dose of 10^{14} cm^{-2} at 150 keV, dual implantation of an equal dose of P at 160 keV results in a significant enhancement of electrical activation efficiency for annealing conditions typically employed for ion-implanted GaAs. Implantation of a higher P doses results in a reduction in the activation, indicating that stoichiometry control is crucial in obtaining high activation efficiencies.

Ion implantation was used to modify the local environment of the DX center in Si-doped $Al_{0.27}Ga_{0.73}As$ grown by Molecular Beam Epitaxy (MBE), and the variation in DX center properties with subsequent rapid thermal annealing processes was examined using Deep Level Transient Spectroscopy [10]. In the as-grown sample, two DX center peaks were found with the same activation energy of 0.47 eV, but with widely different cross sections. The main DX center peak ME3, which appears at higher temperatures due to its smaller cross section, remains stable throughout the experiments. The second DX center peak ME2 has a much larger cross section, and appears at a lower temperature. This subsidiary DX center peak is markedly suppressed in ion implanted samples. Samples which were subject solely to the rapid thermal annealing processes have stable DX center trap signatures, indicating that arsenic loss during annealing does not significantly influence the DX center characteristics. We propose that regions of incomplete ordering and defect complexing in the AlGaAs film give rise to the various subsidiary DX center peaks observed.

The Williams-Watts or stretched exponential decay of the form $A(t) = \exp - (t / \tau)^{\beta}$ and variations of this form was compared to the capture and emission kinetics of the DX center observed by us and other workers. It was found that the time and temperature behavior of the DX center capture and emission characteristics can be reproduced with a thermally activated time constant t and a linear dependence of β on temperature [11]. Activation energies, lattice vibration frequencies and models of implicit distributions of activation energies were compared to values previously found in the literature. Consistency was found between parameters for both capture and emission.

Surface Studies in InP: We have studied the effects of various processing techniques on the metal-insulator-InP structure. In order to determine the effects of various treatments on the stability and interface state density of the devices, we observed the hysteresis and stretch-out of the high-frequency capacitance versus voltage curves of the devices. Indirect plasma enhanced chemical vapor deposition was used since it has been shown to be a useful technique for depositing high quality SiO_2 at low temperatures [13-16].

Since it has been shown that the surface may degrade at temperatures as low as 200°C [14], we have studied the dependence of device quality on deposition temperatures in the range of 180-275°C. Due to degradation of oxide properties at the lower temperatures, attributing the changes in the C-V curves to improved interface characteristics is questionable.

As an alternative to, or in addition to, depositing at lower temperatures, we investigated the effects of chemical treatments of the InP surface prior to deposition, which may prevent formation of native oxides, prevent incongruent evaporation of the substrate, or somehow tie up bonds at the surface in order to improve our device characteristics. We tried a method involving a rinse in Na_2S prior to deposition since it has been shown to be effective in passivating the surface of other III-V surfaces [17]; however, the devices treated in this way show a large negative flatband shift similar to the one seen by Iyer et. al. [16] as well as evidence of ionic conduction. Both effects can be attributed to sodium ions in the oxide and interface regions. Further work will be done using $(NH_4)_2S$ as a source of sulfur, since it seems to cause neither of these effects [15,16].

C. FOLLOW-UP STATEMENT: This work will not be continued under JSEP sponsorship in the next 3-year program beginning in 1989.

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

*K. Sadra, M.S., December 1988, "Monte-Carlo Studies of Electron-Hole Scattering and Minority-Electron Transport in Gallium Arsenide."

V. CONTRACTS AND GRANTS

National Science Foundation Grant ECS 8400002, "Studies of Ion Implanted Multilayer Heterostructures," Professor Ben Streetman, Principal Investigator.

Texas Advanced Technology Program (TATP), "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications," Professors Streetman and Neikirk, Co-Principal Investigators.

Army Research Office, Contract No. DAAL03-88-K-0060,"Quantitative RHEED Studies of MBE Growth of III-V Compounds," Prof. Ben Streetman, Principal Investigator.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE88-2 MOLECULAR BEAM EPITAXY WITH HIGH SPEED DEVICE APPLICATIONS

Principal Investigators: Professor B.G. Streetman (471-1754)
Professor D.P. Neikirk (471-4669)

Graduate Students: T. Block, G. Crook, K. Eyink, D. Hinson, V. Kesan

A. SCIENTIFIC OBJECTIVES: The objectives of this work are to explore new physical phenomena arising in multilayer semiconductors and to identify potential device applications. The research includes growth of GaAs, AlGaAs, and InGaAs 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 is on fundamental issues of materials quality, doping and composition control, interface smoothness, layer thickness uniformity, and heterojunction properties.

The work on multilayer structures emphasizes 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. Our primary emphasis is on devices based on tunneling through AlGaAs/GaAsAlGaAs quantum well structures, which may be useful in either mixers or oscillators at very high frequencies. These devices place very stringent requirements on the control of the epitaxial growth process. Each of the following issues on molecular beam epitaxial growth is being addressed and characterized in this study: the required interface smoothness (and the related question of layer thickness uniformity); the generation of appropriate abrupt doping profiles; and the close compositional control necessary for the heterojunction structures. The objectives of this study are to understand these three inter-related aspects of molecular beam epitaxial growth, and to apply the resulting growth capabilities to appropriate test structures for a careful study of device mechanisms. Application of these techniques to the fabrication of high frequency devices is done in collaboration with the unit EM88-1, "Millimeter Wave Monolithic Array Components."

B. PROGRESS: During the period covered by this report, we have made progress in the development of MBE growth techniques and equipment, fundamental studies of growth mechanisms, the understanding of transport in strained and unstrained heterostructures, and realization of a high-frequency QWITT diode.

RHEED Studies: An important feature of molecular beam epitaxy is the ability to monitor growth in-situ using reflection high-energy electron diffraction (RHEED). Applications of RHEED include monitoring oxide evaporation, determining substrate surface reconstructions, and monitoring growth rates in-situ using oscillations in the diffracted electron intensity during growth [1,2]. We have equipped our MBE system with an imaging RHEED system which employs a CCD camera and image processor to access the entire RHEED pattern [3]. The imaging system displays the RHEED pattern onto a monitor screen where diffracted intensities can be monitored at a single point, at multiple points, or along lines through the pattern.

Recent work using the imaging RHEED system has involved the identification of contributions to the RHEED pattern made by electrons diffracted from the bulk of the growing crystal rather than its surface. In order to use RHEED to understand the growth kinetics occurring at the surface, interference from bulk diffraction must be identified and taken into account. We have particularly examined the effects of Kikuchi scattering [4] from the bulk of the crystal on observed RHEED oscillations during GaAs growth [5]. Figure 1 shows a series of intensity profiles along the specular streak in the RHEED pattern taken at different times during the growth of a monolayer of GaAs. The sharper, more intense peak is from the specularly reflected beam, while the less intense peaks, labeled A and B, are from diffusely scattered Kikuchi features. By calculating the positions of several Kikuchi lines and comparing to observed RHEED patterns, we have determined that the intensity peak labeled A is caused by Kikuchi scattering from (117) bulk crystal planes, while the peak labeled B corresponds to Kikuchi scattering from (004) planes. Intensities of the main features in Figure 1 are plotted versus time in Figure 2, showing the oscillations in intensity of the various features and the phase relationships between them. It can be seen from Figure 2 that the intensity of peak A oscillates nearly 180° out of phase with the oscillation of the specular intensity, while the intensity of peak B oscillates nearly in phase with the specular beam.

The accepted explanation for oscillations of the specular RHEED intensity during growth is that the electron intensity reflected from the crystal is highest when the surface is smoothest. The RHEED intensity therefore decreases when partial monolayer coverage causes the crystal surface to roughen, and increases again as monolayers are completed. Kikuchi scattering intensities from the bulk of the crystal should oscillate with opposite phase to the specular oscillation, because electrons are most likely to be scattered into the bulk at times during growth when the surface is the roughest. The intensity oscillations plotted in Fig. 2 show that one of the Kikuchi scattering peaks (peak B) oscillates in phase with the specular oscillation, contrary to what is expected for a Kikuchi scattering process. This indicates that there is interference between the specular and Kikuchi diffraction. Depending on the incident angle of the electron beam with the substrate, this interference with Kikuchi diffraction can change the phase of the observed specular oscillation [5,6]. This has important implications, as stated by Zhang, et al. in Ref. 6, for growth applications in which growth of successive monolayers is calibrated by assuming the maxima in RHEED intensity oscillations correspond to completed monolayers. Diffraction from the bulk of the crystal must therefore be considered when interpreting RHEED patterns during MBE growth, and our imaging RHEED system should continue to be a powerful tool in identifying the various contributions to diffraction patterns.

Molecular Beam Epitaxy System: The arsenic cracking source developed in our laboratory last year has been in constant use and allows us to grow for several months without replacing arsenic (about 1 millimeter of material). We have found lower compensation ratios in Si-doped GaAs grown with the cracking source than in material grown with a conventional As_4 source. We have also found that growing with the cracking source suppresses deep level concentrations and results in lower photoluminescence intensity of carbon-related luminescence [7].

Another MBE effusion source we have developed is designed to reduce the thermal gradients present in conventional metal sources. Radiation from the mouth of the source normally causes the source crucible to be considerably cooler at the top than at the bottom. This can cause redistribution of the source material in the crucible, resulting in instability of the emitted flux. Our source uses a novel filament design, heat shielding arrangement, and thermocouple design to reduce thermal gradients and improve the efficiency and flux response of the aluminum source on our machine [8]. We are planning to use this design to build a source for gallium which we expect to be helpful in reducing oval defect densities, as observed with other sources made to be hotter at the crucible mouth [9].

The major background impurity in MBE-grown GaAs is carbon, believed to come largely from carbon monoxide (CO) in the MBE system. To help reduce CO levels near the substrate, we have designed a coldfinger to be installed near the substrate to pump active gases. This active gas pump will provide a 10 K surface at a distance of one inch from the substrate manipulator. This should be especially useful since we have found that large amounts of carbon-containing gases are generated right at the substrate by the substrate rotation mechanism [10]. The substrate active gas pump is now being tested on a small vacuum chamber and will be installed on the MBE machine during the next year.

Pseudomorphic modulation-doped structures: We have studied molecular beam epitaxial growth conditions to obtain high quality pseudomorphic AlGaAs/InGaAs/GaAs modulation-doped structures [11,12]. Our studies indicate that optimizing the arsenic overpressure and growth temperature for each layer is very important. Our best as-grown electrical results for a modulation-doped structure with a 125 Å $In_{0.2}Ga_{0.8}As$ channel are a 77 K mobility of 29,000 cm^2/V-s and sheet carrier concentration of 1.55×10^{12} cm^{-2}. These figures are among the highest reported in the literature for similar structures. We have studied the effects of rapid thermal annealing on the electrical and optical properties of these structures. A significant mobility increase is typically obtained after short-time heat treatments [11,12]. We attribute this increase to improvement in the crystalline quality of the channel produced by the annealing. Both the linewidth and the energy of the photoluminescence transition due to channel electrons and photoexcited holes are influenced by the changing free carrier concentration in the channel. Our results also suggest that there is negligible layer mixing in these structures after short-time annealing [12].

We have also made a detailed study of the photoluminescence (PL) properties of pseudomorphic modulation-doped $Al_{0.15}Ga_{0.85}As/In_{0.2}Ga_{0.8}As/GaAs$ structures as a function of temperature [13]. PL spectra provide valuable information such as intersubband spacings and the energy distribution of electrons. At 4.2 K, hole localization influences the PL linewidth; however, at higher temperatures (77 K) the thermal energy of photoexcited holes is sufficiently large to obtain a reliable measure of sheet carrier density from the PL linewidth. Our results also suggest that information about the interface quality can be obtained from a careful analysis of the PL linewidth at 77 K and 4.2 K. The spectra taken from several samples clearly show that the PL transition energy exhibits a free carrier density dependence due to bandgap renormalization and electric field effects.

We plan to continue our studies of the optical (luminescence and absorption) and electrical properties of modulation-doped structures. The emphasis of our future studies will be to develop methods to evaluate interface quality in such structures in various material systems. Such methods will be of considerable benefit in assessing material quality of modulation-doped structures for field effect transistors and other device applications. We also plan to fabricate and test optimized field effect transistors.

Transport through GaAs/AlAs Multilayer Heterostructures: We have performed a detailed study of transport through AlAs barriers of thicknesses ranging from 14 Å to 150 Å. Three transport regimes are noted depending on barrier thickness. For thin barriers of 14.7 Å, the current transport is dominated by pure tunneling through the G conduction band states. As the barrier thickness is increased to 50 Å and 70 Å, the X conduction band minima in AlAs contributes a large inelastic tunneling component which dominates the transport process. For the thickest 150 Å barriers, thermionic emission through the X conduction band in AlAs determines transport through the barrier. These results explain the lack of increase in peak-to-valley ratio for increasing barrier thickness when indirect bandgap barrier materials are used [14,15].

Deep Level Transient Spectroscopy characterization of resonant tunneling diodes with room temperature negative differential resistance have demonstrated a novel transition to a high impedance, capacitively reactive state during low bias capacitance measurements. A mechanism based on carrier trapping by deep levels has been proposed, and this behavior has been found to be correlated with the temperature used to grow the device. These studies suggest that lower MBE growth temperatures may not be necessary to obtain good resonant tunneling device characteristics [16].

Quantum Well Injection Transit Time Diode: Last year we reported the invention of a new microwave oscillator, the quantum well injection transit time (QWITT) diode [17], which uses a quantum well to replace avalanche injection in an IMPATT diode. Small-signal analysis of the QWITT diode [18] indicates that the specific negative resistance and hence output power of this device is significantly higher than that obtained from a resonant tunneling diode. We have also performed a large-signal analysis of this device [19] to relate physical device and material parameters to the output characteristics. The large-signal model uses the Ramo-Shockley theorem for transit time effects and performs a numerical surface integration over the entire rf cycle to calculate the device current and output power density. The model performs a piecewise linearized fit to an experimental dc I-V characteristic for the quantum well to characterize current injection. The electric field and carrier velocity in the drift region are assumed to be constant. Static quantum well I-V characteristics are assumed to be valid at all frequencies. Fourier analysis of the device current gives the device conductance and susceptance per unit area. Imposing a minimum impedance limit of 1 W from circuit design considerations, a maximum contact resistance of 10^{-6} W-cm^2, and a maximum allowable temperature rise of 200 K, the optimum device area, maximum output power and efficiency are then computed. This large-signal analysis indicates that the QWITT structure should yield a higher specific negative resistance than currently reported experimental values at 30 GHz (B-band) and 40 GHz (V-band) for resonant tunneling diodes. The QWITT diode can deliver an output power of around 200 µW at 200 GHz, and at 500 GHz, 6 µW output power may be possible. These predicted results are much higher than the best experimental results reported to date of 0.2 µW at 200 GHz, primarily due to the use of an asymmetric QWITT structure.

