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I. QUANTUM ELECTRONICS

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I.1 Nonlinear Light Mixing Spectroscopy. H. Lotem, R. T. Lynch, Jr., and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 2.

Complete theoretical expressions have been derived for the complex $\chi^{(3)}$ tensor, describing four wave mixing involving three distinct incident frequencies and the generation of light at a new combination frequency. In general there are 48 terms, which reduce to the usual 24 terms only if certain relationships between the damping constants of various energy levels exist. Similar conclusions were reached independently by a group involving Dr. J. P. Taran in France, and Professor Gustavson of the University of California in Berkeley.

The general case may be specialized to the important case of stimulated resonant Raman scattering. The enhancement of the

generation of anti-Stokes radiation by an intermediate electronic resonance is known as resonant CARS. This topic is experimentally pursued at several laboratories and is of considerable current interest. The line shapes of resonant CARS predicted by our theory compare favorably with experimental data.

The material is described in detail in the Ph. D. thesis of R. T. Lynch, Jr.[1], who is now employed at the IBM research laboratories in Yorktown Heights (N. Y.). It is also the subject of two short papers[2,3] and of review article[4] which was prepared for a volume commemorating the 50th anniversary of the Raman effect. Professor Bloembergen also presented an invited paper on this subject at the 1977 Annual Meeting of the Optical Society of America in Toronto (Canada).

The determination of two-photon absorption cross sections of various organic solvents and their naphthalene solutions, discussed in the previous progress reports, have also appeared in print.[5]

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4. N. Bloembergen, H. Lotem and R. T. Lynch, Jr., "Line Shapes in Coherent Resonant Raman Scattering," Indian Journal of Pure and Applied Physics, March 1978 (Raman Effect Golden Jubilee Issue).

5. R. T. Lynch, Jr. and H. Lotem, "Two-Photon Absorption Measurements in Organic Liquids via Nonlinear Light Mixing Spectroscopy," J. Chem. Phys. 66, 1905 (1977).

I.2 Two-Photon Absorption in Solids With Ruby Pumped Dye Lasers.

H. Lotem and C. B. deAraujo, Contract N00014-75-C-0648 and ARPA Grant F44620-75-C-0088; Research Unit 2.

A new method for the direct calibration of two photon absorption (TPA) coefficients has been developed. The TPA cross section is compared directly with the known Raman cross section of the inverse Raman effect in a liquid such as benzene or cyclohexane. By this method the TPA cross section of CdS, GaP, $SrTiO_3$ and TiO_2 at 31660 cm^{-1} has been determined. Details of the method and the results have been published.[1]

More recently the intensity dependent TPA attenuation as also been compared with the intensity dependent gain due to the stimulated Raman effect. This variation of the previous method has now yielded the TPA cross section at some additional wavelengths. The TPA cross sections in GaP, CdS and ZnSe have now been determined at 3.18 ev, 3.56 ev and 3.91 ev. The results which show interesting spectroscopic features have been compared with several theories of multiphoton absorption in a paper which has been submitted for publication.[2]

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I. 3 Optimal Damage and Photoelectric Emission by Picosecond Light Pulses. P. L. Liu, R. Yen, and N. Bloembergen, Contract N00014-75-C-0648 and NASA Grant NGL22-007-117; Research Unit 3.

A comprehensive paper on laser induced breakdown at green and ultraviolet wavelengths has been published.[1] Work is now in progress on damage in materials which are nonpolar and not-ionic. Preliminary results on electric breakdown at 1.06 μm in diamond suggests that the phenomenon in this material is similar to that in ionic crystals. These results discredit a recently proposed theory by Braunlich et al., in which polarons occurring only in ionic materials would play a decisive role.

A paper has also been published in two-photon induced photoelectric emission[2] from refractory metal surfaces. The effects of thermionic emission caused by surface heating could be eliminated. Good quantitative data on the nonlinear photoelectric emission constant have been obtained for tungsten, molybdenum and tantalum. The nonlinear constant is almost an order of magnitude smaller than obtained in older observations with multimode lasers and longer pulses. The polarization dependence and angular dependence of the nonlinear photocurrent will be studied in detail.

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I.4 Two Photon Absorption and Superbroadening with Picosecond Pulses. P. L. Liu and N. Bloembergen, Contract N00014-75-C-0648, ARPA Grant F44620-75-C-0088 and NASA Grant NGL22-007-117; Research Unit 3.

A comprehensive paper on the superbroadening of self-focused picosecond pulses in water has been published.[1] It has been shown conclusively that the formation of a self-focused filament precedes the occurrence of superbroadening.

Extensive measurements were carried out on two-photon absorption coefficients of ultraviolet window materials. These data are relevant for the operation of high power UV laser systems. The two photon absorption at 355 and 266 nm was determined in fused silica, sapphire, calcium fluoride, harmonic generating crystals KDP and its homologues, and a number of alkali-halides. These results have already been presented in the Final Technical Report of ARPA Order No. 2983, under Contract No. F44620-75-C-0088. A paper based on this material has been accepted for publication in the Physical Review and is scheduled for the May 15, 1978 issue. The results were also presented at the 9th Symposium on Materials for High Power Lasers,[3] in Boulder (Col.), August 1977.

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I.5 Ultrahigh Resolution Two-Photon Spectroscopy in Atomic Vapors.

M. M. Salour, Contract N00014-75-C-0648; Research Unit 2.

The technique of Ramsey interference fringes[1-7] in the optical regime has been improved. The interference of two-photon absorption processes in two laser pulses delayed by a time T can be observed without background from two-photon process in either pulse alone. This is accomplished by switching the phase of the optical field by 90°, so that the two-photon matrix element changes sign. The signals before and after this phase switching are electronically subtracted. These results have been presented at the Third International Conference on Laser Spectroscopy[4] (TICOLS) in Jackson (Wyo.), in July 1977.

The reader interested in further detail is referred to several communications which have already appeared in print.[1-6]

In addition this material constitutes one of the chapters in the Ph. D. thesis of M. M. Salour. He has been appointed as an assistant professor of electrical engineering at the Massachusetts Institute of Technology and is on a leave of absence until September 1978 at the laboratory of Professor Bradley in London. This thesis also describes the spectroscopic results on D-states of sodium, reported in the preceding years, and new results on the highly excited states of neon.[8] The whole thesis has been accepted for publication as a series of papers in the journal Annals of Physics.[9]

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I. 6 Laser Studies of Conical Refraction. A. J. Schell and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 2.

The experimental results of the intensity distribution of linear conical refractions have been compared with detailed theoretical calculations. For the first time near-field diffraction effects have been

taken into account. It is shown that the two bright circles on either side of the Poggendorf dark circle do not have the same intensity, except in the Fraunhofer far field. Very good quantitative agreement has been obtained for aragonite, a biaxial crystal with inversion symmetry. This is the first quantitative experimental and theoretical comparison of conical refraction patterns since the advent of the laser. The patterns in α-iodic acid are complicated by the presence of natural optical activity. Here again good agreement with the theory is obtained.

Since α-iodic acid lacks inversion symmetry, second harmonic intensity is generated. The predicted existence of both free and driven harmonic cones has been reported in a brief communication.[1] A detailed comparison between theory and experiment of nonlinear conical refraction has been accomplished.

All these results have been written up in the Ph. D. thesis[2] of A. Jane Schell, who is now a professional member of the scientific staff at IBM Research Laboratories in Yorktown Height (N. Y.). Three manuscripts based on this thesis have been prepared and submitted for publication in scientific journals.[3-5] This research project is herewith terminated.

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I. 7 Picosecond Nonlinear Optics at 10.6 μm. H. S. Kwok and E. Yablonovitch, Contract N00014-75-C-0648 and ARPA Grant F44620-75-C-0088; Research Unit 4.

In multiphoton absorption by polyatomic molecules, the laser field is first coupled to the resonant vibrational mode of the molecule. One very important question to be asked is how fast the energy in that simple mode is coupled to the rest of the vibrational modes. This coupling can be described by the energy transfer rate T_1^{-1} between the resonant mode and a vibrational heat both composed of all the nonresonant modes.[1] A quantitative grasp on T_1 is important to the study of mode selective chemistry, laser isotope separation and molecular energy transfer processes in general.

During this report period, we have performed time resolved spectroscopy on such a molecule, SF_6, using the picosecond CO_2 laser pulses previously reported.[2,3] The 30 psec. 10.6 μ pulse was split into a pump and probe type arrangement and focussed onto an SF_6 gas cell with intensities as high as 3.0 Gw/cm^2. We observed an initial saturation of the probe pulse absorption due to the presence of the pump pulse. But immediately after the pump pulse was gone, this saturation recovered in a time which we could not resolve. The excess saturation

then decayed collisionally with a τ product of 12 nsec. torr. We interpret the initial recovery as an intramolecular transfer of energy from the ν_3 mode to the vibrational continuum formed by the other modes. It is well known that if the vibrational energy stays in the ν_3 mode, the anharmonic shift in the absorption spectrum is more than twice greater than if the energy is thermally distributed among all the 15 modes. We are performing further experiments with preheated SF_6 to confirm this conclusion. The collision dependent recovery afterward can be interpreted as a vibration-rotational equilibration process. This is 10^2 times faster than the collisional vibration-vibrational equilibration time which is 1.5 μsec. torr. The same process has been observed by other groups[4] but they erroneously interpreted their results as a collisionless process because they lacked the resolution to see it over a large pressure range.

