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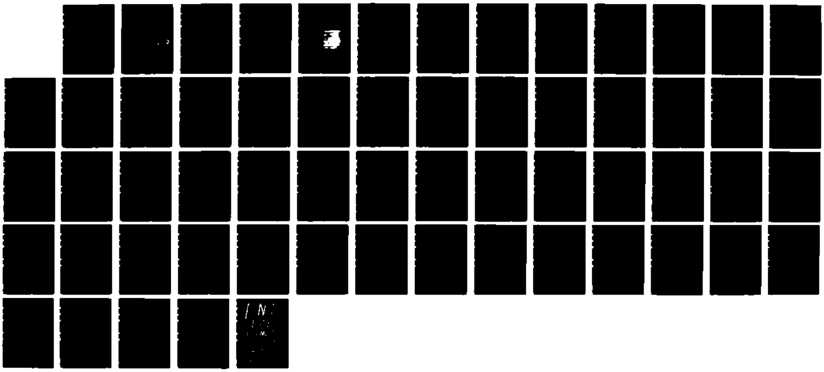

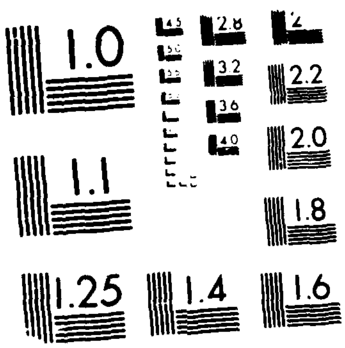

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This Annual Report covers the twelve month period ranging from January 1, 1987 through December 31, 1987. The progress reported herein was accomplished during the second year of our current triennial technical program. Ten faculty members and approximately 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

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DIRECTOR'S OVERVIEW

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SIGNIFICANT ACCOMPLISHMENTS

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DIRECTOR'S OVERVIEW

This Annual Report covers the twelve month period ranging from January 1, 1987 through December 31, 1987. The progress reported herein was accomplished during the second year of our current triennial technical program. Ten faculty members and approximately twenty graduate students from the Department of Electrical and Computer Engineering and the Department of Physics are conducting the research described in this report. The University of Texas DoD JSEP program is a broad-based program with four research units in Solid State Electronics, two in Electromagnetics, two in Quantum Electronics, and two in Information Electronics.

The Solid State Electronics program involves the fundamental issues in semiconductor physics and technology and is designed to address basic problems which must be solved for the development of the next generation of electronic and optical devices. In the following significant accomplishments section, we summarize recent advances in molecular beam epitaxy for ultra-high speed device applications and ion implantation of InP.

In the Electromagnetics area several novel monolithic millimeter-wave integrated circuit structures are being investigated for use as quasi-optical array elements. In particular, a planar quasi-optical receiver has been developed which combines a coupled slot antenna, a balanced mixer and solid state local oscillator into a single entity. Fundamental studies of nonlinear wave phenomena are also being carried out and the results obtained appear to transfer to a number of areas of science and technology including, for example, radar scattering from nonlinear targets, nonlinear spectral energy transfer mechanisms associated with transition to turbulence, and nonlinear motion of ships subjected to random sea wave excitation.

The Quantum Electronics research part of the program has as its overall theme the study of optical quantum effects with emphasis on nonlinear optical phenomena. For example, a significant accomplishment write-up describes recent progress in this area and points out that such research also provides "an ideal meeting ground for the comparison of experiment and theory in the general field of nonlinear dynamics."

Research in Information Electronics is concerned with both the theoretical and practical aspects of the analysis, implementation, and performance of information processing systems designed for the extraction of information from signals. For example, recent progress in extracting information about the state of a system from nonlinear noisy measurements is described in the significant accomplishment entitled "Adaptive Estimation and Control."

With respect to facilities, we are pleased to note that the University has approved plans to build a new research building at its Balcones Research Center site. This building will house microelectronics, manufacturing systems engineering, and material science and engineering. It will provide high quality research facilities for many of our JSEP faculty participants.

Lastly, we continue to aggressively recruit first-rate faculty to fill million-dollar endowed chairs in microelectronics and material science and engineering.

Planar Quasi-Optical Receiver for Millimeter-Wave Array Components

Tatsuo Itoh

A number of novel solid state devices such as metal semiconductor field effect transistors (MESFET), high electron mobility transistors (HEMT), etc., have been developed in recent years for high frequency applications. However, availability of these devices alone does not guarantee high performance communication and radar components at high frequencies such as those for millimeter-waves. Often, the device capabilities are not fully utilized. This problem is caused by a number of factors including lack of design knowledge of the device and inadequate circuit configuration in which the device is placed. At such high frequencies, it is important to understand the wave-device interactions and to develop a circuit configuration that fully utilizes these interactions.

With a view to meeting these requirements, a planar quasi-optical receiver has been developed which combines a coupled slot antenna, a balanced mixer and a solid state local oscillator into a single entity. As shown in Fig.1, the key element in the circuit is a coupled slot, which supports two orthogonal modes, created in a ground plane on the substrate. In the even mode

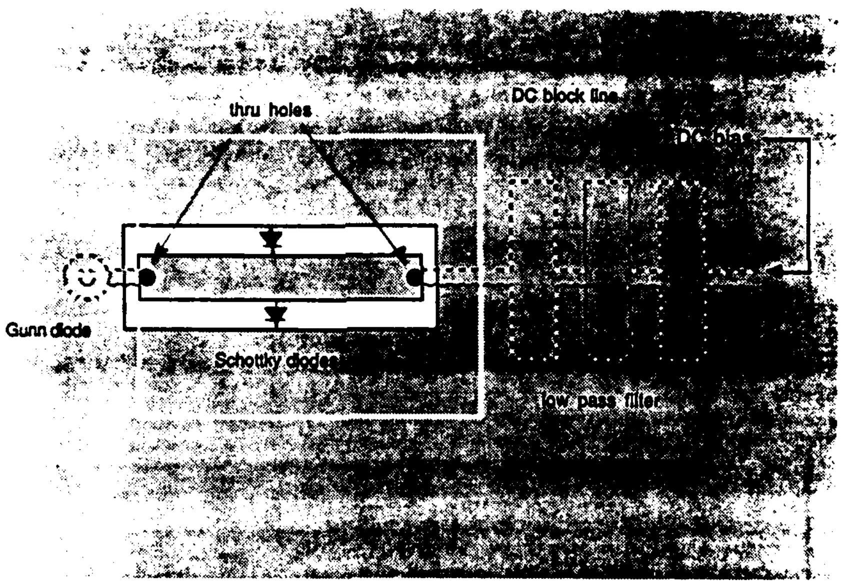

Fig.1 Top view of the planar quasi-optical receiver

operation, the coupled slot becomes an efficient planar antenna. Hence, the Schottky diodes placed in the coupled slot receive an incoming RF (radio frequency) signal in phase. On the other hand, the local oscillator signal produced by the Gunn diode propagates in the odd mode toward the mixer diodes with a negligible radiation. The local oscillator signals applied to the two Shottky diodes are out of phase. Hence, a balanced mixer operation takes place which is in principle insensitive to the noise contained in the local oscillator signal. The solid state device for the local oscillator is placed in the microstrip circuit on the backside of the substrate. Also, the IF (intermediate frequency) signal obtained by mixing of the RF and local oscillator signals is extracted via a microstrip filter circuit on the backside of the substrate. A DC bias required for the local oscillator circuit is supplied through the IF circuit. Because of the use of orthogonal modes in the coupled slot, there is a built-in isolation between the local oscillator signal and the RF signal.

There are several unique features in the circuit in addition to those mentioned above. First, because the receiver is a quasi-optical one, it eliminates a number of transmission lines connecting the basic elements in an ordinary receiver, resulting in the reduction of conversion

Molecular Beam Epitaxy for Ultra-High Speed Device Applications

Ben G. Streetman and Dean P. Neikirk

With the advent of advanced semiconductor growth techniques such as molecular beam epitaxy (MBE), much of modern compound semiconductor device development now involves heterojunctions. The availability of multiple heterojunctions has led to the discovery of a variety of new phenomena, with exciting potential device applications. The ability to tailor the device band structure at the scale of a single atomic layer, as well as the use of systems with discontinuous band edges such as GaAs/AlGaAs, has led to a whole new class of devices. The extremely thin layers used allow us to make use of tunneling phenomena, an inherently very fast transport process. Such devices are particularly suited for use in very high frequency applications, such as in monolithic microwave and millimeter-wave integrated circuits.

One such device is the quantum well oscillator, which has been the subject of much research activity as a potential candidate for a millimeter-wave source. These devices require the growth of AlGaAs layers approximately 20Å thick, which bound a thin layer (about 50Å) GaAs quantum well. Tunneling through quantum wells is inherently a very fast transport mechanism, and hence very high oscillation frequencies (on the order of hundreds of GHz) have been suggested. However, the output power obtained from pure quantum well oscillators has been very low due to low dc bias voltages and area and impedance limitations associated with the capacitance of very narrow junctions. Devices incorporating undoped spacer layers on either side of the quantum well barriers have been found to have larger values of negative differential resistance, leading to improved rf performance. The thicknesses of these nominally undoped spacer layers vary greatly from 50Å to 0.5 μm. Under bias a significant portion of the spacer layer on the anode side of the quantum well will be depleted, resulting in a transit time delay for carriers traversing through this region. Recent studies have considered the transit time effects due to these spacer layers on the rf performance of quantum wells when used as an oscillator.

We have recently proposed an optimized quantum well oscillator structure considering transit time effects using asymmetric spacer layers (Fig. 1). A thin (~50Å) spacer layer is introduced before the quantum well to prevent dopant migration and a thicker unintentionally doped layer is used after the quantum well to form the drift region for transit time operation. We believe that the thickness of the drift region, when appropriately designed using transit time considerations for a particular frequency of operation, can significantly improve the rf performance of the device over pure quantum well oscillators. Since this structure uses quantum well Injection and transit time effects, we call it a QWITT diode. The presence of the drift region increases both the device impedance and bias voltage so higher output power can be obtained. Figure 2 (based on a small signal modeling program) clearly shows the significant increase in negative resistance available from a QWITT diode compared to a pure quantum well oscillator. Further, the quantum well also offers the opportunity to control the injection phase angle as a function of dc bias, a new feature for a transit time device.