Various QWITT diode structures have been fabricated and then mounted in both waveguide and planar oscillator circuits to study their dc and microwave (X-band) characteristics. Our experiments show that, for the same quantum well structure, by systematically increasing the length of the depletion region (i.e., the drift region) on the anode side of the device a corresponding increase in the specific negative resistance and output power is obtained. The significant increase in output power clearly suggests that the intrinsic device characteristics have been improved through the use of a drift region. This is in keeping with the small-signal analysis for the QWITT diode, which predicts an improvement in the rf performance of the device with the use of an appropriate drift region length for a particular frequency of operation. In addition, good agreement between measured and predicted results for specific negative resistance was obtained. A maximum output power of 1 mW at 5% efficiency was obtained at X-band using a planar microstrip resonant circuit [20]. This is the first planar circuit implementation of a quantum well oscillator. This result also represents the highest output power obtained from any quantum well oscillator at any frequency and is five times higher output power than reported in the literature for the same frequency.

In addition, we are working on improving the drift region design through the use of a doping spike of appropriate width and doping concentration. A number of identical QWITT diodes containing a 100Å wide doping spike of different electron concentrations at the beginning of the drift region have been fabricated and tested. Compared to a QWITT diode with a uniformly doped drift region, by using a 100Å wide doping spike with a donor concentration 8×10^{16} cm^{-3}, we have obtained an increase in efficiency from 1.8% to 5% , without compromising on device output power. At present we are working on characterizing the rf performance of the QWITT diode at millimeter wave frequencies.

C. FOLLOW-UP STATEMENT: In future work we intend to explore new physical phenomena arising in multilayer semiconductors and to identify potential device applications of importance to DoD. The research will include MBE growth of GaAs, AlGaAs, InGaAs, and other alloys in lattice-matched and pseudomorphic heterostructures, studies of carrier transport in these structures, and characterization of multilayers which have strong potential for applications in high-speed devices. The emphasis in the crystal growth work is on fundamental issues of materials quality, doping and composition control, nucleation and surface phenomena, interface smoothness, layer thickness uniformity, and heterojunction properties. The emphasis in the device research is on simulation and experimental studies of structures which are promising candidates for high-speed, high-frequency, and optoelectronic applications.

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(Page 7, Res. Unit SSE88-2, "Growth of III-V Compounds by Molecular Beam Epitaxy")

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1. *C. W. Farley and B. G. Streetman, "RHEED Studies of Principal Streak Intensity Profiles and Adatom Coverage of MBE GaAs," J. Vac. Sci. Technol. B, 6, p. 749 (1988).

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II. LIST OF CONFERENCE PROCEEDINGS

NONE

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

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V. CONTRACTS AND GRANTS

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Texas Advanced Technology Program (TATP), "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications," Professors Ben G. Streetman and Dean P. Neikirk, Co-Principal Investigators.

Army Research Office, Contract DAAL03-88-K-0060, " Quantitative RHEED Studies of MBE Growth of III-V Compounds," Prof. Ben Streetman, Principal Investigator.

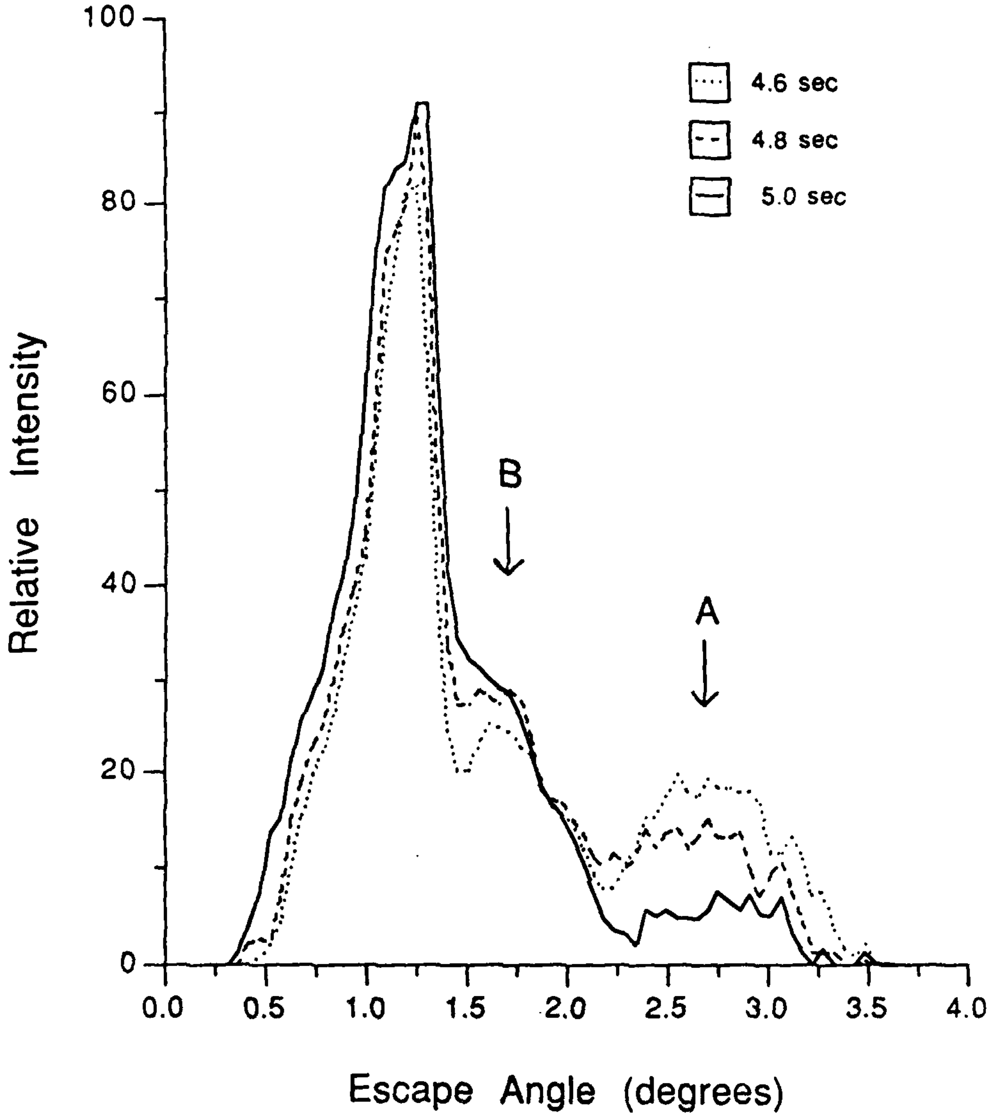

Figure 1. Specular streak intensity profiles for an incident electron beam angle of 1.3°, taken at different times during growth of a GaAs monolayer at 0.5 monolayers per second. An escape angle of 0° corresponds to the shadow edge position for perfectly oriented crystals. The largest peak is the specular intensity, and the peaks labeled "A" and "B" are Kikuchi scattering peaks.

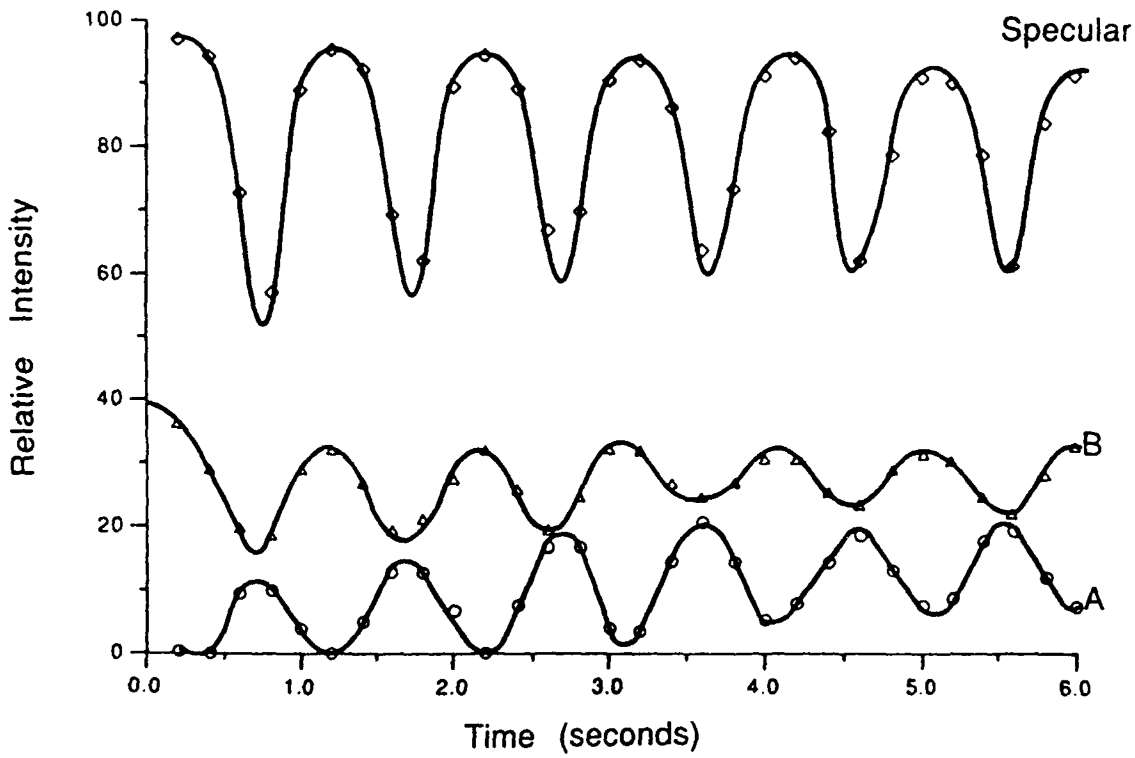

Figure 2. Intensity vs. time data for the three peaks in Figure 1. The intensity of peak "A" oscillates 180° out of phase with the specular intensity oscillation, while the peak "B" intensity oscillates nearly in phase with the specular oscillation.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE88-3 — EPITAXIAL GROWTH, STRUCTURE AND ELECTRONIC PROPERTIES OF SILICIDES ON SILICON SURFACES

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

Graduate Students: Jose Araya-Pochet and Craig Ballentine

A. SCIENTIFIC OBJECTIVES: The scientific objective of this research unit is to explore novel phenomena associated with ultra-thin epitaxial magnetic films grown on single crystal surfaces. This work represents a departure from the primary thrust of work outlined in Research Unit SSE86-3 of the July 31, 1985 proposal, but does address issues raised in the research instrumentation supplement of that proposal (SSE86-5) and also described during the site review by the TCC. The decision to emphasize work on magnetic films rather than on silicide formation was based on our inability to obtain support for instrumentation required to maintain a leading effort in the silicon technology subfield on a time scale consistent with our three year research commitment to JSEP. As indicated in our progress report (No. 34), we have continued to develop our experimental capabilities for conducting work on semiconductor surfaces. Specifically, we have recently installed our new (NSF funded) beamline and endstation at port U-16A of the National Synchrotron Light Source, Brookhaven National Laboratory. This facility along with advanced materials growth capabilities that we have recently developed for silicon, CaF_2, and GaAs epitaxy (which will be incorporated into the beamline facility) now places our group in a competitive position in the field of semiconductor based materials science research. In the meantime, some of the best and most innovative new results that have come out of our laboratory during the last 5 years have been sponsored by JSEP, and are represented by the progress reported below on ultra-thin magnetic layers.

B. OVERVIEW: Magnetic structures form the basis for a broad range of information storage media, and new applications based on magnetic films such as bubble memories and magneto-optic read-out memories continue to attract interest. An important prerequisite for advanced technological applications of magnetic thin films is an understanding of the new phenomena that occur as physical dimensions (either the film thickness or lateral dimensions or both) approach an atomic scale. Relatively thick films (50 Å, for example) which retain certain bulk properties (i.e., temperature dependence of magnetization) can be expected to exhibit properties which depart from bulk properties when lateral dimensions are constrained to sufficiently small distances (i.e., comparable to the magnetic coherence length). As the thickness of a magnetic film approaches one monolayer, the magnetic coupling between atoms is forced to assume a genuine two-dimensional character, which can have dramatic effects on the magnetic properties. Two-dimensional structures have lower coordination (number of nearest neighbor atoms) than three-dimensional structures, and since a two-dimensional structure must be grown on a substrate, the substrate can introduce additional important effects. For example, an epitaxial film is forced to assume a planar lattice constant commensurate with the substrate.

This constraint can be used to vary the lattice constant of the film, and in some cases to artificially stabilize a thin film having a crystal lattice which differs from the naturally occurring bulk lattice (i.e., fcc iron can be stabilized on Cu(100)).

These important features of ultra-thin epitaxial magnetic layers have attracted the attention of band theorists who are now able to perform meaningful first-principles calculations of the electronic and magnetic properties expected from novel magnetic structures. These structures can now also be synthesized using molecular beam epitaxy. Three examples of theoretical predictions relevant to progress reported below are now briefly described. Fu *et al.* [1] have explored epitaxial layers of transition metals and superlattice structures based on transition metal epitaxy on various noble metal templates. These *ab-initio* total energy calculations predict enhanced moments, and novel two-dimensional magnetic behavior for transition metal epitaxial layers on transition metal substrates. Tersoff and Falicov [2] have studied subtile effects on the magnetic properties of epitaxial Ni on Cu(100) and Cu(111) that arise from different sp-d hybridization and local structure of the films on these different surfaces. One specific prediction (that we have tested) is the quenching of ferromagnetism for $n = 1$ monolayer (ML) for p(1x1) Ni on Cu(111), but not on Cu(100). Gay and Richter [3] have investigated the spin anisotropy of ferromagnetic monolayers of Fe, Ni, and V by including spin-orbit terms in their self-consistent calculations. These studies have yielded some very interesting new predictions, one being that at one monolayer thickness, certain films exhibit a very strong spin anisotropy which favors magnetic alignment perpendicular to the surface.

C. <u>PROGRESS</u>: During the past year, using JSEP support, we have refined a Kerr effect instrument that combines molecular beam epitaxy, surface analysis tools (LEED and Auger Analysis) and a precision polarimeter that is capable of optically measuring hysteresis loops of single layer epitaxial magnetic films. Several important experiments have been completed and reported, or are in the process of being published.