These results will be presented as an invited talk in the forthcoming Tenth International Quantum Electronics Conference to be held in Atlanta, Georgia.

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I. 8 Laser-Plasma Interaction Studies. P. Kolodner and Eli Yablonovitch, Contract N00014-75-C-0648; Research Unit 4.

A year ago, we reported[1] the first observation of fast electrons (15 keV) emitted from plasmas produced by optical breakdown of ultra-clean, ultrapure gas. We interpreted this observation in terms of the simple theory of "resonant absorption,"[2] by which transverse light waves are resonantly coupled to longitudinal plasma oscillations in the so-called "critical layer," where the plasma frequency is equal to the laser frequency ($\lambda = 10.6\ \mu m$ for CO_2 laser light). In this theory, the key plasma parameter is the electron density scale length, $L \equiv n_e |\nabla n_e|^{-1}$. In laser interaction experiments, one typically finds $L \sim$ one micron. In avalanche optical breakdown of neutral gas, the plasma density profile is not accurately reproducible from shot to shot, and this was reflected in our data. So the thrust of our experiments, and of those of others,[3] is now to produce reproducible laser targets, in which L can be controlled. On the basis of previous experiments,[4] which showed that gas breakdown proceeds reproducibly in the presence of preionization, we modified our experiments by focussing the laser pulse near a small spark, which emits ionizing soft-uv radiation, and into a diffuse electric discharge. These attempts did not yield reproducible electron emission. We now propose to use as a laser target the front of a shock wave travelling through 40 torr D_2 gas. Strong shock fronts have the steepest density gradients achievable in neutral gas: under our experimental conditions, we expect to find $L \sim 10\ \mu m$. While many properties of laboratory shocks are difficult to reproduce, the density scale length is determined only by the mean free path in the unshocked gas, if the shock

wave is strong. On the basis of previous work,[5] we expect that the plasma density profile will be identical to that of the neutral gas. We are now in the process of constructing an electrothermal shock tube with which to carry out this work.

In the absence of preionization the first electron carriers have to be provided by tunneling. An experiment was done demonstrating tunnel ionization limits in dense purified gases.[6] In pure He gas the tunneling threshold intensity was approximately 10^{13} w/cm^2, four orders of magnitude greater than the avalanche breakdown threshold in the presence of readily available initiative electrons. This is roughly the intensity predicted by the long-standing Keldysh theory.[7]

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I. 9 Collisionless Multiphoton Absorption and Dissociation of SF_6.

J. G. Black, E. Yablonovitch, P. R. Kolodner, and N. Bloembergen,

Contract N00014-75-C-0648; Research Unit 4.

Experiments were performed to explore the nature of energy deposition in single molecules of SF_6, and the resultant dissociation of the molecules. Deposition of laser energy (10.6 micron wavelength) is measured by the opto-acoustic method, essentially a calorimetric technique. Dissociation data are obtained from the depletion of bulk absorption after the gas has been irradiated with many laser pulses. Series of experiments using pulses with widely varying temporal characteristics yielded information about the intensity dependence of light absorption. For example, molecules irradiated at a fluence of 0.8 Joules/cm^2 absorbed an average of 16 photons where the duration was 500 picoseconds; a pulse of 100 nanosecond duration with the same fluence is absorbed half as strongly; a 100 ns pulse composed of one longitudinal laser cavity mode was absorbed only about 35% as strongly as the 500 ps pulse. We have shown[1] that, at a constant fluence above the dissociation threshold, there is very little peak power (pulse duration) dependence in the observed dissociation yield. Combining the opto-acoustic absorption data (photons absorbed vs. fluence) and the dissociation data (percent molecules dissociated per pulse vs. fluence), we obtain the probability of dissociation for the molecules as a function of the number of absorbed photons. We have found[2] that the observed result of such an analysis is consistent with the concept that the absorbed energy is randomly distributed among the vibrational modes of SF_6. This conclusion has considerable importance in the emerging field of

of laser-induced chemistry. Studies with other interesting molecules shall be undertaken in the future to investigate the effects of spectroscopic and steric structure on the distribution of energy within single molecules.

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II. SOLID STATE ELECTRONICS

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II. 1 Raman Scattering in Liquid Crystals. N. A. Clark, S. Asher, and P. S. Pershan, Contracts NSF DMR76-22452 and NSF DMR76-01111; Research Unit 5.

During this report period, the principal efforts were directed toward modernization of the Raman facility. The Harvard University Materials Research Lab. financed the purchase of a 15 watt Spectra Physics 170 argon ion laser together with a Coherent Radiation 590 dye laser. The combination of these two allows Raman scattering over a continuous range of wavelengths throughout the visible, and with selected wavelengths in the near ultraviolet. We have, however,

designed and constructed a nonlinear device for doubling the output frequency of the dye laser. In this way we will have available for Raman spectroscopy a continuous range of wavelengths down to at least 3000 Å. In addition to this, the Harvard Materials Research Lab. has sponsored the purchase of a PDP-11 computer to replace the RIDL multi-channel analyzer and home built control circuits for multiple scan operation of the spectrometer. This latter purchase was necessitated by the fact that the RIDL, being approximately 13 years old, has become obsolescent and repairs on it have become increasingly costly with spare parts increasingly difficult to find. In this last report period the instrument became completely unrepairable. We hope to have the new system operating in the next fiscal year.

The last Raman project to be completed in this unit was described in last year's proposal and was published in the Journal of Chemical Physics.[1] In addition to this, Professor Pershan lectured on the principle of this technique and the results obtained under this project at the NATO sponsored summer school on molecular properties of liquid crystals held at Cambridge, England, in August, 1977.

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II. 2 Brillouin Scattering from Liquid Crystals. M. Fisch and P. S. Pershan, Contracts NSF DMR76-22452 and NSF DMR76-01111; Research Unit 5.

A manuscript on the Brillouin studies from dipalmitoyl phosphatidylcholine, as described in the last report, was prepared and accepted for publication in the Proceedings of the National Academy of Sciences. It has not yet appeared. While that research had significant implications, it also left open some very significant questions that could not be answered at the time that the original experiments were done. Most important among these was the suggestion that for lower water concentrations and lower temperatures there will be strikingly large changes in the relative values of different elastic constants in the lipid phases. The principal obstacle to studying these was difficulties in obtaining optical quality samples. Much of our effort has been spent in that direction this year, and we believe ourselves capable of solving that problem now. In the interim, some of the electronic components necessary for multiple scanning of our four pass Fabry-Perot interferometer had to be replaced. The previous component exhibited intermittent failure, and it was this very intermittency that delayed final diagnosis of the problem.

Finally, analysis of the data previously obtained on dipalmitoyl phosphatidylcholine indicated the need for elastic constant measurements that are more precise than those that can be obtained from Brillouin spectroscopy. We have thus spent some effort analyzing other techniques for measuring these same quantities. This phase of the program was initiated in the year under discussion and will be reported on in the next fiscal year.

II. 3 Optically Induced Effects in Liquid Crystals Using Interdigital Electrodes. D. Luippold and P. S. Pershan, Contracts NSF DMR76-22452 and NSF DMR76-01111; Research Unit 5.

During this report period it became necessary for us to obtain interdigital electrodes from a commercial supplier in place of those that were graciously supplied to us by Lincoln Laboratories. These electrodes were evaluated and a number of experiments were undertaken simply to reproduce results previously obtained with the electrodes supplied by Lincoln Laboratories. During the period we have become interested in a series of materials new to our laboratory and before going to high frequency studies we will systematically examine the low frequency behavior of these materials.

II. 4 Forced Thermal Diffusivity Studies. W. Chan and P. S. Pershan, Contracts NSF DMR76-22452 and NSF DMR76-01111; Research Unit 5.

Experiments on water diffusion in multilamella lipid samples were completed. A manuscript on this subject was published in the Physical Review Letters.[1] In addition, a second and longer manuscript describing further details of these results was prepared. The single most important result of these measurements was the dependence of the water diffusivity on water concentration. Multilamella lipid samples can be described as alternate layers of lipid, water, lipid, water, lipid, water, etc. With increased water concentration, the water layer becomes thicker and in the lipid under study (dipalmitoyl

phosphatidylcholine) the system will remain in a lamella phase up to approximately 40% water by weight if the temperature is above approximately 41°C. One would imagine that at the high concentration range the water in the multilamella stack would be essentially the same as bulk water. On the other hand, at lower concentrations one would expect the water to become more and more constricted and less mobile. This was, in fact, confirmed by our measurements and a quantitative measure of the fluidity of the water was obtained. A theoretical model for the experimentally determined fluidity was developed and applied to the experimental results. The conclusion was that below approximately 10% water by weight the water in the lipid multilamella is relatively immobile and bound to the polar head groups of the lipid. Above this concentration, the extra water is relatively free to move, with viscosities and other parameters very much like that of bulk water. This is consistent with expected behavior of these materials based on indirect measurements and interpretation.