For either of these devices it is necessary that extremely thin layers be grown with very accurately controlled layer thickness. One *in-situ* tool capable of monitoring the growth of single monolayers of the crystal is reflection high energy electron diffraction (RHEED). With this technique an electron beam strikes the surface of the growing crystal at a glancing angle; the reflected beam intensity and diffraction pattern contain information about the state of the interface. For example, RHEED can distinguish between metal or As rich surface conditions, thus allowing optimization of the crystal stoichiometry. In addition, as a single monolayer begins to grow the effective surface becomes rougher, until the layer growth approaches completion. Such effects lead to a reduction in electron reflection as the layer grows, followed by a recovery of the original intensity as the monolayer growth is completed. We have recently completed installation of an imaging RHEED system which allows us to monitor in real time the complete RHEED pattern. This system is linked directly to the MBE-control computer with high speed signal processing capabilities. In its simplest configuration this system allows us to count individual monolayers as they grow, thus providing the precisely calibrated growth rate information necessary to fabricate the quantum well devices discused above.

ADAPTIVE ESTIMATION AND CONTROL

S.I. Marcus

Mathematical models of engineering systems, including those in the fields of aerospace navigation and vehicular control, involve unknown parameters and noise disturbances (such as wind gusts). In addition, in most situations the state of the system cannot be observed directly; instead, one only has access to an observation or measurement process which is contaminated by noise.

The objective of the state estimation problem is the extraction of information about the state of the system from nonlinear noisy measurements. This information is then often used as the basis for control of the system. If there are also unknown parameters in the system, the adaptive control problem is that of determining a control law which achieves a given performance in the face of these uncertainties. However, few results have been available for such problems.

By combining parameter estimation algorithms with state estimation and control algorithms, new algorithms for adaptive control of systems with incomplete state observations have been developed (see Fig. 1). The algorithm iteratively computes an approximately optimal control policy and a parameter estimate, and combines these in a manner that is asymptotically optimal; that is, except for a transient period, the performance is as good as the situation on which the parameters are known. The application to that of problems of machine replacement and quality control has also been investigated.

Three adaptive algorithms were developed for the more complicated problem in which the characteristics of the noise disturbances are unknown. In this nonparametric adaptive control problem with partial state information, each of the adaptive algorithms were shown to be asymptotically optimal. There are tradeoffs between the various algorithms concerning on-line and off-line computation and computer storage, and these have also been addressed.

The insights and algorithms developed in this research are expected to lead to further developments having impact on active control technology in aircraft subject to varying flight conditions and parameters. The potential benefits of the incorporation of such active control technology include size and weight reductions, performance improvement, and fuel savings.

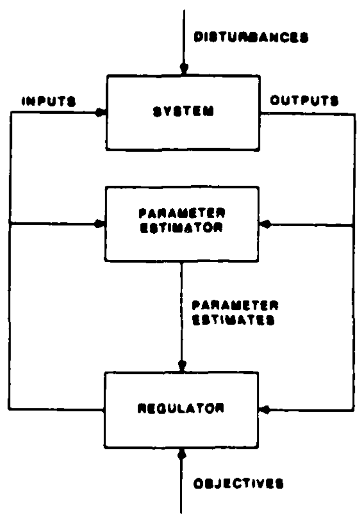

Figure 1. Adaptive Control System

NONLINEAR OPTICAL INTERACTIONS

H. Jeff Kimble

As the level of excitation of an optical system is increased, new dynamical states are encountered which differ dramatically from the familiar time-independent states found near threshold. Extensive quantitative characterizations of these time-dependent steady states have been made for a passive bistable system composed of the most fundamental elements. The investigations have demonstrated the complete inadequacy of theoretical analysis based upon models that neglect the transverse structure of the electromagnetic field. 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.

It should be noted that while on the one hand such states of self-pulsing instability can be detrimental to system performance, on the other hand these oscillatory instabilities may have a number of important practical applications (as for example as tunable high frequency optical oscillators or as means for increasing the average output power of an optical system). In either case, a fundamental understanding is required in order either to avoid or to employ these processes. Beyond the relevance to applications, this research program also provides an ideal meeting ground for the comparison of experiment and theory in the general field of nonlinear dynamics.

The experiments on optical bistability are conducted in the Quantum Optics Laboratory of Dr. H.J. Kimble at The University of Texas at Austin and involve a passive bistable system consisting of two-level atoms contained within an optical cavity. The fundamental nature of the experiments allows precise quantitative comparisons with theory to be made and leads to improved understanding of the generic nature of the nonlinear processes involved. An example of the measurements is shown in Figure 1. The figure represents the domain of self-pulsing instability in the plane of atomic detuning Δ and cavity detuning θ for fixed cooperativity parameter C. An open circle in the figure denotes a point of oscillatory instability, while the filled squares denote stable operation. The full curve is a theoretical prediction for the boundary separating time-independent from time-dependent operation and is calculated from the single-transverse mode theory of self-pulsing instabilities in optical bistability. The dashed curve is the prediction of the standard plane-wave theory that neglects the spatially varying transverse profile of the intracavity optical field. In this figure as in many others that have been constructed over a wide range of operating conditions, the plane-wave analysis predicts large domains of dynamic instability and a multitude of complex higher order dynamic states that are not observed experimentally. However, the single-transverse mode theory of self-pulsing instabilities is found to be in good quantitative agreement with the observations.

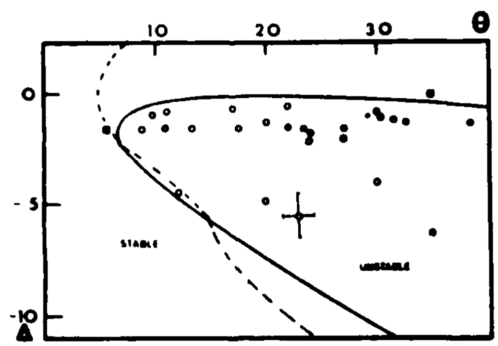

Figure 1 - Domain of instability in the space of atomic detuning Δ and cavity detuning θ for a value of atomic cooperativity parameter $C = 300 \pm 50$. The cavity damping rate $K = 0.4$ in units of the atomic decay rate. Empty circles indicate dynamic instability; filled squares denote stability without oscillation. Inside the continuous line is the unstable region predicted by the single-mode Gaussian theory, while to the right of the dashed line is the plane-wave prediction for the unstable region. The measurements are made for a ring cavity.

ION IMPLANTATION OF InP

Ben G. Streetman

The excellent carrier transport and surface properties of InP make it a particularly attractive material for use in optoelectronic and high-speed device applications. For many of these devices, particularly high speed field-effect transistors (FET's), selective doping by ion implantation is highly desirable.

Several problems complicate the implantation process in InP, including stoichiometric changes that result from unequal recoil of the In and P atoms near the semiconductor surface and degradation of the crystal surface due to P-loss during high temperature annealing. Both of these affect the electrical activation of impurities and the mobility of carriers in the implanted region. Therefore, it is desirable to develop implantation and annealing techiniques to control crystal stoichiometry in the implanted region and achieve reliable high-mobility material.

To suppress P-loss during the annealing process, a controlled-ambient rapid thermal annealing system has been developed which utilizes a temperature-controlled solid P source to provide an adjustable P overpressure, as shown schematically in Fig. 1. This system protects the crystal surface from thermal degradation more effectively than conventional proximity annealing techniques and does not require dielectric encapsulation, which is inherently problematic. In addition, this P-overpressure annealing system effectively enhances the donor activation and electrical mobility of Si-implanted InP:Fe by reducing the availability of P vacancies in the near-surface region of the semiconductor.

This technique has successfully been employed to activate low implanted doses of Si in InP:Fe, which are typically used for FET channels. For $4 \times 10^{12} cm^{-2}$ implants, donor activation was increased 10-30% and mobilities were improved 25-70% compared to those annealed using a proximity method. This technique has also been successfully used in the annealing of high dose Si implants.

In addition, photoluminescence and Hall effect characterization has revealed the presence of an implantation-induced electrically active defect level in ion-implanted InP annealed using rapid thermal annealing. These defect levels can control the electrical properties of implanted material and they must be understood before reliable device technologies based on ion-implanted InP can be realized. The annealing behavior of this defect under a variety of implantation and annealing conditions has been investigated in detail, and procedures that minimize its effects have been studied.

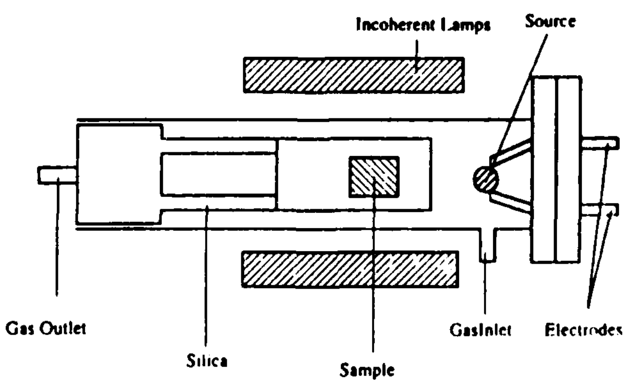

Fig. 1 — Schematic diagram of the annealing system.

I. INFORMATION ELECTRONICS

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

Research Unit IE87-1 ELECTRONIC SIGNAL PROCESSING

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

Graduate Students: N. Nandhakumar and T.-Y. Leou

A. SCIENTIFIC OBJECTIVES: The overall scientific objectives of this research unit are to establish algorithms for computerized analysis of information in signals of different forms and to develop efficient and accurate techniques for digital signal processing. 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 can be easily integrated. A portion of our research effort has been directed towards the development of new and efficient techniques for processing time-variant signals. In particular, we are interested in investigating the basic properties of recursive linear time-variant (LTV) digital filters and exploring better solutions to the analysis and synthesis problems associated with LTV filters.

Coventionally, 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 founded 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 the tightening of the coupling between front-end processing and the higher levels of analysis.

Time-variant techniques have been demonstrated to be useful in a variety of signal processing problems which involve signals whose characteristics change significantly with time. But wider application of time-variant processing techniques is hindered by the lack of well established fundamental theory and techniques. Furthermore, solutions to time-variant signal processing problems often require a significant amount of computational resources in both design and implementation phases. A common approach for circumventing these difficulties is to simplify the problem formulation by using a number of special time-variant system models that have simple structures. Due to the arbitrariness of the model selection process, the system model may differ substantially from the actual system, which often leads to unsatisfactory analysis and synthesis result. In this research, we have formulated the time-variant signal processing problems based upon a general model of recursive LTV systems, and developed suitable solutions accordingly. Due to the inherent complexity of time-variant problems, a delicate balance often need to be reached between efficiency and accuracy of the proposed solutions. Using a general model in the problem formulation not only gives us more flexibility in making such a trade-off, but also enables us to explore a number of important properties of general recursive LTV systems.