In one set of experiments [4], we have explored the spin-anisotropy of ultra-thin p(1x1) Fe films on Ag(100). Gay and Richter's [3] calculations predict that the spin-orbit contribution to magnetic anisotropy is large enough (in comparison to other terms) to force the spin orientation perpendicular to the film plane for $n = 1$ ML. For thicker films, the volume dependent demagnetizing factor dominates forcing the spin moments to be in the plane. Our Kerr effect studies of this system show that at $T = 100K$, the spin moments are perpendicular to the film plane for $n = 1$ ML, and parallel to the film plane for $n \geq 2$ ML (in agreement with the theoretical prediction).

These experiments also revealed what appears to be the first evidence on in-plane magnetic anisotropy for truly thin films (< 20Å). We are planning follow-up experiments at lower temperatures (20K) using a new gas flow cryostat that we have recently adapted to the instrument. These experiments appear important in view of results reported by Stampanoui *et al.* [5] that suggest that the moments lie parallel to the surface at lower temperatures.

In another set of experiments [6], we have explored the magnetic properties of Ni thin films grown on Cu(111) and Cu(100) surfaces. These experiments were undertaken to explore the role sp-d hybridization plays in thin film magnetization, i.e, to test the predictions made by Tersoff and Falicov [2]. Our results support the theoretical predictions: magnetion of the first layer of Ni on Cu(111) appears to be significantly reduced in comparison to subsequent layers, but no such effect is observed on Cu(100). All layers appear to be strongly ferromagnetic, with the same layer independent moment.

In a third set of experiments [7], we have studied the temperature dependence of the saturated magnetization Ms as a function of film thickness. These experiments clearly manifest the departure of ultra-thin film behavior from the behavior of bulk magnetic materials. The Curie temperature Tc of the film is a very sensitive function of film thickness, and the M/Ms vs. T/Tc plots also change dramatically as thickness is varied. For example, $Tc \cong 220K$ for $n \cong 1.5$ ML, $Tc \cong 320K$ for $n = 2.0$ ML. These results demonstrate the feasibility of studying the two-dimensional magnetic phase transformations using Kerr effect spectroscopy.

Our group is also working with M.C. Downer (SSE87-4) in an experiment that combines femtosecond laser technology with angle-resolved photoemission. We have constructed and tested a new time-of-flight energy analyzer to be used in demonstration experiments involving image potential states at metal surfaces. (Refer to JSEP Annual Report No. 35, Sections SSE87-3 and SSE87-4). Recent experiments in our group, and by others at MIT, appear to show that this technique is feasible.

D. FOLLOW-UP STATEMENT: Although our JSEP supported efforts on ultra-thin magnetic films has been highly productive and have established an important new technique for probing magnetic properties of thin film materials, JSEP support of this program will be phased out in 1989. Other funding for this program will be sought. We have agreed to help support a thrust area involving III-V semiconductor surfaces in our JSEP program. Our new emphasis will be to probe the structure, stability, and growth mechanisms associated with III-V semiconductor surfaces and superlattices. Our new instrumentation, including a highly sensitive surface phonon spectrometer and our new beamline and endstation at NSLS, provide the necessary tools to carry out leading edge work in this area.

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(Page 4, Res. Unit SSE88-3, "Epitaxial Growth, Structure and Electronic Properties of Silicides on Silicon Surfaces")

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*Seminar "Magneto-optic Kerr Effect Studies of Ultra-thin Epitaxial Magnetic Films". J.L. Erskine, Rice University, Houston, Texas, April 26, 1988.

*Conference "Magneto-optic Kerr Effect Studies of Fe, Ni and V on Ag(100)", Jose Araya-Pochet and J.L. Erskine, Forty-Seventh Annual Conf. on Physical Electronics, Brookhaven National Laboratory, L.I., N.Y., June 6-8, 1988.

*Seminar "Thin Film Magnetic Anisotropy of Epitaxial Layers", C.A. Ballentine and J.L. Erskine, National Bureau of Standards, Washington, D.C., June 10, 1988.

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*Conference "Synchrotron Radiation Studies of Magnetic Materials", 1988 Fall Meeting of the Materials Research Society, Boston, MA., Nov. 27-30, 1988.

III. LIST OF THESES AND DISSERTATIONS

Jose Araya-Pochet, Ph.D., December 1988, "Magneto-optical Studies of Epitaxial Ultra-thin Film of Fe, Ni, and V on Ag(100) and Ag(111) Substrates", (supported by JSEP)

IV. 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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Air Force Office of Scientific Research 86-0109, "High Resolution Electron Energy Loss Studies", Dr. J.L. Erskine, Principal Investigator, 1986-1988.

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

Research Unit SSE88-4: FEMTOSECOND PROCESSES IN CONDENSED MATTER

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

Graduate Students: Glenn Focht and David H. Reitze

A. SCIENTIFIC OBJECTIVE: We seek insight into the physics of ultrafast processes in technologically important solids using the techniques of femtosecond laser spectroscopy.

B. PROGRESS: During the third year of JSEP funding, progress has centered on application of the femtosecond laser facility and of the new methods of femtosecond pulse generation developed during the first two years.

Last year we reported our invention of an efficient femtosecond source in the ultraviolet [1], where femtosecond sources were previously unavailable, and our development of a quantitative theory of this new class of ultraviolet passively mode-locked source. *This theoretical analysis has now been published in IEEE Journal of Quantum Electronics* [2]. The need for, and context of , this theory was described in last year's report and in the recent three year proposal. Apart from accounting for our observations, important predictions were that intracavity frequency doubling should be possible in other types of passively mode-locked lasers (not yet demonstrated by anyone, to our knowledge), and that 20 mW. average UV power should be possible in the CPM. *C.L. Tang's group at Cornell recently confirmed this latter prediction* [3] by using custom-cut,ultrathin BBO crystals as intracavity doublers instead of our somewhat less efficient KDP. *We have now reconfirmed this result* This JSEP sponsored invention is therefore eminently useful and easy to implement. It has been extremely well received by the ultrafast laser community; as evidence, *the P.I. this year has delivered (or will shortly deliver) three invited talks at international laser conferences on this subject* (Electrochemical Society Symposium on Ultrafast Lasers and Nonlinear Optics, Chicago, October 1988; Lasers '88, Lake Tahoe, December 1988; SPIE Conference on Deep Blue and Ultraviolet Lasers, Los Angeles, January 1989).

Current progress with the new ultraviolet source centers on *experimental investigations of hot carrier relaxation in thin film semiconductors* using time resolved reflectivity techniques. The ultraviolet output is sufficiently strong to be used as a pump pulse to inject extremely hot carriers. In silicon,for example, the direct band gap at the Brillouin zone center can be accessed; the intervalley electron transfer rate from Γ to X valley can then be monitored by reflectivity changes in the red. Monte Carlo methods can be used to model these results (see new JSEP unit SSE89-3, C.M. Maziar, P.I.). Use of a thin film suppresses complications from carrier diffusion, and enhances reflectivity changes by taking advantage of Fabry Perot effects [4,5] Differential detection is required because the experiment uses an unamplified source; on the other hand the high repetition rate (100 MHz) permits us to take maximal advantage of signal averaging and synchronous detection. Extensions to films of III-V semiconductors are of course possible.

Last year we reported our completion of and contributed conference talk on a high power 10 Hz repetition rate amplifier which incorporates a novel gain cell with a conical "axicon" geometry [6]. *A full report on this system and its first experiment have now been published in Optics Letters* [7]. The motivation for the new design was to preserve the phase front, and therefore the focusability, of femtosecond pulses amplified to millijoule energy, while simultaneously preserving 90 fs. pulse duration. Unprecedented peak intensities could thereby be reached, opening up a new arena of strong field physics.Previous high power femtosecond amplifiers, by contrast, have achieved millijoule energy only at the expense of degraded focusability. While last year we reported "substantially improved focusability", *this year we have achieved near diffraction-limited focusing and peak intensities exceeding 10 Petawatts/cm^2 (10^{16} W/cm^2). We have immediately pursued applications of this unique source in strong field ionization of gases* [7,8]. The quantitative physics of the strong field photoelectric effect , first described theoretically by Keldysh [9], has been experimentally inaccessible because of plasma expansion out of the focus of long laser pulses on a picosecond time scale. Recently a red shift in electrons photoemitted by femtosecond pulses, predicted by Keldysh and others [9,10], was observed in low pressure gases [11]. *Using our new source, we have now observed a corresponding blue shift in the energy of the photons which pass through the gas breakdown plasma, but which do not directly contribute to photoemission* [7,8]. This blue shift is required to conserve energy in strong field photoemission [10], but requires higher light intensities for experimental observation than the electron red shift. This higher intensity was uniquely available from our source. Time-resolved observations of the blue shift will address fundamental questions concerning the validity of the macroscopic Drude model of a plasma, as opposed to the microscopic Keldysh model [9], in the strong field regime. We are urgently pursuing these experiments

As a solid state application of high intensity femtosecond pulses, *the P.I. has reported quantitative experimental results on the generation of picosecond soft X-ray pulses at intensely photoexcited refractory metal surfaces* (in collaboration with a group at AT&T Bell Laboratories) [12]. Such pulses offer great potential in high speed structural diagnostics. The experiments were performed at intensities up to 10^{14} W/cm^2, but have not yet been extended to the hundred fold higher intensities now available in our laboratory.

We have completed our first investigation of semiconductors under intense excitation conditions using a femtosecond transmission technique [13]. The unique capability of ultrashort light pulses to probe the nonlinear optical properties of materials by achieving high light intensities at pulse energies low enough to avoid optical damage has been recognized for many years [14]. *We have demonstrated the first use of femtosecond pulses to measure the nonlinear absorption coefficients of semiconductors at fundamental wavelengths* ***above*** *the band gap [], where strong linear absorption causes longer pulses to melt the sample before reaching the intensities at which nonlinearities become dominant.* Pump and probe techniques were used to distinguish the contribution of direct two-photon absorption from that of two-step hot carrier absorption. Our measurement of the direct two-photon absorption coefficient in silicon at 620 nm. is timely: ab initio calculations of $\chi^{(3)}$ for silicon are just being completed [15], and will provide a theoretical foundation for our measured value; in addition, recent (still unpublished) femtosecond reflectivity measurements in silicon have shown a nonlinear increase in plasma density with fluence which appears consistent with our measured two-photon absorption coefficient [16]. Our measured coefficient at above gap wavelengths is more than ten times larger than values measured previously at below gap wavelengths [17]. This discrepancy is explained by availability of direct two-photon transitions at our wavelength, whereas previous experiments measured only indirect (phonon-assisted) two-photon absorption. *We have made a conference report on our results [13], and a manuscript has been submitted to Applied Physics Letters*

Early progress on development of our femtosecond angle-resolved photoemission experiment was described at length in last year's annual report. Since then *we have observed strong two-photon photoemission from image potential states on Ag(111) using ultraviolet femtosecond laser pulses. We have evaluated the two-photon photoemission yield, and have used this data to design an appropriate time-of-flight electron spectrometer* which will greatly improve energy and angle resolution of our instrument while maintaining the high sensitivity required to begin exploiting the new technique in applications to III-V semiconductors. Time resolved and angle-resolved experiments to measure the lifetime and dispersion of the image potential states are in progress. *Additional funding for this and related experiments has now been obtained through contracts with the Office of Naval Research.*

In collaboration with Itoh and Neikirk (Research Unit EM88-1), funding has also been obtained from the Defense University Research Instrumentation Program (DURIP/AFOSR) to establish a parallel femtosecond laser system operating at 800 nm wavelength. The new system will consist of a mode-locked Nd:YAG or Nd:YLF pump laser, which will itself be used in optoelectronic sampling of passive microwave structures, as described in the DURIP proposal. In addition this laser will synchronously pump a near infrared dye laser, of a new design recently published in the ultrafast laser literature [18], which will open up investigations of near band edge carrier dynamics in GaAs heterostructures.

C. <u>FOLLOW-UP STATEMENT</u>: Working during the coming year will focus on time-resolved photoemission experiments on metal surfaces, and time-resolved transmission experiments in semiconductors (as described in detail in the new triennial proposal). The goal is to understand carrier scattering rates in bulk materials. The new DURIP-funded laser system will also be set up. This will become the basic apparatus for transmission live sampling and carrier transport measurements.

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III. LIST OF PRESENTATIONS

T.R. Zhang, D.H. Reitze, and M.C. Downer, "Semiconductor Optical Damage in the Femtosecond Regime", March Meeting of the American Physical Society, New Orleans, March 1988.

W.M. Wood, Glenn Focht, G.W. Burdick, and M.C. Downer, "Focused Light Intensities in the Petawatt/cm^2 Regime from a Conical Axicon Amplifier", Conference on Lasers and Electro-Optics, Anaheim, April 1988.

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M.C. Downer, W.M. Wood, Glenn Focht, D.H. Reitze, and T.R. Zhang, "Blue Shifting of Intense Femtosecond Pulses in Gas Breakdown and Solid State Plasmas", Sixth International Conference on Ultrafast Phenomena, Kyoto, Japan, July 1988.

M.C. Downer, "Ultrafast Optical Methods in Charge Transport Measurements", Special Seminar Series, Central Research Laboratories, Texas Instruments, Inc., September 1988.

D.H. Reitze, T.R. Zhang, W.M. Wood, and M.C. Downer, "Laser Melting of Silicon: The First Few Femtoseconds", 174th Annual Meeting of the Electrochemical Society, Symposium on Nonlinear Optics and Ultrafast Phenomena, Chicago, October 1988.

W.M. Wood, Glenn Focht, and M.C. Downer, " Tight Focusing and Blue Shifting of Millijoule Femtosecond Pulses from a Conical Axicon Amplifier", 174th Annual Meeting of the Electrochemical Society, Symposium on Nonlinear Optics and Ultrafast Phenomena, Chicago, October 1988.

[Invited] M.C. Downer, Glenn Focht, and T.R. Zhang, "A New Class of Ultraviolet Femtosecond Sources", 174th Annual Meeting of the Electrochemical Society, Symposium on Nonlinear Optics and Ultrafast Phenomena, Chicago, October 1988.

[Invited] M.C. Downer, Glenn Focht, and T.R. Zhang, "Intracavity Frequency Doubling in Femtosecond Lasers", Lasers '88, Lake Tahoe, Nevada, December 1988.

IV. LIST OF THESES AND DISSERTATIONS

NONE

V. CONTRACTS AND GRANTS

National Science Foundation (Presidential Young Investigator Award), "Femtosecond Processes in Condensed Matter" (DMR 8858388), M.C. Downer, P.I.

Office of Naval Research (Young Investigator Award), "Femtosecond Angle-Resolved Photoemission Spectroscopy of Electronic Materials" (Contract N00014-88-K-0663), M.C. Downer, P.I..