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II. 5 Mechanical Properties of Smectic Liquid Crystals. C. Rosenblatt, R. Pindak, N. A. Clark, R. Meyer, S. Asher, and P. S. Pershan, Contracts NSF DMR76-22452 and NSF DMR76-01111; Research Unit 5.

A manuscript was published concerning work done in this unit. [1] As a result of this work, we began the study of the defect structures that

appear in lipid multilamella samples during the process of aligning these samples and often in the course of experiments. We have observed textures essentially identical to those observed by Rosenblatt et al. in thermotropic smectic liquid crystals.[1] The defects can be seen microscopically either with crossed polarizers or without any polarizers. In both cases, one sees properties that are sometimes identical to those described in the above manuscript. We plan further studies to characterize the conditions under which these defects form and disappear and also the conditions under which they transform into more complicated defects.

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1. C. H. S. Rosenblatt, R. Pindak, N. A. Clark, and R. B. Meyer, "Parabolic Focal Conic: A New Smectic A Defect," Le Journal de Physique 38, 73 (1977).

II.6 Properties of Liquid Crystal Free Films. R. B. Meyer, R. Pindak, N. A. Clark and C. Rosenblatt, Contracts NSF DMR76-22452 and NSF DMR76-01111; Research Unit 5.

During this report period the principal work on films was restricted to films made from ferroelectric liquid crystals. These systems are of the smectic C type with an electric dipole moment in the plane of the films and perpendicular to the director. In the case of thin films (2 to approximately 10 layers) one can consider them to be two-dimensional nematic liquid crystals. The electric dipole moment in the plane of the film allows direct coupling between the director and an

externally applied electric field. Light scattering studies have been carried out on director fluctuations in these films as a function of this applied electric field. It is possible to measure both the polarization per unit area and the effective "Frank elastic constant" for the two-dimensional nematic. Results on this system can be compared with results obtained on the same material in bulk.

II. 7 Extended Frequency Range for Josephson Effects in "Variable-Thickness" Microbridges. M. Octavio, W. J. Skocpol, and M. Tinkham, Contracts N00014-75-C-0648, N00014-76-C-0032 and NSF DMR76-11323; Research Unit 1.

As reported last year, the use of well-cooled microbridges with thick banks allows us to study the synchronization of internal Josephson oscillations with harmonics of external microwave radiation up to frequencies as high as 2 THz (200 x 10 GHz), which represents a significant extension of the operating range of thin-film microbridge devices.[1] Detailed comparisons between our experimental results and our general theory of the effects of Joule heating[2,3] have been published in a Technical Report.[4] In particular we confirm the magnitude and temperature dependence of the characteristic power level P_0 which governs the exponential reduction of the critical current due to the power dissipated in the device. We have also studied more subtle non-equilibrium effects[5] which lead to an enhancement of the effective critical current at dissipation levels below P_0.

As a result of our success at observing the response to high harmonics of microwave radiation, we have also sought to observe directly the fundamental response to 604 GHz (496 μm) laser radiation. Because of coupling difficulties associated with the low resistance of the microbridges (approximately 1Ω), we have not yet succeeded in observing the ac effect at that frequency, but work aimed at increasing the resistance level of the bridges is continuing.

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II.8 Far-Infrared Frequency Dependence of the Josephson Effect in Point Contacts. *D. A. Weitz, W. J. Skocpol, and M. Tinkham,* Contracts N00014-75-C-0648, N00014-76-C-0032, and NSF DMR76-11323; Research Unit 1.

We have systematically studied the ac Josephson effect induced in Nb cat-whisker point contacts by laser radiation at a series of far-infrared fequencies corresponding to wavelengths ranging from 1.2 mm to 70 μm. By extensive analysis of the results at 604 GHz (496 μm), we

have demonstrated[1] that quantitatively reproducible results can be obtained from different point contacts, and that the results are compatible with theoretical analyses[2] which take into account the frequency dependence of the Josephson effect near and beyond the superconducting energy gap frequency. We have also correlated the observability of the Josephson effect at this and higher frequencies with identifiable features on the dc I-V curves, especially the sharpness of the gap structure.[3,4] By studying the maximum observed size of the Josephson steps at a series of frequencies, we have for the first time been able to measure[3] the intrinsic rolloff of the strength of the Josephson effect beyond the gap frequency, and we find it to be qualitatively similar to the frequency-dependent theory, although the absolute size of the steps is about a factor of two smaller than the theory predicts, even when heating and noise rounding effects are accounted for. At this point we are continuing our measurements and analysis, and are characterizing the performance of our point contacts as detectors at low incident power levels.

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II. 9 Laser-Induced Disequilibrium in Superconducting Films. L. N. Smith, A. D. Smith, and M. Tinkham, Contracts N00014-75-C-0648, N00014-76-C-0032, and NSF DMR76-11323; Research Unit 1.

We have studied phase-slip centers in long tin microbridges under pulsed optical illumination. The illumination is made spatially uniform and reproducible from pulse to pulse to within a few percent by employing diffraction limited optics and our optical scanning system to chop the beam from our cw Argon laser. We find that the critical currents of the phase-slip centers can be driven to zero without any discontinuity upon increasing the intensity of the illumination. This observation excludes the possibility of any first-order transition, even in small isolated pockets of the film, as had been proposed by others.[1] We furthermore find that we cannot reproduce in detail the I-V curves of the illuminated film by merely raising the temperature. The data is suggestive of our recent model of a spatially inhomogeneous state with two values of the energy gap,[2] but we cannot yet rule out inhomogeneous "heating" as a possible explanation. We are planning to make small tunnel junctions in order to study directly the behavior of the energy gap in the illuminated state. We have developed the ability to make micron-size devices using photolithographic techniques and are currently trying to make tunnel junctions with dimensions of order a few microns, which is the spatial scale we expect to characterize the nonuniform state.

We also have observed changes in the current-voltage characteristics of tin tunnel junctions illuminated with far-infrared radiation from our HCN laser. These changes can be related to the distribution function of the nonequilibrium quasiparticles, and can be used to study the dynamics

of the superconducting state. Our efforts during the past year have been concentrated on increasing signal to noise ratio from the tunnel junctions. We have increased this ratio by nearly two orders of magnitude by using electro-formed light cones to increase the intensity of the FIR, and by improving the electronics, so that our signal/noise is now $\sim 10^2$. Preliminary measurements at the 337 μm line of the HCN laser are unable to discriminate between different models of the nonequilibrium distribution. This wavelength corresponds to a photon energy several times the energy gap, however. More interesting results are expected when we begin to use our optically-pumped laser, which can be made to operate at wavelengths closer to the energy gap of tin.

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II. 10 Production and Structural Measurements on Sputtered Amorphous Group 4 and Group 3-5 Compounds. D. A. Anderson, M. A. Paesler, and W. Paul, Contracts N00014-75-C-0468, NSF DMR76-15325, NSF DMR76-01111 and DAAG39-77-G-0059; Research Unit 6.

The deposition of amorphous films of group 4 (Ge, Si) and selected group 3-5 semiconductors (principally GaAs) by r.f. sputtering in argon, with substrate temperature and deposition rate as variable parameters, has been continued. Structural characterization by X-rays, thickness, and density measurements continues.

II. 11 Production of Amorphous Ge and Si, Amorphous Hydrogenated Ge and Si, and Doped (B, N, P) Amorphous Ge and Si. D. A. Anderson, M. A. Paesler, E. Freeman Black, J. R. Pawlik and W. Paul, Contracts N00014-75-C-0468, NSF DMR76-15325, NSF DMR76-01111 and DAAG39-77-G-0059; Research Unit 6.

A very extensive matrix of samples of $Si_{1-x}H_x$ for measurement of electron spin resonance, electrical conductivity, thermopower, infrared vibrational absorption, optical absorption edge, photoluminescence and hydrogen evolution has been produced at substrate temperatures between 25 and 540°C and H partial pressures from zero to 5×10^{-3} Torr. When desired, D has been substituted for the H. Also, as desired, partial pressures of PH_3 or B_2H_6 have been added to produce homogeneously doped n and p type films, or to produce n-p junctions, or to produce a desired interface of low and high resistivity material. These methods have been extended to the hydrogenation of amorphous GaAs, and to the production of off-stoichiometric samples by addition of partial pressures of AsH_3 to the Ar-H sputtering gas.