B. PROGRESS: A significant amount of research has been conducted by this research unit in the analysis and interpretation of signals, both one-dimensional and multi-dimensional. The latter category includes signals sensed by diverse sensors and analyzed concomitantly to provide useful information regarding the sensed parameters. A brief discussion of the approaches adopted for robust interpretation of sensed signals in presented below.

of scene object. 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'.

Linear Time Variant Digital Filtering

In the invited article to the Encyclopedia of Physical Science and Technology [8], we have reviewed both the theoretical background and the practical approaches for time-variant systems and signal processing. Some of the results reported in this article come from our earlier work in the area of time-variant digital filters [9]-[15]. We have documented the relationships among several representations of time-variant systems, which include the impulse response, the generalized transfer function, the time-variant difference equation, and the state-space representation. We have also examined a number of special time-variant systems that lead to significant simplification of the problem formulation. Most of the available time-variant techniques are developed based on these simplified system models. In particular, both time- and frequency-domain methods for analyzing recursive LTV systems have been discussed. Furthermore, the areas of present and future interest in the field of time-variant signal processing have been examined.

Continuing our earlier work on the synthesis of recursive LTV filters [10], [12], [14], [15], we have developed an efficient technique for identifying a recursive LTV system from multiple observations of the input and output to the system [3]. Based upon the least-squares criterion, the optimal solution to such an identification problem can be formulated as a nonlinear minimization problem that is equivalent to a two-point boundary-value problem of a high-order nonlinear difference equation. Due to the complexity of the equations involved, it is not numerically feasible to determine the optimal solution of this identification problem. There have been attempts to simply the problem formulation by assuming that the degradations in the observed data are negligible, which reduces the identification problem to a sequence of independent linear least-squares problems. But this method is very sensitive to the errors in the system model and the data observations, and has poor numerical stability. In this research work, we have developed an efficient suboptimal identification technique through the minimization of a sequence of localized error functions representing the differences between the observed data and the corresponding ones in a reference system model at different instants. Information is passed from the minimization result at each instant to the localized error function at the next instant. If the degradations in the measured data are reasonably small, this technique has been shown to produce very good identification results. Furthermore, this technique can be easily adapted for the deterministic synthesis problem of recursive LTV filters by considering the desired impulse response as the observed outputs corresponding to unit impulse inputs applied at different instants.

C. FOLLOW-UP STATEMENT: Research in the development of various methodologies for the analysis and interpretation of signals is being actively pursued by this research unit. The techniques being developed are suitable for diverse applications. Research is being directed at various aspects of the problem of interpreting signals. Effort is being directed at both low level signal analysis as well as high level interpretation. Methods are being developed for improved low level processing of signals via the development of more powerful digital filtering techniques based on linear time variant models. Strategies for robust interpretation of signals at higher levels of analysis are being developed based on integration of signals from different sensors.

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15. T.-Y. Leou and J.K. Aggarwal, "An Efficient Identification Technique for Recursive LTV Systems Based upon the Minimization of a Localized Error Function," to be submitted.

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

Y. F. Wang, A. Mitiche and J. K. Aggarwal, "Computation of Surface Orientation and Structure of Objects Using Grid Coding," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 9, no. 1, pp. 129-137, Jan. 1987.

S. Y. Lee and J. K. Aggarwal "A Mapping Strategy for Parallel Processing," *IEEE Transactions on Computers*, vol. C-36, no. 4, pp. 433-442, April 1987.

S.Yalamanchili, S. Y. Lee and J. K. Aggarwal, "Parallel Image Normalization on a Mesh Connected Array Processor,"*Pattern Recognition*, vol. 20, no. 1, pp. 17-31, 1987.

S. J. Roan, W. N. Martin and J. K. Aggarwal, "Multiple Resolution Imagery and Texture Analysis," *Pattern Recognition*, vol. 20, no. 1, pp. 17-31, 1987.

A. Mitiche, Y. F. Wang and J. K. Aggarwal, "Experiments in Computing Optical Flow with the Gradient-Based Multiconstraint Method," *Pattern Recognition*, vol. 20, no. 2, pp 173-179, 1987.

N. Nandhakumar and J. K. Aggarwal, "Thermal and Visual Sensor Fusion for Outdoor Robot Vision," at the *1987 ASME International Conference on Computer in Engineering*, New York, August 9-13, 1987.

J. K. Aggarwal, "Structure and Motion from Images," at the University of Houston, Department ofElectrical Engineering, Distinguished Lecturer Series, April 10, 1987.

J. K. Aggarwal, "Determining Motion and Structure of a Rigid Object from Image Sequences," at the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, August 1987.

B. C. Vemuri and J. K. Aggarwal, "Determining Object Posture from Dense Range Maps," at the *Siam Conference on Applied Geometry,* July 1987, Albany, N.Y.

N. Nandhakumar and J. K. Aggarwal, "Synergetic Integration of Thermal and Visual Images for Computer Vision," at the *SPIE Conference on Infrared Sensors and Sensor Fusion,* Orlando, Fl., May 19-21, 1987.

N. Nandhakumar and J. K. Aggarwal, "Multisensor Integration - Experiments in Integrating Thermal andVisual Sensors," at the *First International Conference on Computer Vision,*London, England, June 8-11, 1987.

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

S. M. Kiang, M.S., August 1987, "Triangulation Errors in Stereo Algorithms"

Sridhar Thayumanavan, M. S. August 1987, "A Performance Measure for Hopfield AssociativeMemories (HAMs) and a Hierarchical Paradigm of HAMs."

* Y. F. Wang, Ph.D., May 1987 "Integration of Active and Passive Sensing Techniques for Representing Three-Dimensional Objects."

C. H. Chien, Ph.D. May 1987, "Reconstruction and Recognition of 3D Objects from OccludingContours and Silhouettes."

S. Y. Lee, Ph.D., August 1987, "A Problem-Driven Approach to Parallel Processing: System Design/Scheduling and Task Mapping."

* N. Nandhakumar, Ph.D., August 1987, "Multisensor Fusion for Scene Perception - Integrating Thermal and Visual Imagery."

B. Vemuri, Ph.D., August 1987, "Representation and Recognition of Objects from Depth Maps."

V. GRANTS AND CONTRACTS

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THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE87- 2 NONLINEAR ESTIMATION AND DETECTION

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

Graduate Students: Hangju Cho and Emmanuel Fernandez-Gaucherand

A. RESEARCH OBJECTIVES: Several problems involving estimation, detection, and control of systems involving noise and unknown parameters are considered in this research unit. 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: A major aspect of our research involves adaptive estimation and control problems for stochastic systems with incomplete (or noisy) observations of the state. In [1] and [2], the adaptive estimation of the state of a finite state Markov process is investigated. In this context, the adaptive estimation problem is that of computing recursive estimates of the conditional probability distribution of the state given the past observations, when the state transition matrix (i.e., the model) depends on an unknown parameter. Such problems arise in computer communication networks and in other areas. A new adaptive estimation algorithm for such problems is developed; the algorithm combines a recursive parameter estimation algorithm of the type proposed by Kushner and Shwartz [3] and Ljung and Soderstrom [4] with a recursive state estimation algorithm. The algorithm is analyzed via the Ordinary Differential Equation (ODE) method. That is, it is shown that the convergence of the parameter estimation algorithm can be analyzed by studying an "averaged" ordinary differential equation. The stability of the resulting ordinary differential equation is analyzed in order to prove convergence of the parameter estimates to a set of optimal parameter values. Then it is shown that the adaptive state estimates are optimal.

The related adaptive stochastic control problem for discounted-reward, denumerable state space, Markov decision processes with incomplete state information and unknown parameters is considered in [5]. It is shown that there exists a strongly consistent sequence of estimators which converge to the true values of the unknown parameters. In addition, an

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II. SOLID STATE ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE87-1 IMPLANTATION AND ANNEALING OF InP AND RELATED COMPOUNDS

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

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

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 annealing on these properties. The reason for interest in these issues is the potential for 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 electron drift velocity and saturation velocity [1]. These 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 useful applications in opto-electronic integrated circuits as well as high speed heterojunction bipolar transistor circuits [3,4]. Using suitable deposited dielectrics, the InP-dielectric interface can be processed to have a fast interface state density as low as $6x10^{10}cm^{-2}eV^{-1}$ [5], 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) [6-8]. A major objective of this research is to provide a better understanding of two of the most important issues facing a reliable InP FET technology: (a) impurity migration and activation during various implantation and annealing procedures, and (b) formation of a stable InP/insulator interface with a low density of interface states. Issue (a) requires novel approaches to encapsulation and precise thermal control during annealing, and (b) requires study of surface effects and passivation media.

B. PROGRESS: The research can be generally divided into two areas: (a) implantation and annealing studies, and (b) surface studies. Low temperature photoluminescence is used in both of these areas, along with various electrical measurements (including Hall effect and DLTS). The use of rapid thermal processing for thermal treatment and remote plasma deposition of dielectric films provides us with considerable flexibility in processing these materials. As a result, we have been able to separate various processing-related issues which heretofore have led to confusing results. These results have been reported during the past year in 9 refereed journal articles. Also during this period 2 students have completed their PhD work and one his MS work, based on this research.

Implantation and Annealing: Close contact rapid thermal annealing of Si implants in InP has been studied [9]. The formation of a conducting p-type layer extending ~ 700Å from the surface has been observed and can be attributed to the loss of significant amounts of P during the annealing cycles studied (800°C for 1-30s). The depth of this layer was found to be independent of the anneal times employed here. Also, the solubility limit for net donor activity typically present for high dose Si implants into GaAs and InP was observed. The formation of a surface p-type layer clearly indicates that the close contact method is inadequate for annealing Si

Surface Studies and Photoluminescence in InP: We have observed radiative surface recombination centers on InP by low-temperature photoluminescence [13]. The luminescence band is observed only after etched or annealed surfaces are treated with hydrofluoric acid (HF), and is not found after rinsing in deionized water. These observations and x-ray photoemission studies of the treated surfaces indicate that the recombination centers are related to the near-surface stoichiometry or to the composition of native oxide layers. A model has been presented which attributes this emission band to recombination from the bulk conduction band and bulk neutral donors to surface states distributed from the valence band to at least 300 meV into the band gap [14]. The peak emission energy depends on the occupancy of these surface states and is governed by the position of the quasi-Fermi level for holes at the surface. This model accounts for the properties of this luminescence band as a function of temperature, excitation power density, and substrate doping type.