Office of Naval Research, "Femtosecond Angle-Resolved Photoemission Spectroscopy of Metals and Semiconductors" (Contract N00014-88-K-0054), M.C. Downer, P.I.

Air Force Office of Scientific Research (Defense University Research Instrumentation Program), "Picosecond Laser System for High Speed Characterization of Monolithic Devices" (Control No. 88540-0566), M.C. Downer, D.P. Neikirk, and T.Itoh, P.I.'s.

IBM Faculty Development Award, M.C. Downer, P.I.

Robert A. Welch Foundation (Grant F-1038), M.C. Downer, P.I.

III. QUANTUM ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE 88-1 NONLINEAR OPTICAL INTERACTIONS

Principal Investigator: Professor H. J. Kimble (471-6895)

Graduate Students: R. J. Brecha, M. G. Raizen, W. David Lee, Heung Choo, Silvania Pereira, Hong Cai, John Miller, Robert Thompson, Walter Buell

A. RESEARCH OBJECTIVES: The objective of this research unit has been an investigation of dynamical instabilities in optical physics. The question of nonlinear dynamical behavior has been addressed through studies of optical systems for which nonlinear oscillatory behavior characterizes a variety of time-dependent steady states. Of special interest have been systems where new dynamical states arise directly from the intrinsic nonlinearity of the interaction of radiation and matter. Arguably the most fundamental of all instabilities are those involving a single mode of the electromagnetic field coupled to a simple atomic medium. It is this criterion of fundamental simplicity that has characterized our research and which has made our experiments prototypes for a large class of nonlinear optical systems.

More specifically, we have conducted two different experiments, each of which couples a nonlinear medium to an optical cavity. The first set of experiments explores the phenomena of optical bistability with two-level atoms for which the nonlinearity is the fundamental saturation process. The second set of experiments investigates doubly resonant intracavity harmonic conversion for which the nonlinearity is the lowest order possible in an optical system, namely that of the second order nonlinear susceptibility. In both sets of experiments it has been our objective to obtain detailed quantitative information about the new oscillatory stages that arise and to make first principles comparisions between theory and experiment. Our research on instabilities in optical bistability is by far the most advanced of these two areas. We have explored the stability of the self-pulsing states to perturbations, both externally produced and as a result of the system's own internal quantum noise. We have also studied in detail the role of the transverse variation of the electric field and the manner by which this variation leads to dramatic changes in the character of the unstable states.

B. PROGRESS: Our experimental results for the single mode instability in optical bistability are documented in Ref. (1,2). The principal accomplishment of our research effort has been the construction of absolute boundaries for the domain of self-pulsing instability in optical bistability. Since there are five parameters that characterize the operating point of the system, we have had to develop in situ techniques for the absolute measurement of the atomic cooperativity parameter C, the detuning θ of the driving laser from the cavity resonance, the detuning Δ of the laser from atomic resonance, the intracavity field x, and the ratio μ of cavity damping to atomic damping. In addition, we require knowledge of any nonradiative relaxation processes such as transit broadening, for which the decrease in dipole dephasing time from the radiative value of 2 is denoted by γ. In Figures 1 and 2 we present the instability boundaries in the detuning space (θ,

Δ). The measurements are accomplished by holding the atomic detuning constant and varying the cavity detuning for fixed (μ, C). The theoretical boundaries are found following the procedures described in Ref. 3 and 4. Figures 1 and 2 are for ring configurations and represent absolute quantitative comparisons (without adjustable parameters) with the appropriate theory of Ref. 3. In Figs. 1 and 2 we also present the predictions from the plane wave theory. The instability domain is wider and in clear disagreement with our experimental results. Although our measurements are represented in Figs. 1 and 2 by isolated points in the (θ, Δ) plane, we move experimentally from one point to the other continuously, so we have in fact explored the boundaries in much greater detail than a single point may indicate in the figures.

The value of C in Fig. 2 is more than 30 times that of the critical onset of absorptive bistability. The validity of the uniform field limit may be questionable, since the single pass absorption coefficient αl is now about 12 for the four-pass ring configuration used in the measurement. The work of Snapp (5) on instabilities without the uniform field limit and in the plane-wave model shows that the small parameter for the uniform field approximation is $\alpha L/(1+\Delta^2+|x|^2)$. For the parameters of Fig. 2, $|x|^2$ is around 200, so we believe the limit is still fulfilled. However, the problem may be present at lower intensities.

In terms of an overview of our work on dynamic instability in optical bistability with two-level atoms, we note that our experiments confirm the results of the Gaussian formulation: not only does the output field maintain a Gaussian shape even in the regime of the spontaneous oscillations, but the boundaries of the instability domain in parameter space and the oscillation frequency are both in good agreement with the predictions of the Gaussian model. The plane-wave formulation, instead, turns out to be inadequate. In agreement with the experiments, the Gaussian model displays no period 2, 4..., oscillations and no chaotic structures which are a characteristic prediction of the plane-wave model. The only higher order temporal structure of the Gaussian formulation is an envelope breathing that corresponds to a two-frequency operation. We have thus demonstrated the profound effect of transverse structure on the nature of dynamic instability in optical bistability. This demonstration is of significance beyond the particular problem of optical bistability, since transverse variations of the electric field play an important role in many other areas of optical physics, such as in laser dynamics.

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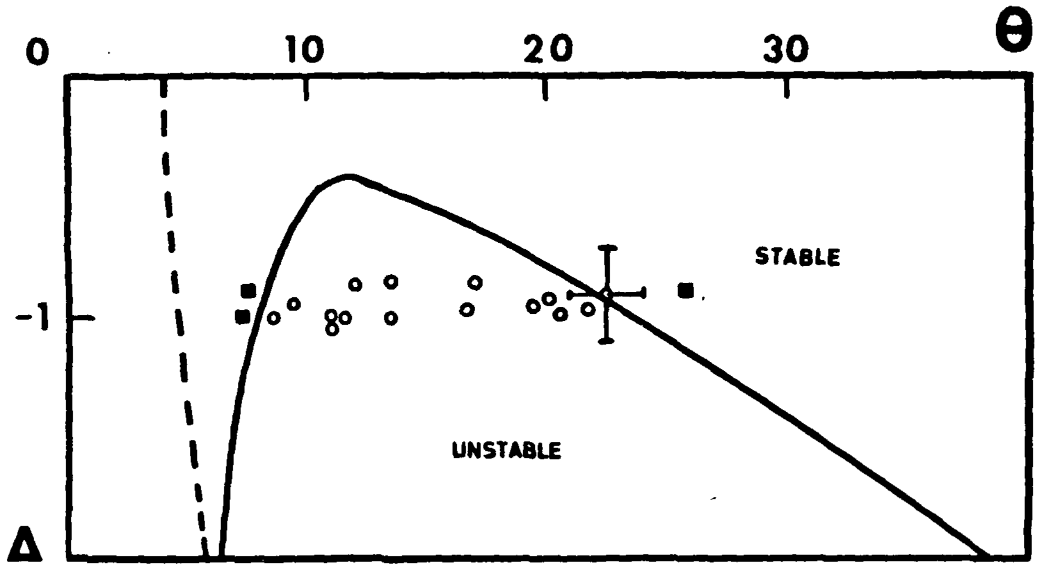

FIGURE 1

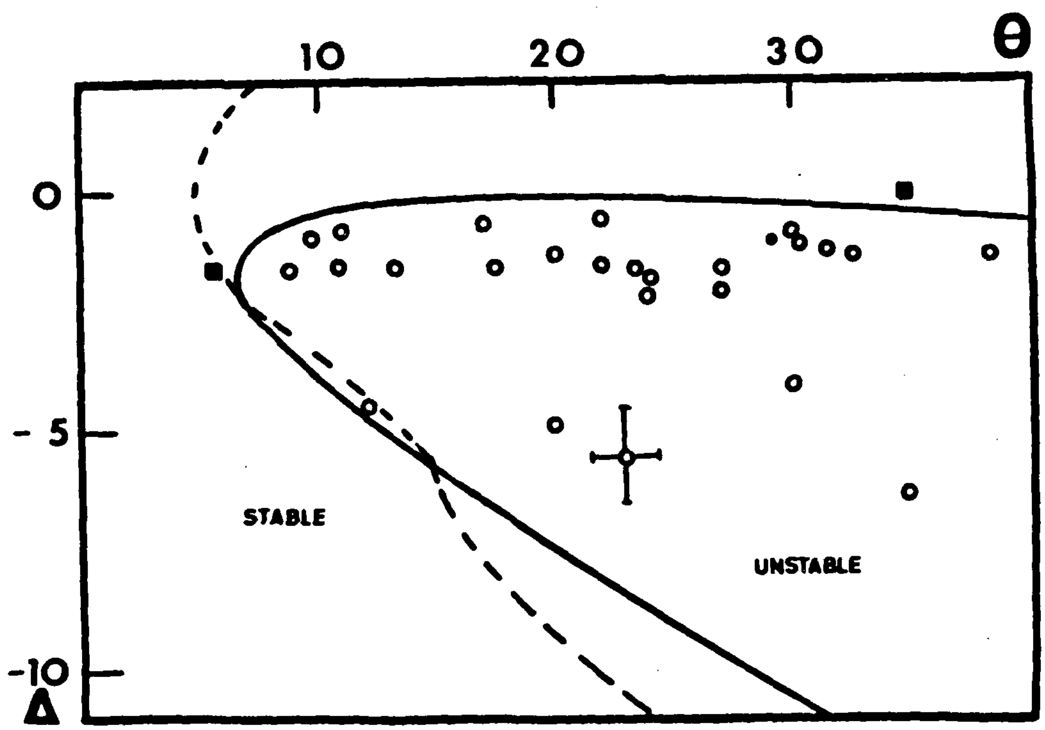

FIGURE 2

D. FIGURE CAPTIONS:

Figure 1 Domain of instability in the detuning space for C =60±5, μ = 0.5 and γ = 1.6. Empty circles indicate instability, filled squares stability. Below the continuous line is the unstable region based on the Gaussian theory, while to the right of the dashed line is the plane-wave prediction of the unstable region. A ring cavity is used in this measurement. Systematic uncertainties in the detunings are ±10%.

Figure 2 Domain of instability in the detuning space for C = 300±50, μ = 0.4 and γ = 1.6. Empty circles indicate instability, filled squares stability. Inside the continuous line is the unstable region predicted by the Gaussian theory, while to the right of the dashed line is the plane-wave prediction of the unstable region. A ring cavity is used in this measurement. Systematic uncertainties in the detunings are ±10%.

1. LIST OF PUBLICATIONS (*JSEP-supported in whole or in part)

*A. T. Rosenberger, L. A. Orozco, and H. J. Kimble,"Experimental Investigation of the Single-Mode Instability in Optical Bistability", in Instabilities and Chaos in Quantum Optics II, eds. N. B. Abraham, F. T. Arecchi, and L. A. Lugiato (Plenum, 1988), 257.

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II. LIST OF CONFERENCE PROCEEDINGS (*JSEP-supported in whole or in part)

None

III. <u>LIST OF PRESENTATIONS</u> (*JSEP-supported in whole or in part)

*H. J. Kimble, "Precision Measurement Beyond the Shot-Noise Limit", invited talk, NATO Advanced Research Workshop on Squeezed and Non-Classical Light, Cortina, Italy, January 25 - 29, 1988.

H. J. Kimble, "Squeezed States of Light", invited talk, University of Chicago, Chicago, Illinois, March 10, 1988.

H. J. Kimble, "Precision Measurement Beyond the Shot-Noise Limit", invited talk, Annual Meeting of the American Physical Society, New Orleans, Louisiana, March 21-23, 1988.

H. J. Kimble, "Squeezed States of Light", invited talk, University of Virginia, Charlottesville, Virginia, April 22, 1988.

H. J. Kimble, "Squeezed States of Light", invited talk, International Symposium on Spacetime Symmetries, University of Maryland, College Park, Maryland, May 24-28, 1988.

H. J. Kimble, "Squeezed States of Light", invited talk, Eleventh International Conference on Atomic Physics, Paris, France, July 4-8, 1988.

*H. J. Kimble, "Squeezing and Quantum Measurement with Sub/Second Harmonic Generation", invited talk, Sixteenth International Conference on Quantum Electronics, Tokyo, Japan, July 18-21, 1988.

H. J. Kimble, "Squeezed States of Light", invited talk, Institute of Optics and Fine Mechanics", Shanghai, China, July 24, 1988.

H. J. Kimble, "Squeezed States of Light", invited talk, Jiao Tong University, Shanghai, China, July 25, 1988.

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H. J. Kimble, "Squeezed States of Light", invited talk, Institute of Physics, Beijing, China, August 2, 1988.

H. J. Kimble, "Optical Measurement Beyond the Vacuum-State Limit", invited talk, Fourth International Laser Science Conference, Atlanta, Georgia, October 2-6, 1988.

H. J. Kimble, "Squeezed States of Light", invited talk, 1988 Annual Meeting of the Optical Society of America, Santa Clara, California, October 30-November 4, 1988.

IV. <u>LIST OF THESES OR DISSERTATIONS</u> (*JSEP-supported in whole or in part)

*Min Xiao, Ph.D., May, 1988, "Quantum Fluctuations in Nonlinear Optics".

Murray Wolinsky, M.S., December, 1988, "Squeezing in the Degenerate Parametric Oscillator via the Positive Representation".

V. LIST OF GRANTS OR CONTRACTS

National Science Foudnation, PHY 8351074, "Quantum Dynamics of a Bistable Absorber", Professor H. J. Kimble, Principal Investigator, August 1, 1986, continuing.

Venture Research Unit of British Petroleum International Limited, "Nonequilibrium Phase Transitions in Optical Systems", Professor H. J. Kimble, Principal Investigator, February 1, 1986 - January 31, 1989.

Office of Naval Research, Contract No. N00014-87-K-0156, "Squeezed States of Light", Professor H. J. Kimble, Principal Investigator, March 1, 1987 - September 30, 1989.

1. Consultative and Advisory Functions: Presentation of colloquium on "Squeezed States of Light" by invitation at Naval Research Laboratory, Washington, D.C., May 23, 1988.

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

Research Unit QE88-2 NONLINEAR RAMAN SCATTERING FROM MOLECULAR IONS

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

Graduate Students: Mike Bruce, Winston Layne, and Roger Taylor

A. Research Objectives: Study of the formation and dynamics of molecular ions in discharges has been slowed by the low particle densities and high background luminosities inherent in these environments. Coherent Raman techniques promise to be ideal probes for these environments as they generate coherent signals, but their sensitivity must be improved to enable them to detect low density species. Coherent Raman probes sensitive enough to detect species in discharges will also be useful for rare gas dimers.