II. 12 Study of Doping, Schottky Barrier Formation and Solar Cell Efficiency in Amorphous $Si_{1-x}H_x$. D. A. Anderson, G. Moddel, and W. Paul, Contracts N00014-75-C-0468, NSF DMR76-01111 and DAAG-39-77-G-0059; Research Unit 6.

After first optimizing the preparation conditions to minimize the state density in the gap, Schottky barrier contacts have been made by evaporating a semi-transparent layer of Pt or Pd onto a suitably

prepared silicon surface. Good rectification characteristics can be obtained provided the sample is first etched and then, following deposition of the metal contact, it is held at elevated temperature in a reducing atmosphere. Dark I-V characteristics are limited by the high series sample resistance but seem to indicate that barriers as large as 0.95 eV can be obtained. Measurements are currently in progress to determine the barrier height more accurately using C-V techniques and from the energy onset of short circuit photocurrent. Under approximate solar AM2 illumination such contacts give open circuit photovoltages of the order of 0.4 volts and short circuit currents of about 0.5 mA/cm^2. Considerable improvement in these numbers is expected from further optimization of sample preparation and in device fabrication. In the former category we believe that by doping the silicon lightly with phosphorus, both V_{oc} and I_{sc} can be increased. In the latter category we have found that if etching of the surface oxide is incomplete, we obtain larger V_{oc}, but this can be offset if the oxide layer is too thick by a reduction in the fill factor and consequent reduction in the usable power the device can deliver.

II.13 Transport in Phosphorus Doped Silicon. D. A. Anderson and W. Paul, Contracts N00014-75-C0468, DAAG39-77-G-0059, and NSF DMR76-15325; Research Unit 6.

Conductivity and thermoelectric power have been measured as a function of temperature in a series of samples doped with phosphorus. The preparation conditions chosen for these films are believed to give

a very low gap state density and allow efficient substitutional doping. We find that by adding as little as 10^{-5} Torr PH_3 to our Ar sputtering gas we increase the room temperature conductivity by seven orders of magnitude. The data clearly show a high temperature transport mechanism dominant above 420 K which is invariant with doping level. These two transport paths are identified tentatively with conduction in host silicon band states and in a phosphorus donor band, respectively.

The data show considerably less scatter than seen in earlier measurements in other laboratories on silicon prepared by plasma deposition, but nothing that we observe is inconsistent with their findings. This suggests that there may be less of a difference between glow discharge and sputtered Si than has previously been supposed.

One rather unexpected result of the present work is that the difference between the conductivity activation energy and the temperature slope of the thermopower, $E_\sigma - E_s$, is close to zero in very lightly doped samples but rises in undoped and in heavily doped samples to about 0.15 eV. More work is required to confirm this result, but if genuine it has important consequences for any discussion of the experimental verification of the existence of a mobility edge in this material.

II. 14 Study of Conditions for the Maximum Reduction of Pseudogap States in Amorphous Silicon. D. A. Anderson, E. Freeman Black, G. Moddel, S. Oguz, M. A. Paesler, and W. Paul, Contracts NSF DMR76-01111, NSF DMR76-15325 and N00014-75-C-0468; Research Unit 6.

As was emphasized in last year's report, it seems advantageous, both from the point of view of pursuing basic investigations on a-Si and the production of efficient devices, to determine the conditions for an r.f. sputtering apparatus to produce a-Si with the smallest density of pseudogap states. We have continued our investigation of samples produced at different substrate temperatures and partial pressures of hydrogen, in a search for these optimum conditions. In addition to the measurements of conductivity, thermoelectric power, absorption edge, and photoconductivity described last year, we have added extensive measurements of (1) the vibrational absorption in the infrared produced by Si-H bonds, (2) mass density, (3) photoluminescence and (4) evolution of H on heating.

It has now been firmly established that the best substrate temperature is probably in the range 250-300°C. Below 250°C the hydrogen added to the argon sputtering gas inefficiently compensates dangling bond defects, and above 300°C less hydrogen is incorporated for a given partial pressure of hydrogen in the plasma.

The behavior as a function of the partial pressure of hydrogen at a fixed substrate temperature is surprising: the hydrogen content increases up to a certain partial pressure of hydrogen, and then decreases slightly at higher partial pressures. This is attributed to

changes in the nature and density of the atomic and molecular species in the sputtering plasma when the gas content is changed with r.f. current held constant. As a result of the maximum in hydrogen content as a function of partial pressure of hydrogen, many other properties also go through an extremum: infrared vibrational absorption intensity, photoluminescence intensity, photoluminescence peak position and conductivity activation energy. However, the absorption edge asymptotes in position: this is tentatively attributed to a changing configuration of the incorporated hydrogen with partial pressure of hydrogen. Thus, generally speaking, the density of states function for energies in the pseudogap is not a unique function of the amount of incorporated hydrogen, but also depends on how it is incorporated.

The crucial next part of this investigation is therefore to try to make a connection between the density of states distribution and the variety of combinations of deposition parameters. It is interesting that essentially the same conclusion, to wit, that the eventual density of electronic states, and so properties, is a function of many parameters of the preparation method, has been reached by the group at Xerox working on a-Si prepared from silane.

II. 15 Photoconductivity in the Amorphous $Si_{1-x}H_x$ System. T. D. Moustakas and W. Paul, Contracts NSF DMR76-15325 and N00014-75-C-0648; Research Unit 6.

Our earlier investigation of a-Ge has been extended to a-Si. The photoconductivity spectra have been measured for samples prepared at

different substrate temperatures and different partial pressures of hydrogen in the sputtering gas. It is found that the photoconductive response and the position of the photoconductivity edge pass through an extremum as a function of substrate temperature for fixed partial pressure of hydrogen in the sputter gas, and these effects have been firmly associated with the percentage of incorporated hydrogen. Both of these parameters also pass through an extremum as a function of partial pressure of hydrogen at fixed substrate temperatures, but the extremum in magnitude of photoresponse does not correspond to maximum incorporated hydrogen. It is speculated that the first effect of adding hydrogen to compensate dangling bonds is to remove recombination centers but that, when the H-content increases too far, the hydrogen tends to reduce the lifetime. An alternative possibility is that, as a function of partial pressure of hydrogen used, the sample is changing over from n-type to p-type and the p-type material is known to have hole mobilities two orders of magnitude lower than the n-type.

A limited number of studies of the transient response have been made. These results have been reported in part in the literature (Moustakas, Anderson and Paul, Solid State Communications 23, 155-158 (1977)) but are also being analyzed further at present.

II. 16 Publications of the Research Reported in Sections II-10 through II-15. W. Paul.

1. Preparation of highly photoconductive amorphous Si by rf sputtering. T. D. Moustakas, D. A. Anderson and W. Paul, Solid State Commun. 23, 155-158 (1977).

2. Transport and recombination in sputtered hydrogenated amorphous germanium. T. D. Moustakas and W. Paul, Phys. Rev. B16, 1564 (1977).

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4. Effect of hydrogen on the transport properties of amorphous silicon. D. A. Anderson, T. D. Moustakas and W. Paul, Proc. of the 7th Int. Conf. on Amorphous and Liquid Semiconductors, Edinburgh, June 1977, p. 334.

5. EPR and photo-EPR in doped and undoped amorphous Si and Ge. J. R. Pawlik and W. Paul, Proc. of the 7th Int. Conf. on Amorphous and Liquid Semiconductors, Edinburgh, June 1977.

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8. Coordination and electronic states in amorphous 3-5 compounds. G. A. N. Connell and W. Paul, Bull. Am. Phys. Soc. 22, 405, 1977.

9. Transport in amorphous $Ge_{1-x}H_x$. T. D. Moustakas and W. Paul, Bull. Am. Phys. Soc. 22, 434, 1977.

10. Photoluminescence of hydrogenated sputtered amorphous silicon. T. D. Moustakas and William Paul, Phys. Rev. B (submitted for publication).

11. Transport in doped sputtered a-Si:H. D. A. Anderson, Bull. Am. Phys. Soc., Washington, D. C., 1978.

12. Photoluminescence of rf sputtered hydrogenated amorphous silicon. M. A. Paesler and W. Paul, Bull. Am. Phys. Soc., Washington, D. C., 1978.

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14. Infrared vibrational spectra of Si-H bonds in a-Si. William Paul and E.C. Freeman, Bull. Am. Phys. Soc., Washington, D.C., 1978.

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III. DECISION AND CONTROL THEORY AND SYSTEM ANALYSIS

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A. SYSTEM ANALYSIS AND CONTROL

III. 1 Nonlinear Oscillatory Devices. R. E. Kronauer and S. Mochon, Contract N00014-75-C-0648; Research Unit 10.

A system of matched, weakly-coupled, self-excited oscillators will come to one of a set of equilibrium states in which the oscillators mutually constrain one another to a single frequency. The number of states matches the number of oscillators. Through the choice of the coupling these states can each be made to have a different frequency.