Low-temperature photoluminescence has also been used to study optical transitions in InP which arise from moderate-temperature annealing or dielectric encapsulation [15]. A total of seven shallow emission lines appear in annealed or encapsulated InP that are not present in unprocessed material. These transitions are easily observed in undoped substrates. They are less intense or absent in Fe-doped material, and are not seen in *p*-type material. Dielectric cappin gwith SiO_2 enhances the formation of several transitions, while phosphosilicate glass or Si_3N_4 effectively suppresses their formation. Surprisingly, some of these recombination centers are found to extend many microns into the substrate after SiO_2 deposition at 350°C or after annelaing at temperatures as low as ~400°C. These centers appear to be related to processing-induced carrier concentration changes.

A commonly observed luminescence band in InP near 1.35 eV has been studied in detail [16]. The dependence of the transition energy on sample temperature and excitation power density indicates the band results from a donor-to-acceptor pair transition involving a donor level with an activation energy of ~33 meV. Luminescence spectra from samples implanted with Si, Al, or P show that the donors responsible for the band are native defects or complexes that result from radiation damage. These results do not support previous assignments of the 1.35-eV band to transitions involving various impurities.

An examination of low-temperature photoluminescence from chemically thinned InP illustrates the effect of multiple absorption and re-emission of photons in bulk liquid-encapsulated Czochralski (LEC) grown material [17]. Luminescence spectra show that such photon recycling dramatically increases the nonequilibrium carrier density in the material and causes excess carrier distribution to penetrate tens of microns beneath the sample surface, an order of magnitude more than a diffusion length. Nonequilibrium carriers also penetrate deeper with increasing excitation levels as a consequence of more efficient radiative recombination. Although these effects have not been widely recognized, they have important consequences in the interpretation of luminescence spectra, and in the design of electronic and optical devices based on InP that are sensitive to minority carrier diffusion lengths.

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

Surface studies will be continued, with an emphasis on the surface properties of chemically treated InP wafers. For example, we will examine the use of Na_2S and other promising

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

Research Unit SSE87-2 — MOLECULAR BEAM EPITAXY WITH HIGH SPEED DEVICE APPLICATIONS

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

Postdoctoral Students: C. W. Farley

Graduate Students: T. Block, G. Crook, 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 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 will emphasize their use in devices for very high frequency applications, such as monolithic integration with millimeter-wave and submillimeter-wave circuits. The potential for control of both doping and composition at a monolayer scale provided by molecular beam epitaxy makes it uniquely suited for these applications. Our primary emphasis is on devices based on tunneling through AlGaAs/GaAs/AlGaAs 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 of 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. Once these issues are understood, work on the application of these techniques to the fabrication of high frequency devices will be done in collaboration with the unit EM87-1, "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, fundamental studies of growth mechanisms at the submonolayer scale, and the invention of a new heterostructure device for high frequency applications.

Molecular Beam Epitaxy System: The devices we wish to study generally require that extremely thin layers be grown with very accurately controlled layer thickness. One *in-situ* tool capable of monitoring the growth of single monolayers of the crystal is reflection high energy electron diffraction (RHEED). With this technique an electron beam strikes the surface of the growing crystal at a glancing angle; the reflected beam intensity and diffraction pattern contain cracker cell with high cracking efficiency often requires high input power. However, low background carrier concentration has been difficult to achieve with such high temperature cracking cells.

Our arsenic cracker design consists of a two-zone, large capacity, ultra-high vacuum compatible solid arsenic sublimator/refractory cracking source. The cracking furnace consists of a sublimator section and cracking section thermally isolated from each other. The sublimator section is horizontal and is placed 90^{o} off axis to the cracking section. The suolimator is machined from molybdenum and is housed in a ceramic tube. The cracker tube is a ten inch long molybdenum tube, supported by a tantalum disk. The cracking section avoids the use of baffles and relies solely on the thermal gradients and collisions between the tetrameric arsenic and refractory metal walls of the cracking tube for the catalytic formation of As_2. This design avoids many of the limitations associated with conventional cracker designs. High mobility and low unintentional background doping have been obtained in GaAs epitaxial layers grown using this cracking cell. Further electrical characterization of material grown with this arsenic source is in progress.

Transport Through GaAs/AlGaAs Heterostructures: The transport properties of thin AlAs and $Al_xGa_{1-x}As$ barriers in GaAs structures are of great interest for the development of high speed devices. These include double barrier resonant tunneling devices and other devices which combine transit time effects with tunneling to produce microwave oscillations. However, interface states and other effects in such structures may drastically influence the transport mechanisms through the barriers. In order to better understand transport through these structures we have examined single AlAs barriers and single quantum wells using swept frequency impedance-phase measurements, swept temperature DLTS and capacitance measurements, and pulsed and continuous I-V curves [6]. Both Schottky and ohmic contacts have been used to study these structures.

Figure 1 illustrates a representative I-V measurement made on an as-grown device with ohmic contacts. Initially, the structure is capable of conducting substantial currents and is in what we call a "low" impedance mode (LIM). As the bias is increased, the device switches into a conductance mode which passes much less current. We call this the "high" impedance mode (HIM). The device maintains the high impedance mode even as the bias is reduced (as indicated in the inset of Fig. 1). In fact, the structure may be completely disconnected from all measurement apparatus and maintained in this mode for days.

Such device performance would not be of great interest if it were not for the fact that we are able to switch the device back to the low impedance mode as illustrated in Fig. 2. The device which had previously been switched into the HIM is forward biased until it is observed to switch back into the LIM. Because of the high voltage at which the switching occurs the current exceeds the compliance limits of our test apparatus after switching back to the LIM mode. This low impedance mode persists as we reduce the forward bias as illustrated in the inset of Fig. 2. Once again, this mode can be maintained for days and switching as illustrated in Fig. 1 can be repeated.

In an effort to better understand the two observed impedance modes, samples with aluminum Schottky barriers suitable for DLTS studies were prepared. An initial examination of capacitance versus temperature resulted in a remarkable drop in capacitance at elevated temperatures. The low capacitance state persists as the temperature is cycled through lower values. The structure may be switched back to the high capacitance mode by applying a large forward bias to the structure. We have not been able to switch the structure to the high capacitance mode through solely thermal means. Impedance phase analysis of the two capacitive states indicates that the high capacitance mode corresponds to the LIM mode of the ohmic collaboration with M.C. Downer (Unit SSE 87-4) we will examine carrier dynamics in these structures on the femtosecond scale. Extensive studies of the QWITT diode will be continued, including device simulation, fabrication, and testing. The simulation efforts will include a large-signal model of the oscillator, making use of Monte Carlo calculations of transport through the drift region. Experimental work will continue with the growth of QWITT structures, dc characterization, and in collaboration with Unit EM87-1, rf oscillator fabrication.

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V.P. Kesan,T.D. Linton,C.M. Maziar, D.P. Neikirk, P.A. Blakey, and B.G. Streetman, "Power-optimized design of quantum well oscillators," to be presented at the 1987 IEEE International Electron Devices Meeting, Dec. 6-9, 1987.

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

D. P. Neikirk, "A Proposed Quantum Well Injection Transit Time Device (QWITT)," Second Topical Meeting on Picosecond Electronics and Optoelectronics, Jan., 1987.

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C. W. Farley, "RHEED Studies of Principal Streak Intensity Profiles and Adatom Coverage of MBE GaAs," 8th Molecular Beam Epitaxy Workshop, Los Angeles CA, September 9-11, 1987.

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V.P. Kesan, "Power-optimized design of quantum well oscillators," to be presented at the 1987 IEEE International Electron Devices Meeting, Dec. 6-9, 1987.

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

NONE

V. GRANTS AND CONTRACTS

National Science Foundation Grant ECS 8420002, "Studies of Ion Implanted Multilayer Heterostructures," Professor B. G. Streetman, Principal Investigator.

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

(Page 9, Res. Unit SSE87-2, "Molecular Beam Epitaxy with High Speed Device Applications")

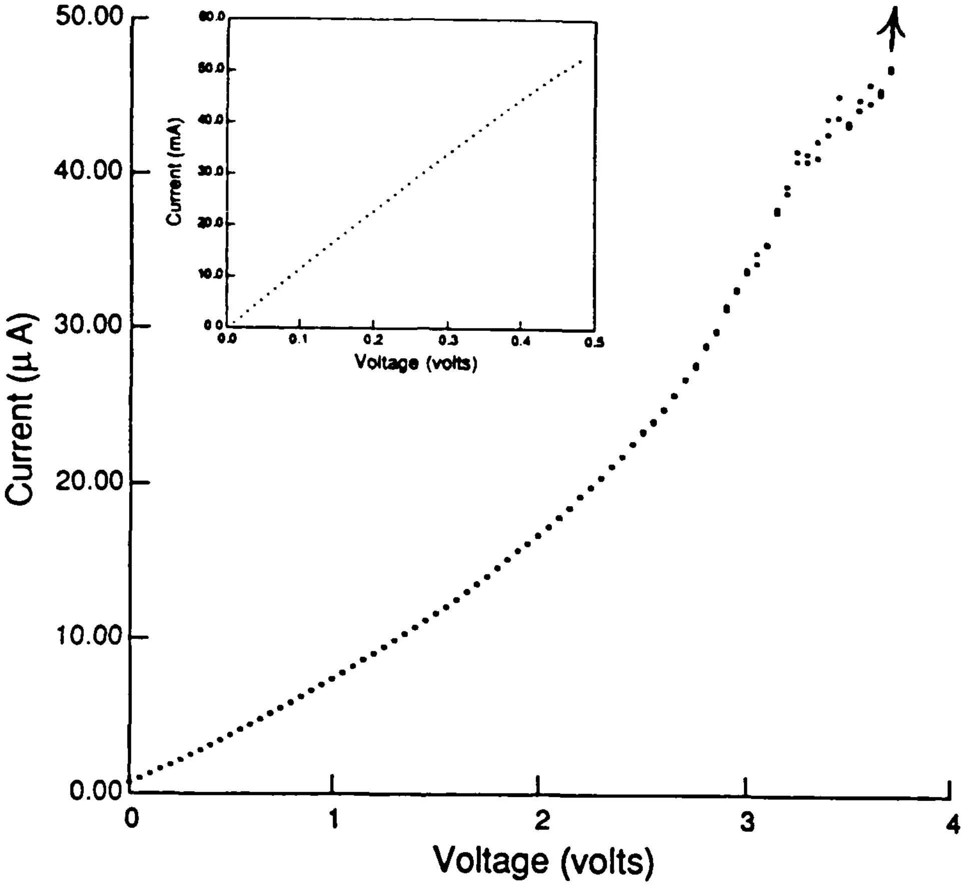

Figure 2: Continuous dc I-V curves for a 50Å AlAs single-barrier sample (with ohmic contacts), showing distinct switching froma high impedance (~ 10-20kΩ) mode to a low impedance (~ 10Ω) mode.