Coherent Raman spectrometers have traditionally used cw probe lasers to carry the signal from the sample to the detector so that laser power fluctuations are minimized and shot noise limits the sensitivity. Since the signal scales linearly with the probe laser power while shot noise scales as the square root of the power, increasing the laser power will increase the signal-to-noise ratio. Pulsed lasers produce greater peak powers than cw lasers and so afford the opportunity to increase the sensitivity of coherent Raman spectrometers if their larger power fluctuations can be reduced.[1]

The RIKES birefringence induced by overlapping laser beams in a medium peaks when the frequency difference between two applied laser fields equals a Raman resonance. If the intensity of the probe laser is measured through crossed polarizers as a function of this frequency difference, a signal is seen against a background having smaller fluctuations.[2] These fluctuations can be reduced by subtracting from the signal a reference laser's intensity having similar fluctuations. RIKES also allows the background due to nonresonant Raman interactions to be minimized.[3]

Coherent Raman processes can be described by the third-order electric susceptibility tensor $\chi^{(3)}$. In RIKES, the interaction of two laser fields with $c^{(3)}$ of a medium produces a polarization wave which can be written as

$$P_1(\omega_1) = K \left| \chi_{1221} e^{i\phi} - \chi_{1212} e^{-i\phi} \right|^2 E_2(\omega_1)\, I^2(\omega_2), \quad (1)$$

where χ_{ijkl} is a component of the third-order electric susceptibility, $E_2(w_1)$ is the probe laser field, $I(w_2)$ is the pump laser irradiance , ϕ is an adjustable phase between polarization components of the pump laser, and K is a proportionality constant. Nonresonant susceptibility tensor elements are nearly equal; so, tuning ϕ with retardation optics in the pump beam can minimize the background and optimize the signal.

Stray birefringence in the optical path of the probe laser should also be minimized, though some birefringence will remain to produce a nonzero background. Accounting for this leakage light, the detected irradiance is

$$I_{sig}(\omega_1)=I_{back}(\omega_1)+2\sqrt{\alpha_R\gamma}\ I(\omega_1)I(\omega_2)+\alpha_R I(\omega_1)I^2(\omega_2), \quad (2)$$

where γ is the fraction of the leakage light coherent with the signal, and α_R is proportional to $\chi^{(3)}$. For small signals--$2\sqrt{\alpha_R\gamma} >> \alpha_R I(\omega_2)$--the cross-term dominates. Controlling the fraction of the probe light $\sqrt{\gamma} I(\omega_1)$ that leaks through the polarizers to heterodyne with the signal can enhance this term. With sufficient probe laser power, the major noise source is probe laser intensity fluctuations which can be minimized if a reference sample of the probe laser having similar fluctuations is monitored and subtracted from the signal beam intensity.[4]

B. PROGRESS: The Raman-induced Kerr effect spectrometer used to test these techniques consists of two Nd:YAG pumped dye lasers with the detectors and signal processing electronics. The probe laser is polarized and analyzed with Glan-Thompson polarizers having an extinction ratio of 10^{-7}. The pump laser's polarization is controlled by wave-plates and compensators. The reduction of laser power fluctuations by the pulse-to-pulse subtraction of a reference laser's intensity from the signal is performed on voltage signals from photodiodes. Each beam is detected by EG&G FND-100 photodiodes mounted on a printed-circuit board where the diodes' outputs are subtracted immediately. This circuit can subtract two laser pulses to within a factor of 0.03% (1.5 times the shot-noise limit).[4] In the past year we found that the quality of the subtraction in a RIKES application is limited because small polarization fluctuations in one beam relative to the other are magnified since the beams are highly extinguished. Both beams, though generated from the same laser, experience different birefringence and reflectivities for s- and p-polarization along their paths causing uncorrelated fluctuations. Careful matching of the paths produces a subtraction of 0.05%.[4] Because of high losses for the configuration, shown in Fig. 1, the measurement was made with non-optimal extinction to reduce the effects of shot and electronic noise. Replacing the optical flat in Fig. 1 by a beam splitter and metal mirror maintained the subtraction capabilities and had the added benefit of reducing the birefringence of the apparatus to 1 part in 10^7! This configuration required that the Raman pump beam be mixed with the probe beam in the sample by crossing at a small angle. Unfortunately, this reduced the gain by a factor of 50. To obtain spectra with optimal extinction and subtraction requires more probe power and custom optics designed to minimize losses in the sampling process.

The effects of the pulse-to-pulse subtraction of a reference laser's intensity from the signal beam and the control of the pump beam's polarization are displayed in Fig. 2 showing spectra from a sample of 0.01 M benzene in carbon tetrachloride.[5,6] Curves (b) and (c) show spectra recorded with and without the reference beam blocked, respectively. Curve (a) shows that a circularly polarized pump beam produced a signal that is barely seen over the fluctuations of the background. If the pump beam is given a slight elliptical polarization, the background shows a slight frequency dependence, but the signal increases (Fig. 2b). This technique has also been used to obtain Raman spectra from gases. Here the primary background signal is from nonresonant contributions from the sample cell windows. We found similar to the data shown in Fig. 2 the subtraction technique is capable of reducing this background. With broadband dye lasers and the large losses (.5% of the probe power detected) resulting from the optical configuration shown in Fig. 1, we were able to observe the spectra from 24 Torr of methane as observed in Fig.3.

We have now modified the spectrometer for greater sensitivity. The gain in the target should be improved if both lasers operate with narrow band. With intracavity etalons we have narrowed the lasers to approximately 400 MHz in linewidth. Spectra of the lasers obtained with an etalon are shown in Fig. 3. With the lasers operated narrow band we have obtained preliminary spectra of H_2. Such a spectra is shown in Fig. 4. We have as well replaced the optical flat in Fig. 1 with a dicroic filter which will transmit at both surfaces the red Raman pump light, but reflect 50% of the blue probe light at the front surface and 100% at the rear surface. This will greatly decrease the loss of probe power in the process of generating a reference beam which accurately follows the fluctuations in both power and polarization. With this apparatus we expect to achieve H_2 spectra at pressures below 1 Torr.

FUTURE IMPROVEMENTS: The 24 Torr spectra were seen with a subtraction 60 times worse than optimal. The poor quality of the subtraction occurred when the probe was optimally extinguished and may be due to increased sensitivity to polarization fluctuations or decreased intensity on the diodes. More attention to polarization fluctuations and more probe laser power will improve the subtraction for optimal extinction. A frequency-doubled, injection-seeded Nd:YAG pump laser will increase the signal by 150 times by increasing the Raman pump power by the same factor. To avoid saturation with such powers larger Rayleigh lengths for the focal regions of the laser will be used. With these improvements signals from less than 1 mTorr pressures should be detectable.

C. FOLLOW-UP STATEMENT: This work is discontinued under joint services support.

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6. Jacek Borysow, Roger D. Taylor, and J.W. Keto, *"Raman Induced Kerr Gain Spectroscopy of Solutions,"* J. Raman Spectroscopy **20**, in press.

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*2.Thomas L. Gaussiran II, Roger H. Taylor, James L. Higdon, and J. W. Keto, "A Multi-pass, Prism Monochromator for Coherent Raman Spectroscopy", to be published, Applied Optics.

*3. Jacek Borysow, Lothar Frommhold and J.W. Keto, *"Third-Order Raman Spectrun of Argon Pairs,"* Mol. Phys. **66**, in press.

*4. Jacek Borysow, Roger D. Taylor, and J.W. Keto, *"Raman Induced Kerr Gain Spectroscopy of Solutions,"* J. Raman Spectroscopy **20**, in press.

5. Michael Bruce, Winston L. Layne, and J.W. Keto, *"Bimclecular and Termolecular Reactions of Xe($5p^5 6p$) with Chlorine Following Two-Photon Excitation,"* to be published, J. Chem. Phys.

6. Michael Bruce, Winston L. Layne, and J.W. Keto, *"A Multichannel Harpoon Model for Bimolecular and Termolecular Reactions of Xe ($5p^5 6p$) with Chlorine,"* to be published, J. Chem. Phys.

*7. Jacek Borysow, Hossein Golnabi, Roger D. Taylor and J.W. Keto, *"An Innovative Technique for Measuring Small Gains,"* submitted to Optics Commun.

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3. C. J. White, T. L. Boyd, R. B. Michie, and J. W. Keto, *"Precision Pulsed UV Wavemeter"*, **Pulsed Single-Frequency Lasers: Technology and Applications**, SPIE Proceedings Vol. 912, p. 234-236, June 1988.

III. Presentations and Conference Abstracts (*supported in part by JSEP)

*1. High Sensitivity Raman-Induced Kerr Effect Spectroscopy, Roger H. Taylor, Jacek Borysow, and J. W. Keto, Twelfth Austin Symposium on Molecular Structure, Austin, TX, USA 2/29/88 to 3/2/88.

*2.Fluorescence Studies of STP Air Excited by an Electron Beam Source, C. A. Whitehead, D. Lyttle, J. W. Keto, and D. Eckstrom, The Joint Meeting of the Texas Section American Physical Society and American Association of Physics Teachers and Zone 10 Society of Physics Students, Austin,. TX, USA, 3/4/88 to 3/5/88.

3.Quenching of Two-Photon excited Xenon Atoms in a Argon Buffer Gas, W. B. Layne, M. R. Bruce, and J. W. Keto, The Joint Meeting of the Texas Section American Physical Society and American Association of Physics Teachers and Zone 10 Society of Physics Students, Austin,. TX, USA, 3/4/88 to 3/5/88.

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6. Reactive Quenching by Cl_2 of Two-Photon excited Xenon Atoms in an Argon Buffer gas, M. R. Bruce, W. B. Layne, Lei Chen, and J. W. Keto, 1988 Joint Spring Meeting of the American Physical Society and Annual Meeting of the Division of Atomic, Molecular, and Optical Physics,.Baltimore, Bull. Am. Phys. Soc. 33, 1034(1988)

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1. "The Development of the Raman-Induced Kerr Effect as a Sensittive Spectroscopic Probe", Roger H. Taylor, Ph.D. Dec. 1988.

V. Grants or Contracts

1. Welch Foundation F788, "Coherent Raman Spectroscopy of Molecular Ions", $75,000, 6/86-6/89.

2. DOE Grant DE-FG05-84ER13191, "Kinetic Studies Following State-Selective Laser Excitation", $298,100., 3/87-3/90.

3. NASA Grant NAG-9-204, "Studies of the Recession of Surfaces by Fast O-Atom Bombardment", $200,000, 1/87-1/88.

4. SRI International, "Fluorescent Yields of Electron Bombarded Atmospheric Pressure Air", $12,557, 10/87-12/87.

5. Texas ARP, "Coherent Raman Spectroscopy of Molecular Ions", $183,000., 6/88-5/90.

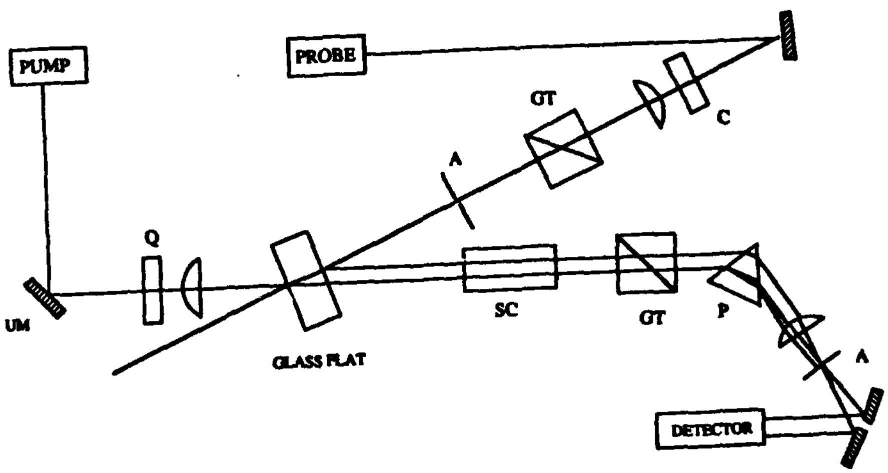

Fig. 1. Optical apparatus using a glass flat to produce a reference beam for subtraction.

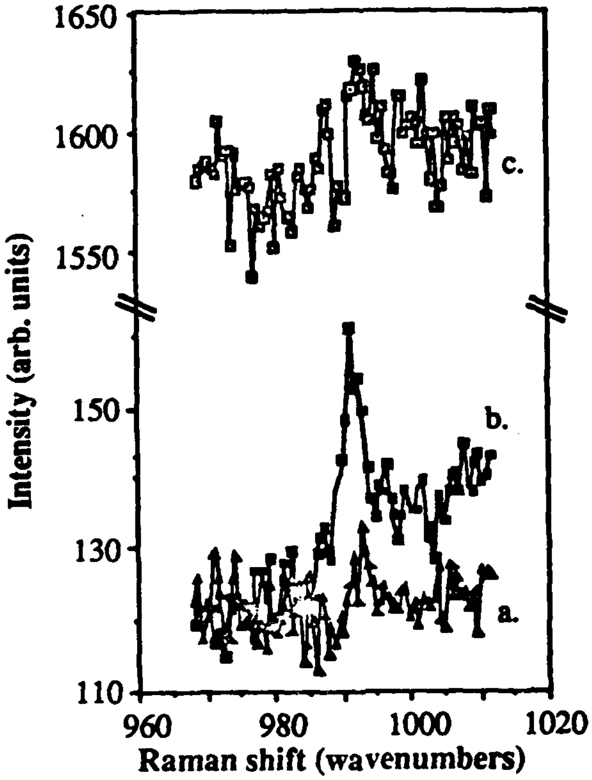

Fig. 2. The signal from a 10 mM benzene in carbon tetrachloride solution detected with a. circularly polarized pump laser light and subtraction of a reference laser's intensity from the signal beam. b. elliptically polarized pump laser light and subtraction of a reference laser's intensity from the signal beam. c. elliptically polarized pump laser light and no subtraction.