We have studied the question of whether a system of this kind could be made to function as a kind of frequency memory device. The idea is that the system would be driven by a strong external oscillation to which it would synchronize, and when the stimulus is switched off it would revert to that free frequency which is closest to the previous drive frequency.

By simulating on the computer a system of three oscillators (the simplest nontrivial case) we have shown that the objective can be largely realized but only by exercising care in how the stimulus is brought to bear on and removed from the system. Simple on-and-off switching does not produce the desired behavior. This is because stimulus strengths adequate to insure synchronization do not always have unique synchronization states. We have found that this difficulty can be overcome by raising the stimulus strength adiabatically through regimes in which the response is unique, thereby selecting the desired synchronized configuration. An abrupt switch-off will then lead to a unique state of free oscillation.

In qualitative terms this procedure meets the design objective: excitation at a frequency close to one of the free frequencies will switch the system to that free frequency from any initial state. Quantitatively the procedure is deficient since it does not partition the frequency domain between the free frequencies evenly. If the stimulus is lowered adiabatically from the high synchronizing level to a specific intermediate level and then switched off the partitioning is considerably improved but still not uniform.

In the context of the simple three-oscillator system the concept of a frequency memory device has been demonstrated. It is possible that the nonuniform partitioning of the frequency domain is an artifact of the low order of the system studied and that with many more oscillators uniform partitioning might be found. This project has been completed during the current reporting period.

B. CONTROL AND OPTIMIZATION

III. 2 Decentralized Control in Satellite and Wire Communication. F. Schoute and Decentralized Scheduling in a Transportation System. Y. C. Ho and D. Stein, Contract N00014-75-C-0658 and NSF Grant ENG76-11824; Research Unit 8.

These two projects described in Annual Progress Report No. 90 were completed in early 1977 and the detailed accounts can be found in:

1. F. C. Schoute, "Decentralized Control in Computer Communication," Division of Engineering and Applied Physics, Harvard University Technical Report No. 667, April 1977.

2. David M. Stein, "Scheduling Dial-A-Ride Transportation Systems: An Asymptotic Approach," Division of Applied Sciences, Harvard University Technical Report No. 670, September 1977.

Reference

1. D. M. Stein, "An Asymptotic Probabilistic Analysis of a Routing Problem," to appear in Mathematics of Operations Research, 1978.

III. 3 Teams, Signaling, and Information Theory. Y. C. Ho, M. Kastner, and E. Wong, Contract N00014-75-C-0648 and NSF Grant ENG76-11824; Research Unit 8.

The work on market signaling described in the last report was extended in a significant way to provide a unified treatment of team decisions, market signaling, and classical information theory. It turns out a broad class of decision problems including market signaling which can be viewed as a kind of information theory with real time constraints. Many of the classical information-theoretic ideas can be adapted to this case and provides sufficient conditions and/or lower bounds for optimal team decision problems.

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1. Y. C. Ho and M. P. Kastner, "Market Signaling: An Example of a Two-Person Decision Problem with Dynamic Information Structure," to appear in the Transactions on Automatic Control, Special Issue on Large Scale Systems, April 1978.

2. Y. C. Ho, M. P. Kastner, and Eugene Wong, "Teams, Signaling, and Information Theory," to appear in the Transactions on Automatic Control, Special Issue on Large Scale Systems, April 1978.

3. B. Kurtaran, "Dynamic Two-Person Two-Objective Control Problems with Delayed Sharing Information Pattern," IEEE Trans. on Automatic Control, vol. AC-22, No. 4, 659-661, August 1977.

III. 4 Peak Loading Pricing for Electric Utilities as a Two-Stage Optimization Problem. Y. C. Ho, D. M. Chiu, and R. Muralidharan (Bolt, Beranek and Newman, Inc.), Contracts N00014-75-C-0648 and NSF ENG76-11824; Research Unit 8.

A model for the interaction of consumer and electric utility through peak load pricing which includes the effect of interdependent demands has been formulated as a problem of Stackelberg control. Validation and implementation issues are discussed.

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1. Y. C. Ho, D. M. Chiu, and R. Muralidharan, "A Model for Optimal Peak Load Pricing by Electric Utilities," Proceedings of the Lawrence Symposium on Energy and Systems, Berkeley, California, October 1977.

III. 5 Distributive Computing. Y. C. Ho and B. Kurtaran, Contract N00014-75-C-0648 and NSF Grant ENG76-11824; Research Unit 8.

The question "How to distribute the workload" in a system of interconnected computer units received considerable attention.[1,2] We took a team theoretic approach and considered the problem of optimal workload interchange among units. All arriving workloads are modeled as Gaussian random vectors whose statistics are known to each unit. On the other hand, due to various technical or economical reasons, communication among the units is supposed to be impossible and unit i does not know the workload of unit j, $j \neq i$. The decision problem faced by unit i is to find the workload u_{ij} he has to transfer to unit j, in

order to minimize the overall computing time, and also taking into account various transfer costs. Formulated as a team decision problem with a singular quadratic cost criterion, we showed that the problem admits a unique linear solution. This is of interest since the same problem in a centralized content would admit nonunique solutions. Thus, somewhat surprisingly, decentralization may help in some cases to obtain meaningful solutions. Explicit formula were found for transfer gains.

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2. J. P. Buzen, "Balancing Load on I/O Devices," Infotech State of the Art Report on System Performance Tuning, Infotech Int'l Ltdt., London, 1-17, 1976.

3. Y. C. Ho and B. Kurtaran, "A Team Theoretical Approach to the Distributive Computing Problem," to appear in the Journal of Optimization Theory and Applications.

III. 6 Dynamic Security and Access in Database System. Y. C. Ho and B. Kurtaran, Contract N00014-75-C-0648 and NSF Grant ENG76-11824; Research Unit 8.

In a multi-user data base (DB) system the questions: "Who has to know what" and "Who can do what" are of considerable importance.[1,2] In a first work we combined important concepts from Refs. 1 and 2 and recasted the DB model in a dynamic system framework where concepts of "state", "input", and "state transition map" are central. We

defined and related concepts of user access level and data security level.

We intend to pursue further research in this field.

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1. D. Denning, "Secure Information Flow in Computer Systems," Ph. D. Thesis, Purdue University (available from University Microfilms), May 1975.

2. P. Griffith and R. Wade, "An Authorization Mechanism for a Relational Database System," ACM Trans. on Database Systems, Vol. 1, No. 3, 242-255, September 1976.

III. 7 System Identification Using Approximate System Models.

P. Caines, Contract N00014-75-C-0648; Research Unit 9.

This work[1,2] gives a general theory of the behavior of parameter estimates of models of stochastic dynamical systems in terms of consistency, asymptotic normality and asymptotic efficiency. An important aspect of our results is that they cover the case where the model set does not contain a representative of the true system generating the observations. This is valuable in practical applications.

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1. P. E. Caines, "Stationary Linear and Nonlinear System Identification and Predictor Set Completeness" to appear IEEE Trans. Automatic Control. A version of this paper was presented at the Conference on Decision and Control, New Orleans, LA, December 1977

2. L. Ljung and P. E. Caines, "Asymptotic Normality of Prediction Error Estimators for Approximate System Models," Research Report, Division of Applied Sciences, Harvard University, March 1978.

III. 8 Non-Stationary System Identification. P. E. Caines, Contract N00014-75-C-0648; Research Unit 9.

Work is being carried out on the asymptotic theory of parameter estimation for non-stationary linear systems from cross sectional data.[1,2] The parameter estimates are generated via the maximum likelihood technique from a large number of independent observations on the transient behavior of a system at a finite number of time points. Consistency and asymptotic normality results are obtained. They depend upon the satisfaction of an identifiability condition which signifies the minimum number of longitudinal observations that are required. This condition, in turn, is produced via the solution of the Inverse Riccati Problem. Applications[2] to psychometrics have been extensively pursued and applications to the analysis of aircraft flight dynamics are being initiated.

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2. R. L. Goodrich and P. E. Caines, "Linear Stochastic System Identification from Cross Sectional Data and Inverse Riccati Problem," to be presented at the Institute of Mathematics and its Applications Conference entitled "The Analysis and Optimization of Stochastic Systems" to be held in Oxford, UK, September 1978.

III. 9 Large Scale and Decentralized Systems. P. E. Caines, Contract N00014-75-C-0648 (work of R. Printis, supported by I. B. M.); Research Unit 9.

The problem of stabilizing a set of dynamical systems whose interconnections form an acyclic digraph has been considered.[1] In our formulation the parameters of any given system Σ in the network are permitted to be non-linear functions of the states of any systems that are connected to Σ. Subject to reasonable conditions, it is shown that such a digraph of variable parameter systems may be stabilized by the use of local compensators and that the performance of the stabilized system is enhanced if the compensators exchange information.