Arrow indicates point at which switching occured; inset illustrates that when the I-V curve was repeated, for small bias voltages, the device had been switched into a persistent low impedance mode.

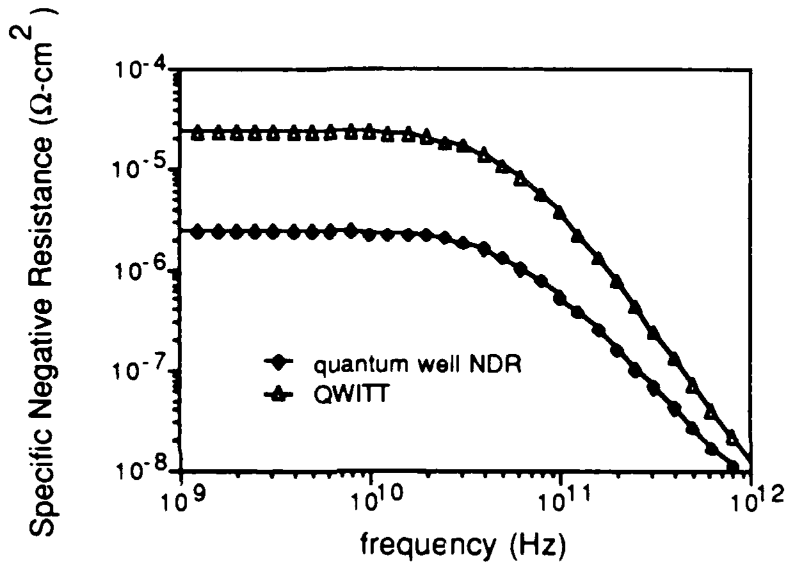

Figure 4: Calculated small signal specific negative resistance for a bare quantum well (due to its negative differential resistance, or NDR) and a QWITT diode, which combines a quantum well and a transit time region.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE87-3 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 nearly completed our new (NSF funded) beamline and endstation that will be installed at port U-16C 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 silicide epitaxy (which will be incorporated into the beamline facility) will place our group again in a competitive position in the field of silicon 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 laterial 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 a 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 that can now be dedicated to the femtosecond photoemission project, and will be used to perform tests and preliminary experiments on image states at Ag(100) surfaces.

D. FOLLOW-UP STATEMENT: We expect to have our new beamline set up at Brookhaven National Laboratory and in operation by June 1988. We will then be able to initiate a leading edge research program involving epitaxial growth studies on Si, and silicide nucleation and growth. In the meantime, efforts will be continued on the two new projects initiated under JSEP sponsorship. One project has already yielded important new results in the field of thin film magnetism, and the second project should soon be yielding results bearing on the feasibility of studying hot electron transport by femtosecond two-photon photoemission spectroscopy.

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IV. LIST OF THESES AND DISSERTATIONS

(None 1987)

V. CONTRACTS AND GRANTS

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

National Science Foundation DMR-87-02848, "Experimental Studies of Intrinsic Surface Electronic and Magnetic Properties," Dr. J.L. Erskine, Principal Investigator, 1987-1989.

National Science Foundation DMR-86-03304, "Fundamental Studies of Magnetic Materials," Dr. J.L. Erskine, Principal Investigator, 1986-1988.

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

Air Force Office of Scientific Research 86-0085, "Advanced Electron Optics for Surface Vibration Spectroscopy," Dr. J.L. Erskine, Principal Investigator, 1986-1987.

Joint Services Electronic Program, "Epitaxial Growth, Structure and Electronic Properties," 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 SSE87-4: FEMTOSECOND PROCESSES IN CONDENSED MATTER

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

Graduate Students: Glenn Focht, David H. Reitze, Paul Williams

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

B. PROGRESS: During the second year of JSEP funding, progress has centered on completion of the basic femtosecond laser experimental facility, development of new methods of femtosecond pulse generation, and results on first experiments, as summarized below.

Advances in Femtosecond Pulse Generation: Completion of the basic femtosecond source laser, based on the cw pumped colliding pulse mode-locking concept [1], was reported last year. During the second year, two complementary amplifier systems, essential to the main thrust of the JSEP work, have also been completed. A 5 KHz repetition rate amplifier system based on a copper vapor laser pump source [2] has been completed, and has yielded pulses of less than 100 fsec. duration at energies as high as 7 microjoules through two amplification stages, with less than 10 % amplified spontaneous emission (ASE). Efficient frequency conversion by white light continuum generation has also been demonstrated. For its first application, this system has been dedicated to time-resolved photodisplacement spectroscopy of carrier dynamics in silicon and germanium, as described more fully below.

A second amplifier system, which achieves millijoule pulse energies at a 10 Hz repetition rate using a frequency doubled Nd: YAG laser pump source [3], has also been completed. For the final (fourth) amplification stage, we have introduced a novel gain cell based on a conical "axicon" geometry proposed by Schafer [4]. In this cell, preamplified femtosecond pulses from the first three amplification stages are expanded to 1 cm. diameter and injected into the gain region, an 8 cm. long cylindrical flow cell containing Rhodamine 640, centered on the axis of a glass cone. Incident to the base of the cone and expanded to match its 8 cm. radius, counter-propagating 532 nm. pump pulses internally reflect from the sides and enter the cylindrical gain medium at radial incidence, thereby maximizing pump absorption efficiency compared to other pumping geometries. The predicted advantages [4] of the new design over conventional gain cells [5] are more efficient amplification and improved cross sectional beam profile, allowing tighter focussing and thus higher peak intensity. With our system we have made the first quantitative measurements of the experimental performance characteristics of such a gain cell [6]. Specifically we obtain typical output powers of 0.5 mJ/pulse with 5% ASE after one pass and 1.0 to 1.5 mJ./pulse with 10% ASE after two passes, a modest improvement over conventional geometries. More importantly, we have observed a good Gaussian gain profile at high-speed devices. Our program is focussing on two novel experimental techniques designed to extract new types of information about femtosecond carrier scattering processes, particularly information concerning the evolving *momentum* distribution of hot carriers.

The first technique, with which we have now obtained initial experimental results [14] , is time-resolved photodisplacement spectroscopy, described in the original proposal, which we use to study the dynamics of photostriction and light induced heating in silicon and germanium. This technique makes use of the lattice volume changes which accompany photoexcitation of semiconductors, which can be caused by electronic photostriction or by thermal expansion. Such volume changes are detected by measuring the angular deflection of a probe laser pulse from a "bump" or depression on the surface of the sample induced by photoexcitation by a much stronger pump pulse [15]. On short time scales (<10 psec.) photoexcitation of electrons induces a volume rescaling due to strain on the crystal created by occupation of conduction band levels [16]. This volume change, or photostriction, can be positive or negative depending on the particular conduction band valley which is occupied. On longer time scales (>50 psec.) energy is transferred into acoustic phonon branches, causing thermal lattice expansion.

Our initial results with silicon [14] show that photostriction can occur on a subpicosecond time scale. Dependence of the sign of this signal on conduction band valley occupation provides a potentially valuable diagnostic of intervalley scattering processes. For example, our results show that silicon initially expands following photoexcitation, then begins contracting after approximately one picosecond. We interpret this sequence as the relaxation of initially hot electrons, which induce expansion, into the X valley minimum, inducing contraction [16]. On longer time scales, thermal expansion is observed as expected. The maximum signals observed correspond to surface bulges or depressions of only 0.5 Å. While these initial results are promising, further measurements with systematically varied excitation conditions and on other semiconductors are required to reach a full understanding. Deeper theoretical understanding of the temporal response of photostriction should also be pursued. Extensions of the technique to other problems, such as melting and ablation dynamics of semiconductors at higher excitation levels, or electron solvation dynamics in liquids, suggest a rich field of potential applications.

Our second new technique is femtosecond angle-resolved ultraviolet photoemission spectroscopy (ARUPS), described in detail in last year's annual report, which we are conducting with collaboration from Professor J. L. Erskine (Research Unit SSE86-3). In this technique an intense femtosecond excitation pulse from our 10 Hz amplifier system is first absorbed by the sample, creating a hot electron distribution. Time evolution of the hot electrons is probed by optically delaying the arrival of an ultraviolet pulse, which photoemits electrons from the transient hot carrier population into an ultrahigh vacuum environment. Intraband relaxation effects are manifested in changes in the energy distribution curves and angular pattern of the photoemitted electrons. Measurement of the kinetic energy and angular distribution of a photoelectron can be used to determine the energy and crystal momentum prior to the photoemission event. This capability of ARUPS results from conservation of energy (the Einstein relation for the photoelectric effect) and conservation of electron wavevector (**k**) parallel to the surface, plus dipole selection rules which govern optically induced interband transitions [17].

Preliminary non-time-resolved measurements of detection sensitivity, described last year, were made using an ultrahigh vacuum chamber and detection system loaned by Erskine. Since this chamber was required for other experiments in Erskine's program, we have devoted most of the past year, while completion of our 10 Hz amplifier system was in progress, to constructing, outfitting, and testing a new chamber which could be permanently dedicated to this experiment. This process is now near completion. Significant properties of the new chamber are: baseline pressure < 10^{-9} torr, argon sputtering and thermal annealing for surface preparation, retarding Auger electron and low energy electron diffraction (LEED) for surface diagnostics. For initial

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IV. LIST OF THESES AND DISSERTATIONS

NONE

V. CONTRACTS AND GRANTS

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

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

IBM Faculty Development Award, M. C. Downer

III. QUANTUM ELECTRONICS

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

Research Unit QE 87-1 NONLINEAR OPTICAL INTERACTIONS

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

Graduate Students: R. J. Brecha, M. G. Raizen, Min Xiao, L. A. Orozco, L. A. Wu, W. David Lee, Heung Choo, Silvania Pereira

A. RESEARCH OBJECTIVES: The objective of this research unit is to obtain a detailed description of the nonlinear oscillatory behavior of certain optical systems. The investigation of the time-dependent steady-states has provided many challenges in optical physics in recent years because of the rich variety of phenomena that are observed. Indeed, the field has been one of the most active areas of research in optical physics (1-7). Of special interest are those 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 characterizes our research and which makes our experiments prototypes for a large class of nonlinear optical systems.