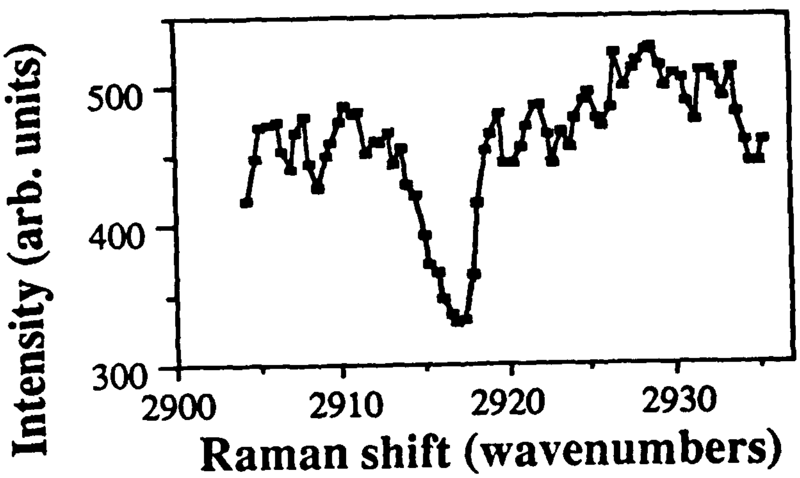

Fig.3. Methane ν_1 fundamental mode recorded at a pressure of 24 Torr.

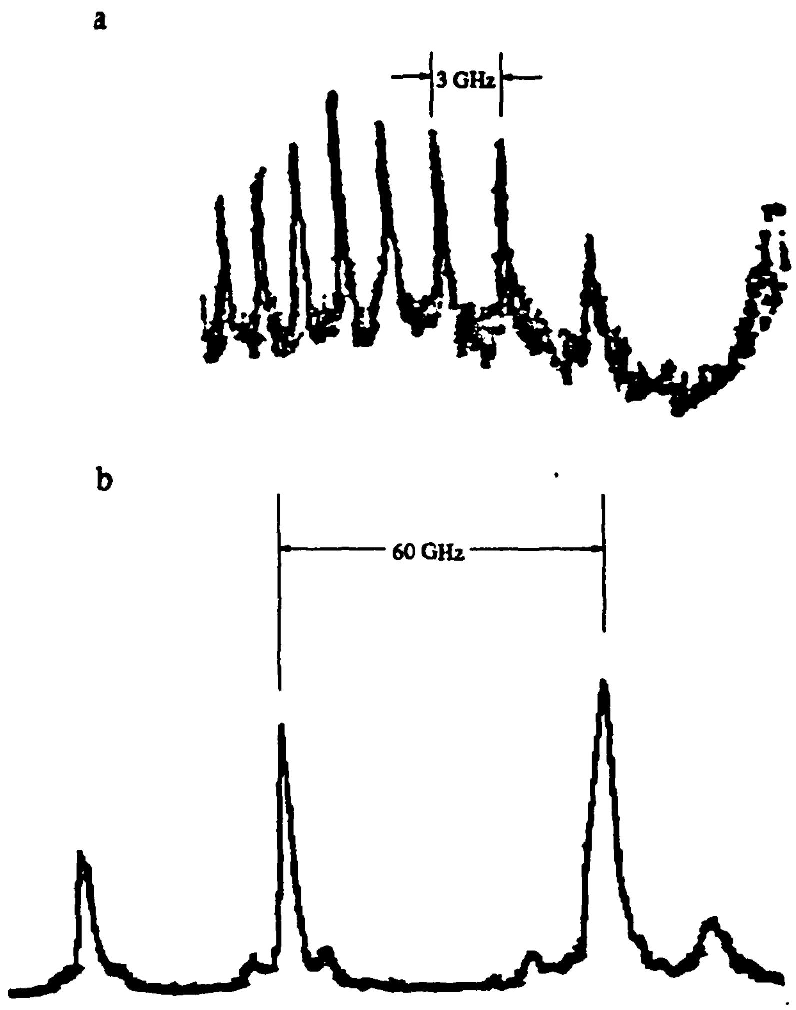

Fig. 4. Trace of spectra of one of the dye lasers used in the experiment. Indicated on the graph is the free spectral range of the analysing etalon.

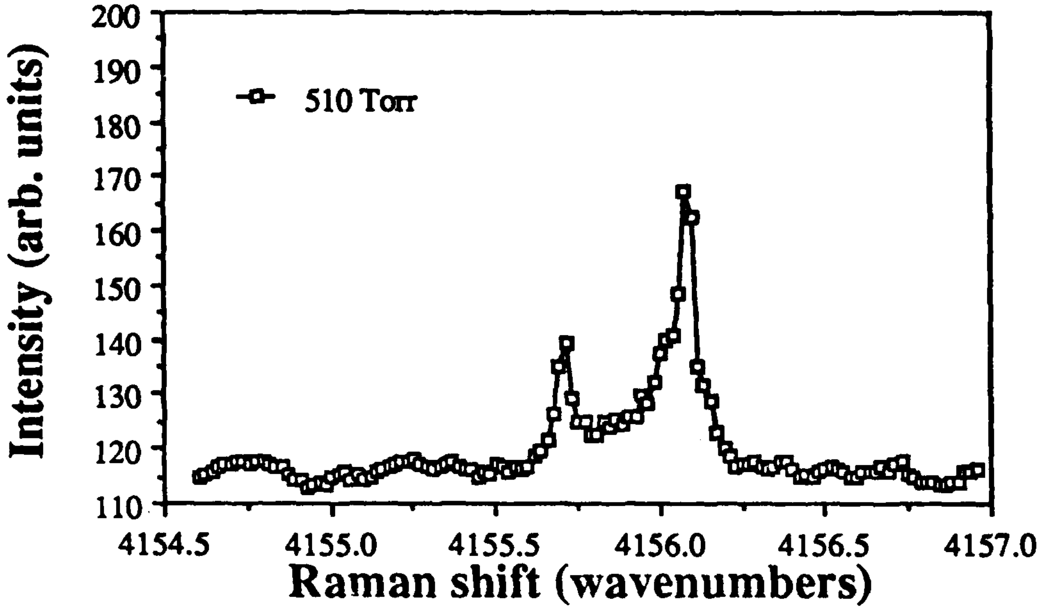

Fig. 5. Preliminary high resolution spectra of H_2. The split peak is due to a loss of synchronization of the laser grating with the etalon. Inproved calibration of the laser will prevent the laser from operation on the side mode of the etalon.

IV. ELECTROMAGNETICS

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM88-1 MILLIMETER-WAVE MONOLITHIC ARRAY COMPONENTS

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

Graduate Students: V. D. Hwang, A. Mortazawi, 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 the 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 dielectric substrate such as GaAs. The local oscillator (LO) signal is to be generated in this structure using a resonant excitation of a CPW (or odd) mode by a built-in active device. As a receiving antenna, the incoming RF signal is to be coupled into the structure by way of the coupled slot line (CSL or even) mode of the resonator. Since the CPW mode is a balanced mode, its radiation loss is small and presents a high Q resonator to the local oscillator circuit. The CSL mode, on the other hand, is an unbalanced mode, and hence its radiation and coupling to free space are efficient. The two slots receive the RF signal in phase and the LO signal out of phase. Hence, a balanced mixing operation will result with proper orientation of the mixing devices in the slots. The balanced mixer has the advantage that the AM noise contained in the LO signal should not appear in the IF (intermediate frequency) 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 integraged quasi-optical receiver. Detailed design for this type of planar structure using Schottky diodes for mixing and either a Gunn or MESFET as the local oscillator has been reported [1].

In monolithic microwave and millimeter-wave integrated circuits (MIMIC), it is preferable to develop a circuit with one type of active device. At present, MESFETs are the workhorse of the MIMIC development. High Electron Mobility Transistors (HEMT) can be adaptable by means of a similar processing technique as MESFET. It is tempting to use MESFETs or HEMTs for development of a balanced mixer. This process however complicates circuit topology and hence the circuit performance can be degraded. Instead, during this reporting period, we developed a gate-coupled MESFET balanced self-oscillating mixer. Since the two MESFETs, one in each slot, act both as the local oscillators and nonlinear mixing devices, the entire circuit is considerably simplified. Furthermore, the self-oscillating mixer can have a conversion gain instead of a conversion loss typical in a diode based resistive mixer such as the one in [1]. We have also used the HEMT in anticipation of a better noise figure and higher gain at a given operating frequency.

Figure1 shows the circuit configuration of this quasi-optical self-oscillating mixer [2,3]. Two transistors are placed on the non-metalized side of the substrate and the drains are connected to the output microstrip lines. The gate and source terminals are connected to the center conductor and the edge of the ground conductor of the coupled slot line, respectively.

The RF signal is received by the coupled slot antenna operated in the even mode. The two transistors are gate-coupled to form a balanced oscillator. The coupled slot and the microstrip tuning stub connected to the center conductor of the coupled slot line by a through-hole make the gate resonator for the oscillator. The IF signal from the darin ports are 180° out of phase dictated by the balanced mixing operation. The two output microstrip lines are combined to form a 180° hybrid coupler. The IF signal are then power-combined and are propagated as the odd mode of the coupled microstrip line. The IF power is extracted between the two microstrip center conductors.

In this circuit, the transistors (MESFETs or HEMTs) are used both as the local oscillator and as the mixer. This mixer is called the drain mixer in which the devices arebiased to the knee voltage and the gates are unbiased. Because no DC bias is needed for the gates, the circuit is very simple. In fact, the circuit complexity is not much more than a simple antenna-detector circuit.

X-band versions of the circuits have been fabricated with both MESFETs and HEMTs. Since the self-oscillating mixer has a conversion gain instead of a conversion loss, the isotropic conversion gain was measured. This quantity is a combination of the antenna gain and the mixer gain which are inseparable due to the very nature of the configuration. Also, the noise figure was characterized by the standard hot-cold measurement technique. For the circuit with MESFETs, the best isotropic conversion gain was 3.0 dB and the lowest noise figure was 9.0 dB at 11.76 GHz of the RF signal. For the HEMT circuit, the best numbers were 4.5 dB and 7.5 dB, respectively, at 11.86 GHz. This clearly demonstrates superiority of the HEMT over the MESFET. A complete description of the design, characterization and test as well as the theoretical basis are presented in [4].

All of the integrated antenna-receivers are developed on a dielectric substrate. In many cases, the substrate is electrically thick. Hence, a companion study on the effect of the substrate on the radiation property of the integrated antenna has been carried out. This year, analytical studies of the radiation properties of single and twin slot and dipole radiators on electrically thick multilayered substrates were completed [5,6]. These structures are attractive for millimeter-wave applications because of their simplicity, potential for obtaining a desired beam pattern, and good efficiency. These configurations will allow antennas fabricated on electrically thick high permittivity substrates such as GaAs to couple the radiation efficiently to free space. For example, a three-layered substrate using GaAs and polyethylene can provide an 80% efficiency as well as a symmetric radiation pattern at 94 GHz with a twin-slot antenna as indicated in Fig.2. This is increasingly more attractive as the frequency of operation is increased, because at such high frequencies, electrically thin substrate become physically too thin to be handled and processed easily. Preliminary modeling experiments at 10 GHz exhibited good correlation between measued and calculated radiation patterns.

A preliminary study has been initiated in preparation of the proposal for the next grant period. As a new type of monolithic integrated millimeter-wave source, circuit configurations useful for high frequency active devices such as the quantum well injection transit time (QWITT) devices have been studied. In recognition of the lack of a high Q resonant circuit in the planar integrated circuit, it is proposed to use a periodic array of active devices which are mutually injection-locked by the Bragg type stopband phenomena. Use of multiple diodes has an additional advantage that it automatically incorporates a power combining scheme to generate higher levels of power [7]. The first microwave oscillation at X band has already been observed [8].

C. FOLLOW-UP STATEMENT: Of the three types of work reported above, the first one on quasi-optical receivers has been completed. Quasi-optical transmittersusing traveling wave antennas, a related subject but based on a different principle, are being investigated by a contract from the

Army Research Office. The subject of the integrated antenna on an electrically thick subject is nearing its completion at the time of this writing by installation of a feed network and detectors suitable for millimeter-wave operations. The third topic on millimeter-wave oscillators based on new devices such as QWITT will be fully explored under the new JSEP contract.

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"Effect of Carrier Injection into MESFET Substrates: Comparison of MESFET on a SI Buffer, MESFET on a P Substrate, and Substrate-Less MESFET," Annales des Telecommunications, (Special Issue), Vol. 43, No. 7-8, pp. 415-422, July/August 1988 (S. El-Ghazaly and T. Itoh).

*"Monolithic Millimeter Wave Oscillator Using a Transmission Line Periodically Loaded by QWITT Diodes," Electronics Letters, Vol. 24, No. 11, pp. 666-667, May 1988 (A. Mortazawi, V. P. Kesan, D. P. Neikirk and T. Itoh).

"Inverted-Gate Field-Effect-Transistors: Novel High Frequency Structures," IEEE Trans. Electron Devices, Vol. ED-35, No. 7, pp. 810-817, July 1988,(S. El-Ghazaly and T. Itoh).

H.-Y. Lee and T. Itoh, "Wideband and Low ilnsertion Loss Coplanar Strip Feed Using Intermediate Microstrip," Electronics Letters, Vol.24, No.19, pp.1207-1208, (September 15, 1988).

*R. L. Rogers and D. P. Neikirk, "Use of Broadside Twin Elements to Increase Efficiency on Electrically Thick Dielectrid Substrates," International J. Infrared and Millimeter Waves, Vol.9, No.10, (October 1988).

*V. P. Kesan, A. Mortazawi, D. Miller, T. Itoh, B. G. Streetman and D. P. Neikirk, "Microwave Frequency Generation of the Quantum Well Injection Transit Time (QWITT) Diode," Electronics Letters, Vol. 24, No. 24, pp.1473-1474, (November 24, 1988).

"Spectral Domain Analysis of a Coupled Slot Antenna," IEEE Trans. Antennas and Propagation, Vol. 36, No. 11, Nov. 1988, (T. H. Wang, T. Itoh and H. Ling).

*"Confirmation of Slow-Waves in a Crosstie Overlay Coplanar Waveguide and its Applications to Band-Reject Gratings and Reflectors," IEEE Trans. Microwave Theory and Techniques, Vol. 36, No. 12, December 1988, (T.H. Wang and T. Itoh).

"Time-Domain Method of Lines Applied to Planar Guided Wave Structure," IEEE Trans. Microwave Theory and Techniques, Vol. 36, No. 12, December 1988, (S. Nam, H. Ling and T. Itoh).

"Quasi-Optical HEMT and MESFET Self-Oscillating Mixers," IEEE Trans. Microwave Theory and Techniques, Vol. 36, No. 12, December 1988, (V. D. Hwang and T. Itoh).

II. LIST OF CONFERENCE PROCEEDINGS (* JSEP Supported in whole or in part)

*"Integrated Millimeter-Wave Components Using a Quasi-Optical Design Combined with Planar Structures," MIOP (Microwaves and Optoelectronics) Paper 4A-1, March 2-4, 1988, Wiesbaden, W. Germany.