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1. P. E. Caines and R. S. Printis, "The Stabilization of Digraphs of Variable Parameter Systems", to appear IEEE Trans. Automatic Control, Vol. 23, No. 2, 1978. A version of this paper was presented at the Joint Automatic Control Conference, San Francisco, CA, June 1977.

III. 10 Feedback and Causality. P. E. Caines, Contract N00014-75-C-0648, partially supported by Canada Council Grant held jointly with S. P. Sethi of University of Toronto; Research Unit 9.

The theory of feedback and causality for stochastic processes and associated statistical and computational methodology has been further developed.[1,2] In addition, statistical techniques and system identification programs that we have developed have been applied to new

feedback and causality detection problems for micro-economic time series.[2]

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1. P. E. Caines and S. P. Sethi, "Recursiveness, Causality and Feedback," Research Report, Faculty of Management Studies, University of Toronto, Canada, May 1977.

2. S. Sethi, P. E. Caines, C. W. Keng, "A Bivariable Econometric Analysis of Supermarket Sales," Research Report, Faculty of Management Studies, University of Toronto, Canada, Feb. 1978.

III. 11 Nonlinear Systems. R. W. Brockett, Contract N00014-75-C-0648; Research Unit 7.

The effect of feedback on linear systems is of primary importance in practical automatic control since there are many examples of systems which are well approximated by a linear system in their operating regions. However, for those systems having important nonlinear effects the linear theory is not of much help. In Ref. 1 we give a number of results on the effect of feedback on nonlinear systems and, in particular, we give an easily useable method for finding a nonlinear feedback control law for linearizing a nonlinear system whenever such a control law exists. This result, based on earlier work done here and elsewhere using geometric methods, shows that there are a number of significant questions about nonlinear systems which we can solve without resorting to approximations.

Reference

1. R. W. Brockett, "Feedback Invariants for Nonlinear Systems," Proceedings of the 1978 IFAC Congress, Helsinki, Finland.

III.12 Stochastic Modeling. R. W. Brockett, Contract N00014-75-C-0648; Research Unit 7.

In Refs. 1 and 2 we study an important class of models which consist of linear systems with coefficient matrices which are finite state Markov processes in continuous time. These models are widely used in fault detection and other applications but are usually treated in an ad hoc way. In Ref. 1 we show how a certain representation for jump process which involves Poisson counters can be used to arrive at a simple and general method for computing the statistical properties of the solutions of such systems. In Ref. 2 we show that any set of second order statistics associated with a scalar random process can be approximated to any degree of accuracy by a process generated by a finite state model. This gives added significance to the results of Ref. 1 and is of interest in its own right.

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2. R. W. Brockett, "Stationary Covariance Generators with Finite State Markov Processes," 1977 Joint Automatic Control Conf., IEEE, New York.

Publications:

1. R. W. Brockett and P. Krishnaprasad, "Scaling Rational Functions and Linear Systems Identifications," Proceedings of the 1977 Conference on Information Sciences and Systems, Johns Hopkins University.

2. R. W. Brockett, "Lie Algebras and Rational Functions: Some Control Theoretic Connections," Proceedings of the Queens Conference on Lie Algebras and Applications, Queens University, Kingston, Ont.

3. R. W. Brockett, "On Improving the Circle Criterions," Proceedings of the 1977 Decision and Control Conference, IEEE, New York.

4. P. Krishnaprasad, "The Geometry of Minimal Systems and the Identifications Problem, Ph. D. Thesis, Division of Applied Sciences, Harvard University, 1977.

5. J. Ja'Ja', "On the Algebraic Complexity of Classes of Bilinear Forms," Ph. D. Thesis, Division of Applied Sciences, Harvard University, 1977.

6. P. Crouch, "Dynamical Realizations of Finite Volternal Series," Ph. D. Thesis, Division of Applied Sciences, Harvard University, 1977.

IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. R. W. P. King
Prof. T. T. Wu (until July 1)
Prof. M. Krook (after July 1)
Dr. R. W. Burton (summer)
Dr. J. deBettencourt (after July 1)
Dr. D. H. Preis
Dr. T. K. Sarkar (after Dec. 1)
Dr. L. C. Shen (summer)
Mr. R. Bansal (after June 15)
Mr. D. J. Blejer
Ms. M. E. Burton (summer)
Mr. H.-M. Lee
Mr. M. J. Miller (after June 15)
Mr. M. Morris (until May 1)
Ms. M. Owens
Ms. B. H. Sandler (part-time)
Mr. S.-K. Wan (until Sept. 1)

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical and experimental techniques and the use of high-speed computers and precision instrumentation. Most practically significant problems in this area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are conveniently grouped under two main headings, viz., antennas and waves in and over dielectric, conducting, and plasma media, and antennas in air. The first group is concerned with the circuit,

radiating, and scattering properties of antennas and arrays and the waves generated by them in their dependence on the electrical properties of a material medium (lake water, sea water, earth, ice, living tissue, plasma, etc.) in various forms and degrees of proximity. The antennas may be directly embedded in the medium or separated from it by a layer of insulation. The second group of investigations deals with the detailed electrical properties of complicated metal radiating and scattering structures in air including especially electrically thin and thick crossed conductors used to model an aircraft.

A. ANTENNAS AND WAVES IN AND OVER DIELECTRIC, CONDUCTING, AND PLASMA MEDIA

IV.1 Theoretical and Experimental Investigations of Insulated Linear Antennas in Various Dissipative Media. K.-M. Lee, R. W. P. King, and T. T. Wu, Contracts N00014-75-C-0648; Research Unit 11.

The model of a finite, highly conducting, tubular antenna that is center-driven by an ideal delta-function generator, surrounded by an infinitely long insulating cylinder (with wave number k_2), and immersed in a dissipative medium of infinite extent (wave number k_4) has been studied theoretically.[1] The integral equation for the current is derived and found to be similar in form to that for a bare cylindrical antenna in an infinite dissipative medium, but with a more complicated kernel and an arbitrary constant $\varkappa$ instead of k_2. The properties of the kernel are discussed in detail and approximate solutions for the complex wave number k_L are obtained that are valid for different ratios of the wave numbers, k_4/k_2. A numerical method for solving the integral equation for the current is discussed and compared graphically with measured data and a new approximate iterative method, based on an earlier zero-order solution[2] but with more general expressions for the wave number k_L and the characteristic impedance Z_c. It is shown that the transmission-line-like, zero-order solution applies for $|k_4/k_2| \geq 2$ when the generalized forms for k_L and Z_c are used. This is considerably less restrictive than the original condition, $|k_4^2/k_2^2| \gg 1$.

Measured currents and admittances of air- and oil-insulated linear antennas immersed in sand, for which $|k_4/k_2| \geq 1.3$, have been compared[3] with the zero-order solution using the more general expressions for k_L and Z_c. The agreement is good. The effect of a thin-walled plastic container on the properties of a liquid-insulated antenna were measured and displayed graphically.

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1. K.-M. Lee, T. T. Wu, and R. W. P. King, "Theory of an insulated linear antenna in a dissipative medium," Radio Science, vol. 12, 195-203, March/April 1977.

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3. K.-M. Lee, R. W. P. King, and T. T. Wu, "Measurement of the circuit properties of insulated linear antennas in a dissipative medium," IEEE Trans. Antennas Propagat., vol. AP-25, 836-840, November 1977.

IV.2 Theoretical and Experimental Study of Coupled Insulated Antennas Immersed in a Relatively Dense Medium. R. W. P. King, T. T. Wu, and L. C. Shen, Contracts N00014-75-C-0648; NSF Grant ENG74-13705 with the University of Houston; and NSF Grant GK40575 with Northeastern University; Research Unit 11.

Since the single insulated antenna in a relatively dense medium corresponds in its directive properties to a long collinear array of bare elements, it should be a very useful element in highly directive broadside and endfire arrays designed either for direct transmission through

the medium or for lateral-wave transmission along the interface between a semi-infinite medium and air. Owing to the high exponential attenuation, parallel insulated antennas in sea water interact significantly only when very closely spaced. On the other hand, the same antennas in lake water should experience strong interactions over quite large distances. This is a consequence not only of the low attenuation in the fresh water, but also of the electrically long lengths of the antennas. These may be many wavelengths long in the ambient medium and yet contain only substantially unidirectional currents along each insulated element. Evidently, the interaction of coupled insulated antennas is very different from that of the same antennas when bare. In order to provide a physical basis for understanding the phenomena involved and to make available a quantitative background, a complete theoretical and experimental investigation was made.