More specifically, we are conducting two different experiments, each of which couples a nonlinear medium to a single-mode of 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 is our objective to obtain detailed quantitative information about the new oscillatory states that arise and to make first principles comparisons between theory and experiment. We are exploring 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 also are studying 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: Over the past two years of the current JSEP contract, we have concentrated on the construction of the necessary pieces of apparatus, the observation of dynamical instability, the quantitative comparison of our measurements with theory, and modifications in the apparatus as dictated by these investigations. In the following two sections, we outline the progress over the past year made in our studies of dynamic instability in optical bistability and in harmonic conversion.

1. Optical Bistability - Over recent years we have conducted an investigation of the time-independent steady states in both absorptive (8) and dispersive bistability (9) in order to lay a foundation for our work on the time-dependent steady states. We have demonstrated quantitative agreement between our observations and the theoretical predictions of the single-Gaussian-mode model of optical bistability (10-13) for the time-independent steady-states. The significance of this work relates to both the fundamental nature of the investigations and to the potential applications to such areas as optical signal processing. We have intended our work to

Xenon gas is used between the crystal and cavity mirrors to adjust the phases of fundamental and harmonic fields in order to optimize conversion efficiency. This circumstance is not peculiar to our experiment but is a feature of nonlinear processes in general. We have addressed the question of interference effects in second harmonic generation in our work (21).

With the current experiment, we have observed signatures of dispersive bistability as the detuning of the cavity is swept for a constant injected field. There is clearly an appreciable conversion of the intracavity field at frequency ω_1 to the harmonic field at frequency $2\omega_1$. Indeed this conversion should result in the appearance of instability. However , we have yet to observe dynamic instability after repeated attempts with several experimental arrangements involving different mirror coatings and nonlinear crystals. A continuing problem appears to be an inability to reduce the intracavity losses γ_2 at the harmonic frequency ω_2 relative to the losses γ_1 at the fundamental frequency $\omega_1 = \omega_2/2$. Since the threshold for instability increases as the cube of the ratio γ_2/γ_1, high pump powers are required to observe self oscillation. However, even for the very small intracavity losses at ω_1 (per pass intensity loss of 7×10^{-3}), and at ω_2 (per pass intensity loss of 2×10^{-2}), thermal processes associated with bulk absorption lead to an upper limit on the allowed pump power. We stress that the difficulty is not one of nonlinear conversion efficiency, but rather is associated with the disparity of time scales of the two photon reserviors at ω_2 and ω_1.

C. <u>FOLLOW UP STATEMENT</u>: The research on both dynamic instabilities in optical bistability and harmonic conversion is continuing. The program of future work includes an investigation of the role of quantum fluctuations in optical bistability. We have constructed a "small" bistable system (cavity length $\cong$ 800 μm) which has a saturation photon number $N_s \lesssim 10$. Since quantum fluctuations scale as roughly $1/N_s$, we should be able to investigate questions such as the intrinsic linewidth for dynamic instabilities due to intrinsic quantum fluctuations. As well, the small cavity moves us into a domain of increased cavity damping rate K relative to the atomic decay rate γ, where our numerical work indicates a rather dramatic growth in the size of the instability domains. (Our previous work was carried out for $K/\gamma \cong 0.5$, while in our new cavity, $K/\gamma \cong 14$). Our effort in the frequency doubling experiment is directed toward obtaining new crystals with improved dielectric coatings. We have just received new samples of KTP that exhibit very low loss at both ω_1 and ω_2 in our preliminary measurements. The crystals are now being polished and antireflection coated to provide a matched pair. Additionally, a completely new resonator structure has been constructed for the experiments. This new apparatus allows us to control precisely the cavity confocal parameter relative to the crystal length to optimize the coupling between the modes at frequencies ω_2 and ω_1. In the coming year, a visiting scholar (Professor K-C. Peng) will join our group to enter into these experiments. Professor Peng has considerable expertise in the area of nonlinear optics required for these experiments.

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II. LIST OF CONFERENCE PROCEEDINGS (*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 Proceedings of the NATO Advanced Studies Institute, (Il Ciocco, Italy, June 28 - July 7, 1987)

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

H.J. Kimble, "Squeezed States of Light", invited talk, ATT Bell Laboratories, Murray Hill, New Jersey, (January 6, 1987).

H.J. Kimble, "Squeezed States of Light", invited talk, Atomic Physics Colloquium, National Bureau of Standards, Gaithersburg, Maryland, (January 8, 1987).

H.J. Kimble, "Squeezed States of Light", invited talk, Yale University, New Haven, Connecticut, (January 29-31, 1987).

H.J. Kimble, "Squeezed States of Light", invited talk, Venture Research Conference, British Petroleum Company of North America, London, England, (June 23-24, 1987).

*A.T. Rosenberger, L.A. Orozco and H.J. Kimble, "Experimental Investigation of the Single-Mode Instability in Optical Bistability", invited paper presented at Annual Meeting of the NATO Advanced Study Institute, Lucca, Italy, (June 28-July 7, 1987).

H.J. Kimble, "Squeezed States of Light", invited talk, Atomic-Physics 1987 Gordon Research Conference, Brewster Academy, Wolfboro, New Hampshire, (July 6-10, 1987).

H. J. Kimble, "Squeezed State Generation in Three Simple Systems", invited talk at US/Japan Seminar on Quantum Mechanical Aspects of Quantum Electronics, Monterey, California, (July 21-24, 1987).

M.G. Raizen, Min Xiao, "Squeezed States of Light: Generation and Application", invited talk at Non-Linear Optics and Lasers Gordon Conference, Brewster Academy, Wolfboro, New Hampshire, (July 27-31, 1987).

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H.J. Kimble, "Squeezed States of Light", invited talk, Rice University, Houston, Texas, (September 30, 1987).

Min Xiao, H.J. Kimble, and H.J. Carmichael, "Squeezed State Generation for Two-Level Atoms in a Spatially Varying Field Mode", invited talk, Annual Meeting, Optical Society of America, Rochester, New York, (October 19-23, 1987).

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

*Luis A. Orozco, Ph.D., August, 1987, "Optical Bistability with Two-Level Atoms".

*Ling-An Wu, Ph.D., August, 1987, "Squeezed States of Light from an Optical Parametric Oscillator

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE87-2. 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: Few accurate experiments investigating the reactions of ions exist at high densities because of the lack of a suitable probe. This lack of a suitable diagnostic has effectively prevented an accurate understanding of the ion processes in high-pressure, gas-dynamic lasers such as the rare-gas halogen lasers.We have been studying the use of coherent Raman spectroscopy as a dynamic probe of ion processes in laser plasmas operating at high pressures. Coherent Raman spectroscopy (CRS) holds promise of high sensitivity combined with good temporal and spectral resolution. CRS has the advantages over spontaneous spectroscopy in that it is insensitive to the fluorescence of the plasma. We were first attracted to the use of CRS for this application by early work by Taran[1] using Coherent Antistokes Raman Spectroscopy (CARS) to observe small densities of H_2 in N_2.

In coherent Raman spectroscopy, two lasers--often named the pump and probe laser-- are focussed either colinearly or counter propagating onto a gas target. The third order susceptibility induced by the pump laser produces gain of the probe laser. In CARS, two waves from the pump beam combine with the probe to generate gain at the antistokes frequency. That the third-order susceptibility displays resonance behavior for Raman transitions allows the use of this technique as a probe of the vibrational and rotational properties of samples. Both techniques have sufficient sensitivity to observe scattering from ion densities of 10^{14} cm^{-3}; but experimentally require all aspects to be optimized.

Many of the important developments in the study of high resolution Raman spectra of gases have been originated by Owyoung[2]. He has developed the most sensitive spectrometer to date. In his experiments, Owyoung used a quasi-c.w. laser as the probe laser. Gain of the probe laser was then produced by a 10 nsec, high-power dye laser. The quasi-c.w. probe power is limited by the c.w. saturation current of the photodector to approximately 250 mW. The signal-to-noise is then limited by fluctuations in the number of photons incident on the detector during the 10 nsec gain pulse.

The difficulty in Raman gain spectroscopy is trying to measure a small change in the large probe laser intensity. This problem is reminiscent of early experiments in saturation spectroscopy by Hansch; he solved the problem by using polarization techniques[3]. In the field of nonlinear Raman spectroscopy, polarized gain or loss specroscopy has been named RIKES (Raman induced Kerr effect spectroscopy) by Levenson[4]. We have concentrated on improving the sensitivity of RIKES as a probe for studying the spectra and reactions of molecular ions at high pressures.

B. PROGRESS: In RIKES a highly polarized probe laser is crossed with a high power pump laser in the sample. The probe laser then travels through a crossed polarizer onto the detector. When the pump and probe lasers are in resonance with the sample, induced birefringence generates a component in the probe of opposite polarization which is transmitted by the polarizer at the detector. The birefringence signal is then observed on a "black" background by the detector (see Fig. 1).

A judicious choice of the polarization of the pump laser will dramatically improve the sensitivity of this technique. A major noise source for many nonlinear Raman techniques is nonresonant contributions from the sample, be they from the solvent, background gases, or even the species of interest. The polarizations of the two lasers are critical parameters in the interaction of the two beams through the third-order susceptibility. In general, the RIKES signal may be written the birefringence in the polarizers as well as intervening optics. The fluctuations in this expression are represented by the ε terms and may be separated for clarity:

$$P_{noise}=\langle P_1\rangle\left[\delta\varepsilon_1+\sigma_{NR}\left(\varepsilon_1+\varepsilon_2^2\varepsilon_1+\varepsilon_2^2+2\varepsilon_2+2\varepsilon_1\varepsilon_2\right)\right]. \qquad (6)$$

The reduction of this noise by reducing σ_{NR} has been dicussed above. The noise contribution due to birefringence can be minimized by placing polarization compensaters in the beam in order to reduce delta.