"Dielectric Loss Reduction in Superconducting Transmission Lines," Proc. of SPIE Meeting on Advances in Semiconductors and Superconductors: Physics and Device Applications, March 13-18, 1988, Newport Beach, CA (B. Young and T. Itoh).

"Experimental Confirmation of Slow-Waves in a Crosstie Overlay Coplanar Waveguide and Its Application to Band-Reject Gratings," 1988 IEEE MTT-S International Microwave Symposium Digest, pp. 383-386, May 25-27, 1988, New York NY (T. H. Wang, T. M. Wang and T. Itoh).

*"A Quasi-Optical HEMT Self-Oscillating Mixer," 1988 IEEE MTT-S International Microwave Symposium Digest, pp. 1093-1096, May 25-27, 1988, New York, NY (V. D. Hwang and T. Itoh).

"Time-Domain Method of Lines Applied to a Partially Filled Waveguide," 1988 IEEE MTT-S International Microwave Symposium Digest, pp. 627-630, May 25-27, 1988, New York, NY (S. Nam, S. El-Ghazaly, H. Ling and T. Itoh).

"Loss Reduction in Superconducting Microstrip-Like Transmission Lines," 1988 IEEE MTT-S International Microwave Symposium Digest, pp. 453-456, May 25-27, 1988, New York, NY (B. Young and T. Itoh).

"Perspectives on Guided Wave Phenomena," (Invited) 1988 IEEE MTT-S International Microwave Symposium Digest, pp. 133-136, May 25-27, 1988, New York, NY (T. Itoh).

"An Integrated Planar Oscillatc ' :ing a Microstrip Leaky-Wave Resonator/Antenna," 18th European Microwave Conference, pp. 130-135, Sept. 12-16, 1988, Stockholm, Sweden (J. Birkeland and T. Itoh).

"Analysis of Travelling-Wave Inverted-Gate Field Effect Transistors," 18th European Microwave Conference, pp. 168-173, Sept. 12-16, 1988, Stockholm, Sweden (S. El-Ghazaly and T. Itoh).

"Evanescent Mode Waveguide Bandpass Filter with Non-Touching E-plane Fins and Capacitive Iris," 18th European Microwave Conference, pp. 950-955, Sept. 12-16, 1988, Stockholm, Sweden (K. S. Kong, Y. Nikawa and T. Itoh).

"Distributed Slow-Wave Chebyshev Reflector," 18th European Microwave Conference, pp. 599-604, Sept. 12-16, 1988, Stockholm, Sweden (T. H. Wang and T. Itoh).

"Time-Domain Method of Lines Applied to Finned Waveguide," 18th European Microwave Conference, pp. 1095-1099, Sept. 12-16, 1988, Stockholm, Sweden (S. Nam, H. Ling and T. Itoh).

"Spectral Domain Analysis of E-lane Circuits," Second Asia-Pacific Microwave Conference, pp. 123-124, Oct. 26-28, 1988, Beijing, China (T. Itoh).

"Power Combining Quasi-Optical FET Oscillator Using Coupled Meander Line Antennas," 13th Int. Conf. Infrared and Millimeter Waves, December 5-9, 1988, Honolulu, Hawaii, (J. Birkeland and T. Itoh).

*"Periodic Monolithic Millimeter-Wave Quantum Well Oscillator," 13th Int. Conf. Infrared and Millimeter Waves, December 5-9, 1988, Honolulu, Hawaii, (A. Mortazawi, V. P. Kesan, D. P. Neikirk and T. Itoh).

"GaAs Traveling-Wave Optical Modulator Using a Modulated Coplanar Strip Electrode with Periodic Cross-tie Overlay," 13th Int. Conf. Infrared and Millimeter Waves, December 5-9, 1988, Honolulu, Hawaii, (H.-Y. Lee and T. Itoh).

"Experimental Performance of a Periodically Illuminated Optically Controlled Coplanar Waveguide Phase Shifter," 13th Int. Conf. Infrared and Millimeter Waves, December 5-9, 1988, Honolulu, Hawaii, (P. Cheung, D. P. Neikirk and T. Itoh).

*"Antennas on eEectrically Thick Multilayered Substrate," 13th Int. Conf. Infrared and Millimeter Waves, December 5-9, 1988, Honolulu, Hawaii, (R. L. Rogers, D. P. Neikirk, H. Ling and T. Itoh).

*"Recent Advances in Numerical Methods for Microwave and Millimeter-Wave Passive Structures," (Invited) The Third Biennial IEEE Conference on Electromagnetic Field Computation, December 12-14, 1988, Bethesda, MD (T. Itoh).

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

"The Spectral Domain Method for Nontouching E-plane Structures," Massachusetts Institute of Technology, Research Laboratory of Electronics Seminar, Cambridge, MA, Jan. 15, 1988.

*"Microwave Research at The University of Texas," M/A COM Corporate Technology Center, Burlington, MA, Jan. 16, 1988.

*"Microwave Research at The University of Texas," Centre National d'Etudes des Telecommunications, Paris, France, March 1, 1988.

"Microwave and Millimeter Wave Research for MIMIC Projects at The University of Texas," Wright Patterson Air Force Base, Ohio, June 21, 1988.

"Inverted-Gate GaAs MESFET Characteristics," Special Colloquium, Sonderforschungsbereich 254, Duisburg University, Duisburg, W. Germany, July 14, 1988.

*"Microwave Research at The University of Texas," University of Lille, France, Sept. 8, 1988.

*"Microwave Research at The University of Texas," Arizona State University, Tempe, AZ, October 11, 1988.

*"Recent Trends in Microwave and Millimeter Wave Research," NHK Broadcasting Technology Research Center, Tokyo, Japan, October 24, 1988.

*"Recent Trends in Microwave and Millimeter-Wave Planar Transmission Structures," IEEE Tokyo Chapter, Tokyo, Japan, October 31, 1988.

*"Recent Trends in Microwave and Millimeter-Wave Integrated Circuits," Toshiba Research and Development Center, Kawasaki, Japan, November 1, 1988.

IV. LIST OF THESES AND DISSERTATIONS (*JSEP Supported in whole or in part)

S. El-Ghazaly, Ph.D., May 1988, "Analysis and Improvement of MM-Wave GaAs MESFET's."

T. H. Wang, Ph.D, May 1988, "Confirmation of Slow-Waves in a Crosstie Overlay Coplanar Waveguide and its Applications to Band -Reject Gratings and Reflectors."

* V. Hwang, Ph.D. May 1988, "Planar Integrated Quasi-Optical Receivers."

S. S. Chang, M.S., December 1988, "The Boundary-Integral Method for Planar Microstrip Circuits."

K. S. Kong, M.S., December 1988, "CAD Algorithm for the Evanescent Mode Waveguide Bandpass Filter with Non-Touching E-Plane Fins."

* A. Mortazawi, M. S., December 1988, "Nonlinear Analysis of a Monolithic QWITT Oscillator"

V. GRANTS AND CONTRACTS

Army Research Office Contract DAAG-84-K-0076, "Guided Wave Interactions in Millimeter-Wave Integrated Circuits," Professor T. Itoh, Principal Investigator.

Office of Naval Research Contract N0000-79-C-0553, "Millimeter Wave Transmission Lines," Professor T. Itoh, Principal Investigator.

Air Force Office of Scientific Research Contract AF0SR-86-0036, "Monolithic Phase Shifter Study," Professors D. P. Neikirk and T. Itoh, Co-Principal Investigators.

Hughes Aircraft Company Grant, "Millimeter Wave Planar Circuits," Professor T. Itoh, Principal Investigator.

Hughes Aircraft Company , P.O. 10-145527-X28, "E-Plane Filter Analysis Design," Professor T. Itoh, Principal Investigator.

NTT Electrical Communication Laboratories, "Studies of Millimeter Wave Monolithic Circuits," Professor T. Itoh, Principal Investigator.

IBM Corp., "IBM Faculty Development Award," Professor D. P. Neikirk, Principal Investigator.

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.

National Science Foundation, "Presidential Young Investigator Award," Professor D. P. Neikirk, Principal Investigator.

3M Corporation, "3M Nontenured Faculty Grant," Professor D. P. Neikirk, Principal Investigator.

Texas Instruments, "A Study of Molecular Beam Epitaxial Growth of $Ga_xIN_{1-x}As$ for Non-Alloyed Ohmic Contacts to GaAs," Professor D. P. Neikirk, Principal Investigator.

Army Research Office Contract, DAAL03-88-K-0005, "Guided Wave Phenomena in Millimeter Wave Integrated Circuits and Components," Professor T. Itoh, Principal Investigator.

Office of Naval Research Grant, N00014-89-J-1006, "High Temperature Superconducting Planar Circuit Structures for High Frequency Applications," Professor T. Itoh, Principal Investigator.

CRAY Research 1988 University Research and Development Grant, "GaAs Based Millimeter-Wave Integrated Circuit Characteristics and Design," Professor T. Itoh, Principal Investigator.

Texas Advanced Technology Program, "Monolithic Millimeter-Wave Integrated Circuits," Professor T. Itoh, Principal Investigator.

(Page 9, Res. Unit EM88-1, "Millimeter-Wave Monolithic Components")

Texas Advanced Technology Program, "Computer Aided Design of Millimeter-Wave Integrated Circuits," Professors T. Itoh and H. Ling, Co-Principal Investigators.

Texas Advanced Technology Program, "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications, " Professors D. P. Neikirk and B. G. Streetman, Co-Principal Investigators.

Texas Advanced Research Program, "Quantum Transport Studies and Double Barriere Heterostructures," Professor D. P. Neikirk, Principal Investigator.

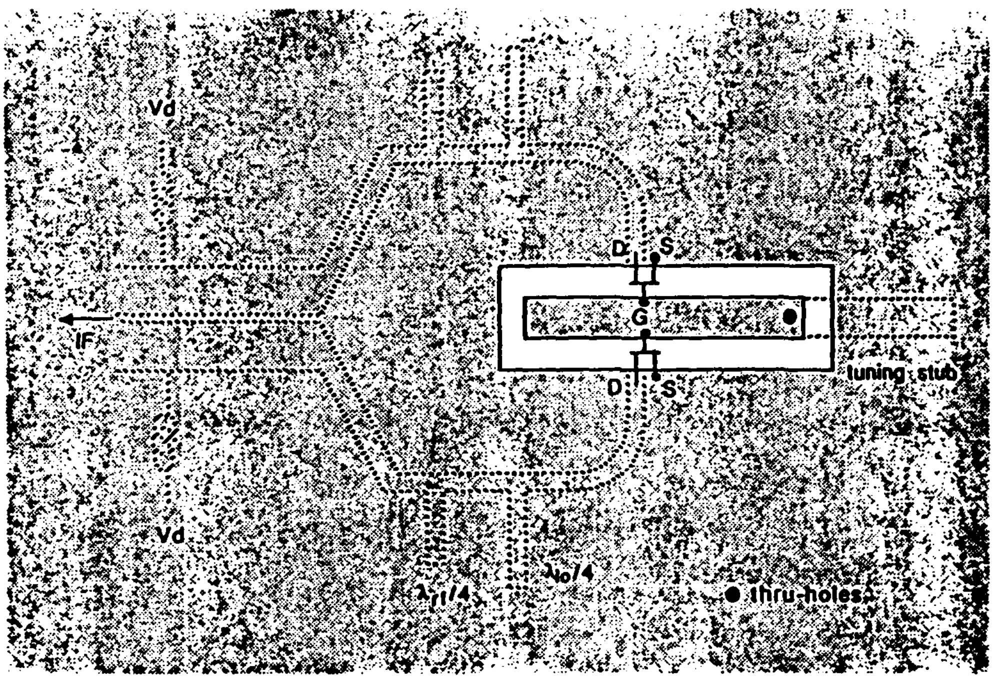
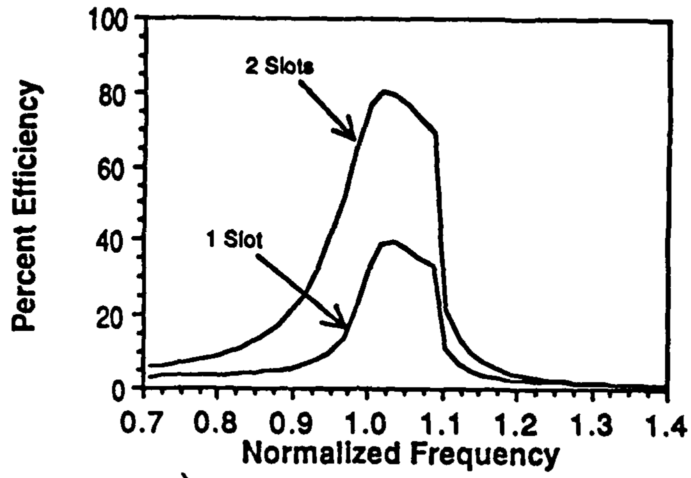
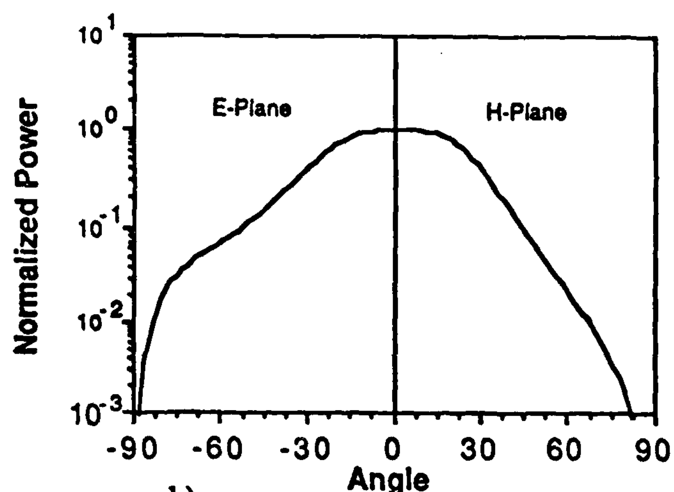


Figure 1. Receiver uses HEMT (or MESFET) self-oscillating mixer



a)



b)

Figure 2. Calculations for slots on a $\varepsilon_1 = 13$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$ layered dielectric structure. All layers are one quarter of a dielectric wavelength thick at normalized frequency (f_N) = 1. a) Efficiency vs normalized frequency for single and broadside spaced twin elements The separation for the twin slots is $0.244\lambda_0$ where λ_0 is the free space wavelength at $f_N = 1$. b) This is the beam pattern for power transmitted through the dielectric stack by a single slot. Note that the E and H plane patterns are quite symmetric out to 13db below boresight.