The theoretical distributions of current and driving-point admittances have been reported[1] for the parallel, identical elements of a circular array when these are individually insulated and immersed in a general ambient medium that is assumed to be homogeneous, isotropic, and relatively dense compared with the insulating material. Extensive measurements have also been made of the properties of coupled conducting monopoles with air insulation in thin acrylic tubes immersed in a fresh-water lake.[2,3] All data were obtained with the antennas driven both in phase and in phase opposition. Current distributions and input admittances have been measured for three thicknesses of the insulation ($c/a = 2.5$, 4.0, and 8.0), four antenna lengths ($h = 15$, 30, 45 and 60 cm) and a wide range of separations ($d = 7.64$ to 38.1 cm in steps of 3.82 cm). Note that the value of k_L varies with the size of the insulation

so that the electrical lengths $\beta_L h$ of the antennas also differ for different values of c/a. A comparison is made in the earlier paper[5] between the measured data and theory, and generally good agreement is observed for the currents. Differences in the admittances due to the effects at the junction between the monopole and the driving coaxial line and the approximations of the theory are discussed. Since the choice of a dielectric ambient medium with a large permittivity is a more sensitive test of the theory than either a more conducting medium or a medium with smaller permittivity, it seems reasonable to assume that the simple formulas developed for the phase-sequence currents and admittances should be at least as accurate for antennas in other media that satisfy the condition $|k_4^2/k_2^2| \gg 1$ as they are for antennas in lake water.

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IV. 3 Single and Coupled Horizontal-Wire Antennas Over a Dissipative Half-Space. R. M. Sorbello, K.-M. Lee, L. C. Shen, R. W. P. King, and T. T. Wu, Contracts N00014-75-C-0648 and F19628-76-C-0057; Research Unit 11.

The theoretical and experimental study of the circuit and radiating properties of single-wire antennas placed horizontally above an imperfectly conducting half-space has been completed. The antennas are either open-ended or terminated in a resistor connected to a quarter-wave section of line to form the modified Beverage antenna with its characteristic traveling-wave distribution of current. Unlike earlier work, this study has investigated the effect of the half-space on the properties of the antenna.

The original assumption that radiation into the air is negligible compared to the transfer of power into the imperfectly conducting or dielectric half-space is a good approximation only when the antenna is quite close to the earth ($d/\lambda_0 \leq 0.02$). In order to generalize the theory to greater antenna heights above the earth, account must be taken of radiation into the air. It has been shown[1] that the transmission-line form for the current remains a reasonable approximation for heights up to at least $d/\lambda_0 = 0.25$ and that the effect of radiation into the air can be treated approximately as a property of the open end in the shape of a lumped terminating impedance. The generalization is verified by a comparison of theory and experiment for short-circuited (effectively infinite), open-ended (finite), and terminated (Beverage) antennas over fresh and salt water.

The circuit properties of coupled parallel horizontal-wire antennas above an electrically dense dissipative half-space have been studied theoretically and experimentally.[2] The complex wave number, distribution of current, and admittance of the antennas are determined theoretically for symmetrical and antisymmetrical excitations. The theory is approximate in the same sense as the earlier theory for the single horizontal-wire antenna in that radiation into the air is neglected and a limitation to small heights is imposed. It is generalized, as for the single horizontal antenna, to take account of radiation into the air through a complex terminal function and so enlarge its range of validity while preserving the transmission-line form for the current. The numerical values of the terminal function are determined from a least-squares fit of the measured and theoretical current distributions. Current measurements were made on coupled horizontal antennas driven in zero-phase and first-phase sequences for six different antenna separations and three heights above both fresh- and salt-water solutions. The antennas were either open-ended or terminated in a lumped resistor and a quarter-wave extension of the antenna to produce traveling-wave distributions of current. Good agreement is displayed between theoretical and measured currents on the open-ended antennas and between theoretical and measured values of the terminal function for the terminated, modified Beverage antennas.

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2. L. C. Shen, K.-M. Lee, and R. W. P. King, "Coupled horizontal-wire antennas over a conducting or dielectric half-space," Radio Science, vol. 12, 687-698, September/October 1977.

IV.4 Theoretical and Experimental Study of the Scattering from an Obstacle Above the Earth. K.-M. Lee, L. C. Shen, and R. Bansal, Contracts N00014-75-C-0648 and F19628-77-C-0146; Research Unit 11.

The properties of radiating and scattering structures in the presence of a dissipative or dielectric half-space like the earth are complicated since they involve not only the shape, dimensions, and height of the obstacle, but also the electrical properties of the earth. Work has begun on a theoretical investigation to determine the currents induced on a thin circular loop in air above a general half-space by a prescribed incident field and the radiated field generated by them. Both parts of the problem have been reduced to the evaluation of Sommerfeld-like integrals. The fact that the distance from the loop to the point of observation of the scattered field is always large compared with both the size of the loop and its height above the interface can be used to simplify the integrals for the radiated field. This simplification does not apply to the integrals for the currents so that it will be necessary to evaluate them in the regions where the integrands are the most complicated.

An experimental program to measure the scattered field of a circular loop placed horizontally above earth or water has been initiated. The height of the loop above the interface will range from a few

millimeters up to 20 centimeters. The incident wave is to be launched by a six-element Yagi array operated at 1.5 GHz; an identical array will be used to pick up the scattered field. Both are supported by circular arcs made of polyfoam. The incident angle of the wave and the receiving angle can both be varied from 15° to 90°.

An outdoor experiment to measure the scattered field of a circular loop over the earth has been constructed and preliminary measurements taken.[1] The relative permittivity of the ground varied from $5 + i0.6$ to about $14 + i2.2$. The field strength scattered from the loop was measured as a function of the azimuthal angle, the polar angle, the size of the loop, and the height of the loop above the earth. This last is of particular interest. The height was varied from 1 cm to 26 cm in steps of 1 cm. The results show two peaks located at approximately 6 cm and 20 cm and a deep null between them at about 12.6 cm. This distribution does not correspond to the variation with height of the intensity of the total incident field on the loop. (With the incident field 45° from the normal to the ground, the total incident field on the loop is at its minimum when the loop is placed on the ground. This minimum value is about 14 dB below the peak value which occurs when the loop is approximately 7 cm above the ground.)

Because the power output of the generator was limited in this experiment to 5 Watts and the scattered field could not be measured accurately when the loop was within 1 cm of the ground, the decision was made to rebuild the transmitting antenna and to increase the generator power output to about 50 Watts. A trial-and-error method of varying the length of the directors of the Yagi array was used to increase the forward-to-backward ratio from 3 dB to more than 18 dB. Also, it

was decided to build a receiving antenna to be attached to the transmitting antenna so that it will be possible to measure the back-scattered field directly. The feasibility of this idea has yet to be tested. More extensive measurements with the improved setup over the earth are planned for the coming summer.

The construction of a laboratory experiment to measure the scattered field from a circular loop over water contained in a 10-foot diameter tank is nearly complete.

Reference

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IV.5 Numerical and Analytical Determination of Electromagnetic Fields of Antennas in the Earth Near Its Interface with Air. B. H. Sandler and T. K. Sarkar, Contract N00014-75-C-0648; Research Unit 11.

The numerical study by Siegel and King[1] for antennas in a conducting medium near an interface with air has been extended to other than conducting half-spaces.[2] The three cylindrical components of the electric field of a horizontal electric dipole in sea water, lake water, and dry earth have been computed and intercompared as functions of the frequency and of the distance between the source and the receiver. It is concluded that E_ρ is the only generally useful component. The applicability of the

approximate analytical formulas of Baños is examined. It is seen that over restricted ranges Baños' approximate formulas are in good agreement with the numerically determined results. Finally, the numerical results are confirmed experimentally through comparison with selected data measured by Siegel and King[3] and by Shen, King and Sorbello.[4]

The method used to calculate the integrals involved in the fields was a Remes polynomial approximation in λ^2 to the non-oscillating portion of the kernel. The resulting integrand is an integrable function. New approximate analytic procedures to compute the integrals near the extremely sharp peaks are being investigated. A combination of these two procedures will produce a rapid method of computing the fields to the desired accuracy.

In a related study of the currents on and fields due to wire antennas over an imperfect ground plane, the semi-infinite integrals involved in the solution are being evaluated by integrating along the vertical branch cuts. Some success has been obtained for $\rho = 0.1/k_0$ to $100/k_0$ for all values of z, h, and the complex dielectric constant of the imperfect ground plane. This has been achieved by the application of the Gaussian-Laguerre quadrature formulas. At present an attempt is being made to cover the range $\rho > 100/k_0$ by a saddle-point method of integration and for $\rho < 0.1/k_0$ by numerical integration. The above methods hold for antennas situated in either half-space.

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IV. 6 Experimental Study of the Electromagnetic Field of Bare and Insulated Antennas in Material Media. G. S. Smith, Contract F44620-72-C-0021; Research Unit 11.