The noise may be reduced further if a fraction of the probe laser $P_{sub}=\beta\langle P_1\rangle(1+\varepsilon'_1)$, where β is an experimentally determined factor, can be subtracted from Eq. 6. Then, the noise will decrease to the extent that $\varepsilon_1=\varepsilon'_1$.

$$P_{noise}=K\langle P_1\rangle\left[(\delta\varepsilon_1-\beta\varepsilon_1')+\sigma_{NR}\left(\varepsilon_1+\varepsilon_2^2\varepsilon_1+\varepsilon_2^2+2\varepsilon_2+2\varepsilon_1\varepsilon_2\right)\right]. \qquad (7)$$

The factor β is determined by minimizing this expression once σ_{NR} is made as small as possible. The difficulty is that small changes in the intensity of a short (10 nsec), pulsed probe laser must be measured.[6]

This subtraction can be performed by measuring the probe beam intensity before and after the sample chamber. Care must be taken to make the two light paths as identical as possible (Fig. 1). The laser pulses are measured by EG&G FND-100 photodiodes which prove to be fast enough to accurately reproduce the pulses. The photodiodes as well are as identical as possible, being produced from adjacent sites from an original silicon wafer. The subtraction of the laser pulses is performed as soon as possible after detection by the photodiodes. The circuit employed for this subtraction is shown in Fig. 2. In an ideal set-up where there are no optical elements in either light path, subtraction to within a factor of 3 of the quantum noise limit has been achieved. In the actual experimental conditions, at least the sample cell must be in one beam and not the other. Typically, an experiment is run with a subtraction 10 to 15 times worse than the ideal alignment. Nonetheless, the subtraction decreases P_{sub} by a factor of 100. Fig. 3a. shows a spectrum of 0.011 M C_6H_6 in CCl_4 taken without the subtracting beam, which should be compared to Fig. 3b which shows what this subtraction can do under the same experimental conditions.

The standard used to compare the sensitivities of nonlinear Raman techniques is the ability to measure the 992 cm Raman mode of C_6H_6 diluted in CCl_4. The best RIKE spectra to date were taken by Eesley [7]. In the detection limit (S/N equal to 2), he was able to see a signal from a 0.1 M solution of C_6H_6. Using a variation of the RIKE called Optically-HeteroDyned (OHD)-RIKE, he saw the 992 cm line of C_6H_6 in a 0.1 M solution with a S/N of 10. Fig. 4. presents a spectrum of 0.0092 M C_6H_6 in CCl_4 obtained with the spectrometer described herein. This concentration corresponds to a density of scatterers of 900 ppm.

C. <u>FOLLOW-UP STATEMENT</u>: This work is continuing under joint services support. We propose to continue to investigate the use of coherent Raman scattering as a probe of molecular ions in high pressure discharges. As described in the progress section , we have developed technology for measuring small gains in a pulsed probe laser. This technique has been combined with polarization techniques to obtain improved sensitivity for Raman gain spectroscopy. It is now feasible to obtain Raman spectra for partical densities as low as 10^{13} cm^{-3}. We have obtained Raman spectra of solutions of NaOH, NH_4OH, and KOH in water in the vicinity of the OH^- resonance. By observing the change in the spectra with concentration we are currently able to study the solvation of OH^- in water. These

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

M. R. Bruce, Enno Meyer, W. B. Layne, and J. W. Keto, "Reactive Quenching by Cl_2 of Xenon Atoms Excited by Two-Photon Absorption", 18th meeting, Div. Atomic, Molecular, and Opt. Phys. of the Am. Phys. Soc. , Boston ,1987; Bull. Am. Phys. Soc. **36**, 1276 (1987).

M. R. Bruce, W. B. Layne, and J. W. Keto, "Harpoon Model for Reactive Quenching of Xe $5p^5 6p$ by Cl_2", 18th meeting, Div. Atomic, Molecular, and Opt. Phys. of the Am. Phys. Soc., Boston, 1987; Bull. Am. Phys. Soc. **36**, 1276 (1987).

J. W. Keto, "Dynamics of Atomic Interactions using lasers", Physics Colloquium, Univ. of Texas at Austin, Austin, Tx., Sept. 1987.

J. W. Keto, "Bombardment of Surfaces by Swift (1-20 eV) Atoms", Physics Seminar, Univ. of Texas at Austin, Austin, Tx, Oct. 1987.

IV. LIST OF THESES OR DISSERTATIONS

None

V. GRANTS OR CONTRACTS

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

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

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

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

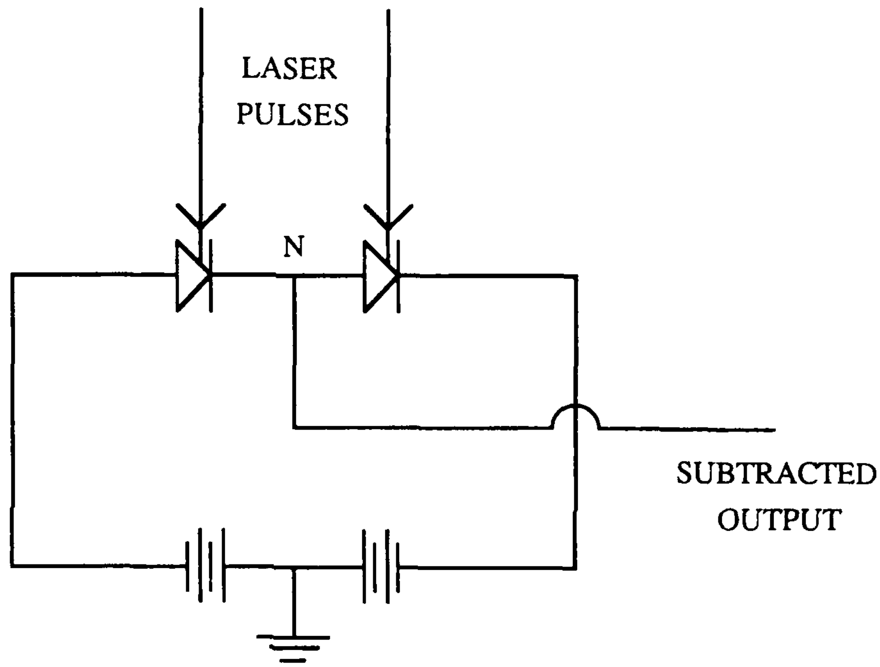

Figure 2. Photodiode bridge circuit. Subtraction occurs at N.

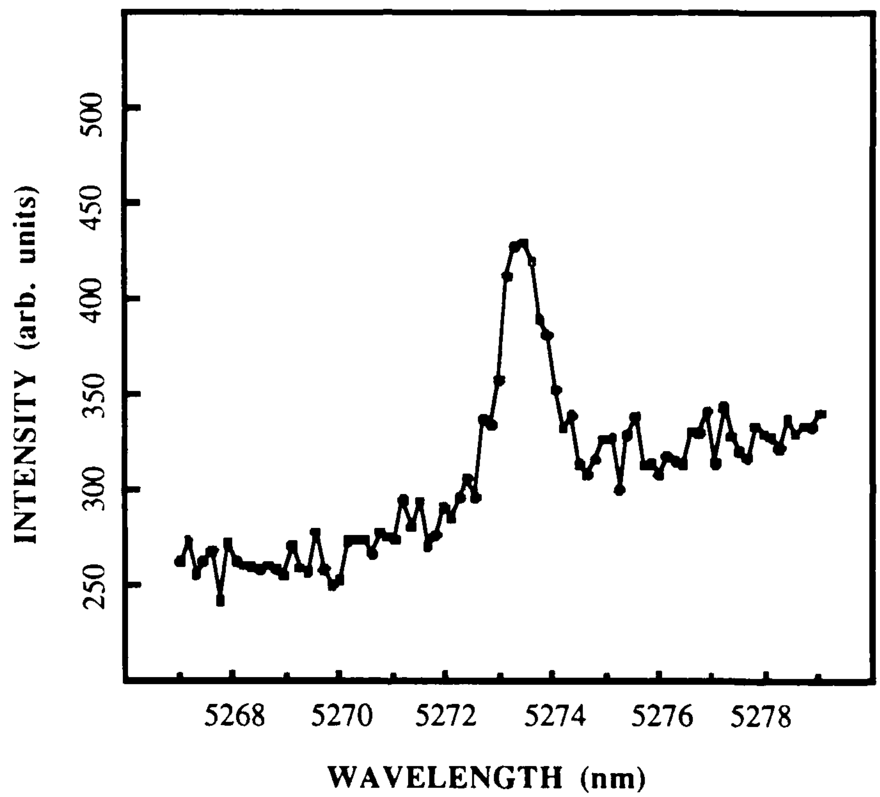

Figure 4. b. Subtracted RIKE spectrum of 0.0092 M C_6H_6 in CCl_4. Each point is an average of 500 laser pulses.

IV. ELECTROMAGNETICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM87 -1 MILLIMETER-WAVE MONOLITHIC ARRAY COMPONENTS

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

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

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

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

The first accomplishment during this period was a modification of the quasi-optical receiver with a Gunn diode local oscillator fabricated on a high permittivity substrate. This substrate, called Epsilam-10, has a relative permittivity of 10 and is used for simulating the receiver structure to be fabricated on a GaAs substrate required for possible monolithio integration. The basic circuit topology of this quasi-optical integrated receiver is identical to the one reported in the previous period. As shown in Fig.1, a Gunn diode local oscillator feeds two mixer diodes in a coupled slot antenna with opposite phase, while these diodes receives an incoming free space RF signal in phase. Hence, balanced mixing takes place. A receiver of this type is characterized by the isotropic conversion loss, which is the ratio of the down converted IF frequency power to the RF power that would be received by an ideal isotropic antenna . Thus, this indicates the combined effect of the antenna gain and the mixer conversion loss. Use of the isotropic conversion loss is necessary because no accessible measurement port exists between the mixer and antenna The isotropic conversion loss obtained in this modeling experiment is about 5 dB for a local oscillator frequency of 9.45 GHz and an RF frequency of 10 GHz. The 3 dB bandwidth is more than 0.2 GHz. These results have been reported at the International Microwave Symposium [1].

3. V. D. Hwang, T. Uwano and T. Itoh, "A Planar Integrated Antenna and Receiver Front End," IEEE Trans. Microwave Theory and Techniques, Vol. 36, No.1, January 1988.

4. R. L. Rogers, D. P. Neikirk and H. Ling, "Planar Matching of Antennas on Electrically Thick Dielectric Substrates," The 12th International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, Dec. 14-18, 1987.

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

Q. Zhang and T. Itoh,"Spectral Domain Analysis of Scattering from E-plane Circuit Elements," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-35, No. 2, pp. 138-150, (February 1987).

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B. Young and T. Itoh, "Effects of Insulating Dielectric Layers in Millimeter-Wave Planar Transmission Lines," 17th European Microwave Conference, pp. 687-692, Rome, Italy (Sept. 7-11, 1987).