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER ELECTROMAGNETICS

Research Unit EM88-2 NONLINEAR WAVE PHENOMENA

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

Graduate Student: C. K. An and S. W. Nam

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 nonGaussian 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 nonGaussian 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 twelve month period covered by this report we have focussed on all three sub-objectives mentioned above. Of particular note is the fact that we have made the first (to the best of our knowledge) measurements of three-wave coupling coefficients from raw time series fluctuation data of a "turbulent" (as opposed to coherent) nature.

Since demonstrating the validity and relevance of our approach is an important aspect of this project, we also report on applications of nonlinear digital signal processing techniques developed entirely or partially under current and past JSEP support. Specific application areas and the principal sponsors of the work are: fluctuations and transport in plasmas (DoE), transition to turbulence in neutral fluids (NSF and the Texas Advanced Research Program), nonlinear seakeeping (ONR), and nonlinear response of tension leg platforms to irregular seas (Texas Advanced Technology Program and NSF). In the publications cited at the end of this report and which deal with such applications, it is acknowledged that the nonlinear digital signal processing procedures were developed under JSEP sponsorship.

Quadratic Transfer Functions for Non-Gaussian Inputs. As previously described in Annual Report No. 34 and 35, our approach to determining three-wave complex coupling coefficients is to monitor the fluctuation field at two spatial points and then to model the linear and nonlinear wave (three-wave) physics occurring between those two points with the aid of linear and quadratic transfer functions. Since the fluctuations are intrinsically nonGaussian because of their past nonlinear history, it is necessary to develop a digital technique for determining quadratic transfer functions when the excitation is nonGaussian. We have successfully accomplished this and our approach, which rests upon innovative applications of polyspectra, is described in detail in refs. [1, 7, 8]. Furthermore, we have extended this approach to dual nonGaussian inputs and have presented our initial results in refs. [15, 24].

Three-Wave Coupling Coefficients and Energy Transfer: Our approach to determining three-wave coupling coefficients is based on the similarity between the frequency domain Volterra representation of a nonlinear system and the three-wave coupling equation which, of course, is derived from the basic "equation of motion" governing the system. Specifically, if one is able to determine the linear and quadratic transfer function models, then one can determine the linear growth (or damping rate), the dispersion relation, and the complex three-wave coupling coefficients. Experimental knowledge of the three-wave coupling coefficient is important because (1) the physics of the interaction is imbedded in the coupling coefficient, (2) it allows comparison between theory and experiment, and (3) it is necessary to quantify the rate at which energy is transferred to or from any given frequency ω_3 by three wave interactions satisfying the selection rule $\omega_3 = \omega_i + \omega_j$. We have successfully developed a digital approach for measuring three-wave coupling coefficients and resulting energy transfer, and the results are described in detail in ref. [9] and summarized in refs. [4, 11, 12, 16, 17, 19].

In summary, we have met the major goals of this triennium which were to develop a digital procedure, based on the properties of polyspectral density functions, to measure: (1) quadratic transfer functions for nonGaussian inputs, (2) complex three-wave coupling coefficients, and (3) the resulting energy transfer.

Other Applications: During this period various digital signal processing techniques developed under previous JSEP sponsorship (either sole or partial) were utilized in a variety of investigations supported by other agencies. These applications are mentioned here because they substantiate the validity and practicality of the previous work and because the role of JSEP in fully or partially supporting the digital signal processing techniques is acknowledged. For example, various techniques have been used in fundamental investigations of nonlinear wave phenomena associated with transition-to-turbulence [2, 3, 25, 26], in studies of plasma turbulence [5, 6, 20, 21], and in quantifying various nonlinear and parametric aeroelastic phenomena [13, 18, 23]. In addition, we have investigated parametric methods of digitally estimating the bispectrum [14, 22] as well as optical approaches utilizing acousto-optical techniques [10].

C. FOLLOW-UP STATEMENT: This work is continuing. The primary focus in the next year will deal with further refining and applying our approach to measuring energy transfer associated with three-wave coupling. During the forthcoming triennial period, the objective will be on measuring four-wave coupling coefficients, which will necessitate the measurement of cubic transfer functions using digital trispectral analysis.

I. LIST OF PUBLICATIONS (*JSEP supported in whole or in part, or JSEP acknowledged for nonlinear signal processing contribution as indicated in this report.)

1. *K. I. Kim, E. J. Powers, Ch. P. Ritz, R. W. Miksad and F. J. Fischer, "Modeling of the Nonlinear Drift Oscillations of Moored Vessels Subject to Non-Gaussian Random Sea-Wave Excitation," IEEE Journal of Oceanic Engineering, OE-12 (4) 568-575 (October 1987).

2. *F. L. Jones, Ch. P. Ritz, R. W. Miksad, E. J. Powers and R. S. Solis, "Measurements of the Local Wavenumber and Frequency Spectrum in a Plane Wake," Experiments in Fluids, 6, 365-372 (June 1988).

3. *R. W. Miksad, F. L. Jones, Ch. P. Ritz and E. J. Powers, "The Role of Nonlinear Wave-Wave Interactions in Laminar-Turbulent Transition," Archives of Mechanics, 39, 177-205 (1987).

4. *Ch. P. Ritz, E. J. Powers et al., "Advanced Plasma Fluctuation Analysis Techniques and Their Impact on Fusion Research," Review of Scientific Instruments, 59, 1739-1744 (August 1988).

5. *E. J. Powers, H. S. Don, J. Y. Hong, Y. C. Kim, G. A. Hallock and R. L. Hickok, "Spectral Analysis of Nonstationary Plasma Fluctuation Data via Digital Complex Demodulation," Review of Scientific Instruments, 59, 1757-1759 (August 1988).

6. *S. J. Levinson, S. B. Kim, T. Koh and E. J. Powers, "Plasma Fluctuation Diagnostics via Maximum Entropy Spectral Estimation," Review of Scientific Instruments, 59, 1754-1756 (August 1988).

7. *K. I. Kim and E. J. Powers, "A Digital Method of Modeling Quadratically Nonlinear Systems with a General Random Input," IEEE Transactions on Acoustics, Speech and Signal Processing, 36, 1758-1769 (November 1988).

8. *Ch. P. Ritz, E. J. Powers, R. W. Miksad and R. S. Solis, "Nonlinear Spectral Dynamics of a Transitioning Flow," Physics of Fluids, accepted for publication and in press.

9. *Ch. P. Ritz, E. J. Powers and R. D. Bengtson, "Experimental Measurement of Three-Wave Coupling and Energy Cascading," Physics of Fluids, accepted for publication and in press.

10. M. H. Kauderer, M. F. Becker and E. J. Powers, "Acousto-Optical Bispectral Processing," Applied Optics, accepted for publication and in press.

I. LIST OF CONFERENCE PROCEEDINGS (*JSEP supported in whole or in part, or JSEP acknowledged for nonlinear signal processing contribution as indicated in this report.)

11. *E. J. Powers and R. W. Miksad, "Polyspectral Measurement and Analysis of Nonlinear Wave Interactions," in Nonlinear Wave Interactions in Fluids, R. W. Miksad, T. R. Akylas and T. Herbert, editors, Proceedings of the Symposium on Nonlinear Wave Interactions in Fluids, Boston, Massachusetts (December 13-18, 1987), 9-16 (ASME Book No. G00380, 1988).

12. *Ch. P. Ritz, E. J. Powers, R. D. Bengtson, R. W. Miksad, T. L. Rhodes, R. S. Solis and A. J. Wooton, "Nonlinear Aspects of Turbulence in Plasmas and Neutral Fluids," Proceedings of U.S.-Japan Workshop on Plasma and Fluid Turbulence, Austin, Texas (December 7-10, 1987).

13. T. Kim, R. Stearman and E. J. Powers, "Non-Classical Flow-Induced Responses of a Lifting Surface Due to Localized Disturbances," Proceedings of the 6th International Modal Analysis Conference, Vol. II, Kissimmee, Florida, 1288-1299 (February 1-4, 1988).

14. *C. K. An, S. B. Kim and E. J. Powers, "Optimized Parametric Bispectrum Estimation," Proceedings of the 1988 IEEE International Conference on Acoustics, Speech and Signal Processing, Vol. IV, New York (April 11-14, 1988), 2392-2395 (IEEE Catalog No. 88Ch2561-9).

15. *C. K. An, E. J. Powers and Ch. P. Ritz, "Frequency Domain Modeling of Dual-Input/Multiple-Output Quadratic Systems with General Random Inputs," Proceedings of the 1988 IEEE International Symposium on Circuits and Systems, Vol. 3, Espoo, Finland (June 6-9, 1988), 2209-2212 (IEEE Catalog No. 88Ch2458-8).

III. LIST OF CONFERENCE PRESENTATIONS (*JSEP supported in whole or in part, or JSEP acknowledged for nonlinear signal processing contribution as indicated in this report.)

16. *Ch. P. Ritz, E. J. Powers, R. D. Bengtson, R. W. Miksad, T. L. Rhodes, R. S. Solis and A. J. Wooton, "Nonlinear Aspects of Turbulence in Plasmas and Fluids," U.S.-Japan Workshop on Plasmas and Fluids, Austin, Texas, December 7-10, 1987.

17. *E. J. Powers and R. W. Miksad, "Polyspectral Measurement and Analysis of Nonlinear Wave Interactions," presented at the Symposium on Nonlinear Wave Interactions in Fluids at the ASME Winter Annual Meeting, Boston, Massachusetts, December 13-18, 1987.

18. T. Kim, R. Stearman and E. J. Powers, "Non-Classical Flow-Induced Responses of Lifting Surface Due to Localized Disturbances," presented at the 6th International Modal Analysis Conference, Kissimmee, Florida, February 1-4, 1988.

19. *Ch. P. Ritz and E. J. Powers, et al, "Advanced Plasma Fluctuation Analysis Techniques and Their Impact on Fusion Research," presented at the 7th American Physical Society Topical Conference on High Temperature Plasma Diagnostics, Napa, California, March 13-17, 1988.

20. *S. J. Levinson, S. B. Kim, T. Koh and E. J. Powers, "Plasma Fluctuation Diagnostics via Maximum Entropy Spectral Estimation," presented at the 7th American Physical Society Topical Conference on High Temperature Plasma Diagnostics, Napa, California, March 13-17, 1988.

21. *E. J. Powers, H. S. Don, J. Y. Hong, Y. C. Kim, G. A. Hallock and R. L. Hickok, "Spectral Analysis of Nonstationary Plasma Fluctuation Data via Digital Complex Demodulation," presented at the 7th American Physical Society Topical Conference on High Temperature Plasma Diagnostics, Napa, California, March 13-17, 1988.

22. *C. K. An, S. B. Kim and E. J. Powers, "Optimized Parametric Bispectrum Estimation," presented at the 1988 IEEE International Conference on Acoustics, Speech and Signal Processing, New York, April 11-14, 1988.

23. T. Kim, J. Schwartz, R. Stearman and E. J. Powers, "The Identification of Non-Classical Aeroelastic Responses of a Lifting Surface Due to Localized Flow Disturbances," presented at the 29th Structures, Structural Dynamics, and Materials Conference, Williamsburg, Virginia, April 18-20, 1988.

24. *C. K. An, E. J. Powers and Ch. P. Ritz, "Frequency Domain Modeling of Dual-Input/Multiple-Output Quadratic Systems with General Random Inputs," presented at the 1988 International Symposium on Circuits and Systems, Espoo, Finland, June 6-9, 1988.

25. R. W. Miksad, R. S. Solis and E. J. Powers, "Nonlinear Characteristics of Unsteady Wakes," presented at the XVIIth International Congress of Theoretical and Applied Mechanics, Grenoble, France, August 21-27, 1988.

26. *R. W. Miksad, M. R. Hajj, Ch. P. Ritz and E. J. Powers, "Sub-Harmonic Generation in an Unsteady Mixing Layer," presented at the Forty-first Annual Meeting of the Division of Fluid Dynamics, Buffalo, New York, November 20-22, 1988.

IV. LIST OF THESES AND DISSERTATIONS

Mark Kauderer, Ph.D., May 1988, "Acousto-Optical Bispectral Processing."

Peter Allison, M.S., May 1988, "Bispectral Inversion: The Estimation of a Time Series from Its Bispectrum."

(The above dissertation and thesis were not directly supported by JSEP, but are mentioned here because of their close connection to the JSEP work reported herein.)

V. CONTRACTS AND GRANTS

E. J. Powers and R. W. Miksad, "Applications of Frequency and Wavenumber Nonlinear Digital Signal Processing to Nonlinear Hydrodynamics Research," Office of Naval Research, Contract N00167-88-K-0049, April 22, 1988 - April 21, 1989.

E. J. Powers and R. W. Miksad, "Applications of Frequency and Wavenumber Nonlinear Digital Signal Processing to Nonlinear Hydrodynamics Research," Office of Naval Research, Contract N00014-88-K-0638, September 1, 1988 - April 21, 1991.

E. J. Powers and R. W. Miksad, "Application of Nonlinear Digital Time Series Analysis Techniques to Tension Leg Platform Model-Test Data," Texas Advanced Technology Program, TATP Grant 4604, May 1988 - August 1989.

R. W. Miksad and E. J. Powers, "An Experimental Study of the Nonlinear Dynamics of Unsteady Mixing Layers," Texas Advanced Research Program, TARP Grant 3280, May 1988 - August 1989.

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 1988.

CONSULTATIVE AND ADVISORY FUNCTIONS

Consultative and Advisory Functions

Prof. Keto consulted with Western Research Corporation on the design and construction of a narrow-band, high-power XeCl laser and an ultraviolet wavemeter. This was a major project required travel to Western Researach Corporation for experiments and testing of the laser. This project was funded by the Office of Naval Research and resulted in a conference proceedings listed.

Prof. Kimble presented a colloquium on "Squeezed States of Light" by invitation at Naval Research Laboratory, Washington, D.C., May 23, 1988.

On June 21, 1988, Prof. Itoh visited the Air Force Avionics Laboratory at Wright Patterson Air Force Base, Ohio and presented a seminar on the microwave and millimeter-wave research at The University of Texas related to DoD MIMIC projects to Dr. R. T. Kemmerley and other personnel at the Microwave Technology Branch.

Prof. Itoh participated in a briefing by MITRE Corporation on the possible joint project with The University of Texas on Over the Horizon Radar and Communication studies on August 26, 1988.

On October 12 - 13, 1988, Prof. Itoh was invited to the 1988 MIMIC CAM/CAD/CAT Workshop at Asbury Park, New Jersey, which was organized by the Office of the Under Secretary of Defense, Advisory Group on Electron Devices and coordinated by the Army Electronics and Technology Laboratory, Fort Monmouth, New Jersey. He participated in discussions on passive component characterizations.

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No patent disclosures.

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