*V. D. Wang and T. Itoh, "An Integrated Antenna-Mixer and MESFET Local Oscillator Circuit," 17th European Microwave Conference, pp. 853-858, Rome, Italy, (Sept. 7-11, 1987).

Q. Zhang and T. Itoh, "Analysis and Design of Evanescent Mode Waveguide Filter with Non-Touching E-Plane Fins," 17th European Microwave Conference, pp. 1032-1037, Rome, Italy, (Sept. 7-11, 1987).

P. Cheung, D. P. Neikirk and T. Itoh, "Experimental Performance of an Optically Controlled Coplanar Waveguide Phase Shifter," 12th International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, (Dec. 14-18, 1987).

H. Y. Lee, T. H. Wang and T. Itoh, "Crosstie Overlay Slow-Wave Structure for Broad-Band Traveling-Wave Electrooptical Modulators", 12th International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, (Dec. 14-18, 1987).

Y.-D. Lin, D. P. Neikirk and T. Itoh, "Periodically Illuminated CPW Phase Shifter," 12th International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, (Dec. 14-18, 1987).

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

C.-K.C. Tzuang, D. Miller, T.-H. Wang, D. P. Neikirk, T. Itoh, P. Williams and M. Downer, "Picosecond Responses of an Optically Controlled Millimeter Wave Phase Shjifter," Topical Meeting on Picosecond Electronics and Optoelectronics, Lake Tahoe, NV, (January 14-16, 1987).

*T. Itoh, "Recent Advances in Quasi-Optical Planar Structures," (Invited) Melecon '87, Rome, Italy, (March 24-26, 1987).

T. H. Wang and T. Itoh, "Compact Grating for Applications to Filters and REsonators for Monolithic Microwave Integrated Circuits," 1987 IEEE MTT-S International Microwave Symposium, Las Vegas, NV, (June 9-11, 1987).

C. Zhang and T. Itoh, "Analysis and Design of Evanescent Mode Waveguide Filter with Non-Touching E-Plane Fins," 17th European Microwave Conference, pp. 1032-1037, Rome, Italy,(Sept. 7-11, 1987).

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Y.-D. Lin, D. P. Neikirk and T. Itoh, "Periodically Illuminated CPW Phase Shifter," 12th International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, (Dec. 14-18, 1987).

T. Itoh, "Millimeter Wave Transmission Lines," Millimeter Wave Workshop, National Chiao Tung University, Hsinchu, Taiwan, (April 16, 1987).

T. Itoh, "Millimeter-Wave Research Trend," UNIDEN Corp., Ichikawa, Japan, (April 20, 1987).

T. Itoh, "Recent Trends in Millimeter Wave Research," Tohoku Chapter of Institute of Electronics, Information and Communication Engineers, Sendai, Japan, (April 22, 1987).

*T. Itoh, "Recent Advances in Quasi-Optical Microwave and Millimeter-Wave Integrated Circuits," Joint Meeting of IEEE MTT-S Tokyo Chaper and Group on Microwave Techniques of Institute of Electronics, Information and Communication Engineers,Tokyo, Japan, (April 24, 1987).

T. Itoh, "Millimeter Wave Integrated Circuits," U.S. Army Electronics Research Strategy Planning Workshop, Quail Roost, NC, (May 4-6, 1987).

T. Itoh, "2D and 3D Electromagnetic Models at Frequencies above 5GHz," DARPA Meeting on Electromagnetic Simulations, Packaging and Measurement of High-Speed Devices, San Diego, CA, (July 13-15, 1987).

T. Itoh, "Millimeter Wave Research at The University of Texas at Austin," UCLA Electrical Engineering Seminar, Los Angeles, CA, (July 16, 1987).

T. Itoh, "Millimeter Wave Research at The University of Texas at Austin," University of California, Berkely, Electrical Engineering Seminar, Berkely, CA, (July 17, 1987).

*T. Itoh, "Recent Development of Planar an Quasi-Planar Millimeter-Wave Components," IEEE Middle and South Italy Chapter of MTT-S, University of Palermo, Palermo, Italy, (September 11, 1987).

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.

THE UNIVERSITY OF TEXAS AT AUSTIN — ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM87-2 NONLINEAR WAVE PHENOMENA

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

Graduate Student: C.K. An

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

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

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

B. PROGRESS: During the twelve month period covered by this report we have focussed on the first two sub-objectives mentioned above, namely, the measurement of nonlinear transfer functions for non-Gaussian inputs, and the determination of complex three-wave coupling

C. FOLLOW-UP STATEMENT: This work is continuing. The primary focus in the next year will deal with sub-objective (3) mentioned in Sec. A, namely, the experimental measurement of energy cascading associated with three-wave interactions in a fluctuation spectrum.

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. *Ch.P. Ritz, D.L. Brower, T.L. Rhodes, Roger D. Bengtson, S.J. Levinson, N.C. Luhmann, Jr., W.A. Peebles and E.J. Powers, "Characterization of Tokamak Edge Turbulence by Far-Infrared Laser Scattering and Langmuir Probes," Nuclear Fusion 27, (1987), 1125.

2. *Ch.P. Ritz, R.V. Bravenec, Roger D. Bengtson, K.W. Gentle, C.C. Klepper, P.E. Phillips, E.J. Powers, T.L. Rhodes, B. Richards, W.L. Rowan and A.J. Wootton, "Edge Diagnostics and Transport in the TEXT Tokamak," J. Nucl. Mater. 145-147 (1987) 241.

3. *F.L. Jones, C.P. Ritz, R.W. Miksad, E.J. Powers and R.S. Solis, "Measurements of the Local Wavenumber and Frequency Spectrum in a Plane Wake," accepted for publication in J. of Experiments in Fluids.

4. *K.I. Kim, E.J. Powers, Ch.P. Ritz, R.W. Miksad and F.J. Fischer, "Modelling of Nonlinear Drift Oscillations of Moored Vessels Subject to Non-Gaussian Random Sea Wave Excitation," accepted for publication in IEEE Journal of Oceanic Engineering (1987).

5. *R.W. Miksad, F.L. Jones, C.P. Ritz and E.J. Powers, "The Role of Nonlinear Wave-Wave Interactions in Laminar-Turbulent Transition," accepted for publication by Archives of Mechanics, Polish Academy of Sciences (1986).

6. *R.D. Bengtson, R.V. Bravenec, D.L. Brower, P.H. Diamond, K.W. Gentle, C.C. Klepper, N.C. Luhmann, Jr., W.A. Peebles, P.E. Phillips, E.J. Powers, T.L. Rhodes, B. Richards, Ch.P. Ritz, W.L. Rowan and A.J. Wootton, "Fluctuations and Transport Measurements in the TEXT Tokamak," in "Proceedings of the Conference on Small-Scale Turbulence and Anomalous Transport in Magnetized Plasmas" (Cargese, Corsica) by Les Editions de Physique (1986) 121.

7. *Ch.P. Ritz, E.J. Powers, R.W. Miksad, and R.S. Solis, "Nonlinear Spectral Dynamics of a Transitioning Flow", to be submitted to Physics of Fluids.

8. *Ch.P. Ritz, and E.J. Powers, "Experimental Study of Wave-Wave Coupling and Energy Cascading" to be submitted to Physica D "Nonlinear Phenomena."

CONSULTATIVE AND ADVISORY FUNCTIONS

CONSULTATIVE AND ADVISORY FUNCTIONS

Paul MacGrath, with the National Security Agency, visited Dr. Jeff Kimble on January 8, 1987 to discuss squeezed states research.

Dr. J.L Erskine visited with Dr. Peter Johnson, Physics Department, Brrokhaven National Laboratory January 27-30 and again March 20-21, 1987 to discuss the beamline U5 project.

Dr. J.K. Aggarwal was an invited participant at the National Science Foundation Workshop on Multisensor Integration, at Snowbird, Utah, February 4-7, 1987.

J.K. Aggarwal served as a member of the National Science Foundation Panel on Engineering Equipment Awards, Washington, D.C., March 25, 1987.

On May 3-6, 1987, Dr. Itoh participated in the U.S. Army Electronics Research Strategy Workshop held at Quail Roost, NC as an invited speaker and a panel member to identify millimeter-wave and electromagnetic research areas important to the Army.

On May 5-6, 1987, Dr. Edward J. Powers attended, participated in and presented a paper entitled "Measurement of Nonlinear Transfer Functions for Fluid-Structure Interaction," at the Office of Naval Research Structure-Fluid Interaction Workshop, Bethesda, Maryland.

Dr. Gary Prinz, Naval Research Labs, visited Dr. Jim Erskine May 12-13, 1987, to discuss a joint project involving thin film magnetism.

Dr. J.L Erskine visited with Drs. Dan Pierce and Bob Celotta of the National Bureau of Standards May 16-17, 1987, to discuss a joint project involving thin films magnetism.

On May 18, 1987, Dr. Erskine visited Dr. Gary Prinz at Naval Research Lab to discuss a joint project on molecular beam epitaxy system.

On July 13-15, 1987, T. Itoh participated in a DARPA Workshop on Electromagnetic Simulations, Packaging and Measurements of High-Speed Devices organized by the Materials Research Council. Prof. Itoh presented an invited talk on "2D and 3D Electromagnetic Models at Frequencies above 5 GHz."

J.K. Aggarwal was a member of the Workshop on Human Processing of Computer-Aided Target Images Sponsored by the Committee on Vision of National Research Council, July 16-17, 1987.

Dr. Aggarwal was Chairman of a Review Panel appointed by the Department of Energy to address Intelligent Machines Research at Oak Ridge National Laboratory, July 30-31, 1987.

Dr. J.K. Aggarwal served as a member of the Army Research Office Panel on Analytical Foundations of Multisensor Fusion, August 5, 1987.

Dr. Neil Shinn, Sandia National Labs, visited with Dr. Erskine August 13-14, 1987, to discuss the U-16C beamline project, a joint project with Brookhaven National Lab.

Dr. H.J. Kimble participated in an invited lecture series on "Squeezed States of Light" hosted by Dr. C.M. Bowden, Department of the Army, United States Army Missile Command, Redstone Arsenal, Alabama, September 1-2, 1987.

NEW DISCOVERIES, INVENTIONS OR PATENT DISCLOSURES

NEW DISCOVERIES, INVENTIONS OR PATENT DISCLOSURES

The quantum well injection transit time (QWITT) diode and arsenic cracker have been reported by Profs. Ben Streetman and Dean Neikirk as invention disclosures for possible patent filing, and is being investigated by The University of Texas System.

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