Field patterns of bare and insulated linear antennas immersed in fresh water have been measured and the results reported.[1] Limitations due to the physical dimensions of the experimental model made it impossible to measure the far-zone field directly so an alternative approach was required. The electric field tangential to a spherical surface at a distance $R = 10\lambda$ from the antenna was measured in amplitude and phase and then transformed to obtain the far-field pattern. Measurements were made on linear antennas ranging in length from $0.5\lambda \leq h \leq 3.0\lambda$. The field patterns of bare antennas are compared with those of insulated antennas with concentric and eccentric insulation. The effect of varying the diameter of the insulating Teflon cylinder was also investigated. The measured field patterns are in good agreement with theoretical patterns calculated from recently developed theories applicable to concentric and eccentric insulations.[2,3]

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IV. 7 Transmission and Reception with Bare and Insulated Antennas Embedded in Skin. R. W. P. King, Contract N00014-75-C-0648, NSF Grant GK-40575 with Northeastern University, and Los Alamos Scientific Laboratory; Research Unit 11.

For various telemetric applications such as, for example, the electronic identification of animals, encapsulated transponders are embedded in or just below the hide. These include an antenna that is illuminated by a beam from an outside interrogator. The successful operation of such a device both in reception and transmission depends critically on the properties of the antenna when embedded in the dissipative medium. The design of practical receiving and transmitting antennas for embedding in a dissipative medium near its boundary with the surrounding air has been investigated. First, the receiving qualities of antennas when embedded a short distance below the surface of a material medium with the properties of skin were analyzed[1] in terms of the complex transfer function and the properties of the antenna. (Since the electrical properties of muscle are quantitatively quite similar to

those of skin, the results are also meaningful for it.) The types of antenna investigated include bare and insulated dipoles as single elements and in two-element broadside arrays. The eccentrically insulated dipole is also studied. Actual voltages across practical load impedances are determined when the antennas are embedded specifically at depths of 0.1, 0.5, and 1.0 cm in hide or skin. The results indicate that with the proper choice of antennas, frequency and load, significant voltages can be maintained when the incident field does not exceed the prescribed maximum. It is shown that the frequency for maximum voltage across the load with skin as the material is 700 MHz and that resonant bare dipoles have a practical length. However, the higher directivity of insulated dipoles provides comparable voltages with the same antennas and loads at 3 GHz. Application of the formulas and procedures to other media than skin is straightforward. A similar but more involved analysis is required if quantitative account is to be taken of a subcutaneous layer of fat between the skin and muscle.

With the application of the reciprocal theorem, the transmitting qualities of antennas embedded in a dissipative half-space with the characteristics of skin are then obtained from the previously determined receiving properties.[2] A quantitative study is made of transmission and reception between a 10-element Yagi array in air and two-element arrays of bare and insulated dipoles embedded in a dissipative half-space. The distance between the embedded transmitter and outside receiver is 4.3 m at the optimum frequency of 700 MHz or 1 m at 3 GHz. If the outer unit must be placed at greater distances from the surface of the skin, more directive antennas than the 10-element Yagi array can be provided, though they are likely to lack the structural simplicity of the Yagi.

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IV. 8 Theoretical and Experimental Study of Electromagnetic Fields and Antennas in Dissipative and Dielectric Cylinders. R. Bansal, Contract N00014-75-C-0648; Research Unit 11.

The complex physical problem associated with the transmission of a signal from one antenna in air to another located at an arbitrary distance inside a material body is of considerable practical interest. Such a situation arises, for example, in communicating with a submarine or a point under the surface of the earth from a transmitter located in air. Past studies, which have modeled the material body as a dissipative half-space, have yielded much valuable information on the transmission and distribution of electromagnetic waves in the material body. It is proposed to extend these investigations, both theoretically and experimentally, by taking the finite size of the material medium into account since the size of the material body plays an important role in determining the electromagnetic interaction, particularly at low frequencies. Experimental studies will include accurate measurements of electromagnetic fields inside salt water that is contained in a styrofoam cylinder and illuminated with an external plane/cylindrical wave source. The loss tangent of the saline solution will be varied over a wide range to include the characteristics of various media of practical interest over a broad frequency band.

IV. 9 The Finite Cylindrical Antenna in a Warm Isotropic Plasma.

M. A. V. Ward, NSF Grant ENG75-14455 and Contract N00014-75-C-0648; Research Unit 11.

This research project has been completed. In the first of two publications issuing from this investigation Maxwell-Vlasov equations are formulated and solved for a hot, isotropic, homogeneous plasma which occupies the region exterior to an infinitely long, perfectly conducting rigid cylinder.[1] The problem is formulated rigorously. The assumption of circular symmetry and specular reflection of electrons at the antenna surface yields coupled integral equations in radial and axial electric-field components. The kernels of these equations are complicated six-fold integrals. The boundary relationship between the perturbed electron distribution function and the electric field at the antenna surface can be simplified under certain conditions. Subject to these conditions, the equations are then solved for Fourier-transformed antenna current and charge distributions maintained by a delta-function generator at the center of the antenna.

The second paper develops an approximation to the Maxwellian which is analytic in the complex velocity plane and is characterized by four symmetric, simple poles.[2]

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IV. 10 Experimental Studies of Antennas in Plasmas. D. H. Preis and M. J. Miller, Contract N00014-75-C-0648 and NSF Grant ENG75-14455; Research Unit 11.

The current and voltage probes have been calibrated in the frequency range 400-1000 MHz, and the electrical length of the associated transmission line was calculated over the same frequency range. Initial tests of the probes and transmission line were made by measuring the impedance of monopole antennas in free space. The effect of the glass plasma tube on the antenna admittance was also determined.

Computer programs have been written to enable the admittance measurements to be recorded in real time using a H.-P. 9821A calculator-plotter and an interface which transfers the probe measurements directly into the memory of the calculator. In this way, graphs of the antenna admittance as a function of frequency are plotted during the course of the experiment. Programs have also been written to automate the probe-calibration procedure in order to improve the experimental accuracy. The plasma experiment has been run successfully and extensive admittance data were collected.

Initial analysis of the data has indicated that it would be useful to extend the frequency range of the experiment down to approximately 75 MHz in order to reach the plasma frequency under all experimental conditions. Presently, the probe-transmission line system has been calibrated in the frequency range, 75-1000 MHz. Preparations are being made to run the experiment to obtain simultaneously recorded data of the admittance and current and charge distributions.

IV. 11 Antennas in Matter: Fundamentals, Theory, and Applications.

R. W. P. King, G. S. Smith, T. T. Wu, and M. Owens,

Contracts N00014-75-C-0648, F19628-C-0057, and NSF Grant ENG75-14455; Research Unit 11.

The results of current and past researches, supported by the above Contracts and Grant, on bare and insulated antennas in and over dissipative or dielectric media have been integrated into a three-part book manuscript. Part I is devoted primarily to the simple, transmission-line-like behavior of the insulated antenna. A brief introduction is also given to the bare antenna in an approximate, quite simple form. Both types of antennas are studied as probes in material media. The propagation of plane waves and pulses in such media is also treated. Part II is an advanced treatment of antennas in various media. It begins with a detailed study of the electromagnetic equations in homogeneous, isotropic media including the careful formulation of constitutive relations. The complete theory of the bare dipole in a general medium is presented and this is followed by a rigorous analysis of the insulated antenna. Similar analyses are provided for the bare and insulated loop antennas. The concluding chapter in Part II treats the problem of subsurface communication between antennas near the plane interface between air and a general half-space. Finally, Part III is concerned with the construction of experimental models and the techniques of measurement relating to antennas and probes in a general dissipative or dielectric medium.

B. ANTENNAS IN AIR

IV. 12 Investigations of Electrically Thin Crossed-Dipole Antennas.

R. W. P. King and T. T. Wu, Contract N00014-75-C-0648; Research Unit 11.

The currents in a thin-wire cross with mutually perpendicular arms of equal length and radius have been determined when the incident field is not normally incident and the electric vector is not required to be parallel to one of the members.[1] The analysis is formulated in general terms but explicit formulas are obtained only for the zero-order currents which are generally adequate to determine the scattered field of very thin wires. The relatively simple formulas consist of even and odd parts for both the vertical and horizontal wires; they include components due to mutual coupling as well as those excited directly by the incident field.

The determination of the currents and charges on the surfaces of conductors that intersect at angles Δ other than 90° either as a continuing cross or to achieve a swept-wing configuration can be accomplished for electrically thin cylinders by a generalization of the analytical procedure described in previous reports for orthogonal conductors. All of the thin-cylinder conditions previously imposed when $\Delta = 90^{\circ}$ must be satisfied and, in addition, a restriction on the angle of intersection Δ must be enforced. This is needed in order to keep the junction region electrically small enough to preserve the validity of the assumption that the total charge on its surfaces is negligible. The integral equations for the currents in the swept-wing configuration are

derived in the same manner as those for the orthogonal cross but several additional terms and integrals occur since the crossed conductors are now coupled inductively as well as capacitively. The arms are taken to be of equal length ℓ. The effect of the presence of the side arms is especially significant when their electrical length $k\ell$ is $\pi/2$ or π. Although the zero-order formulas for the currents and charges per unit length are not quantitatively accurate when kh_1, kh_2, and $k\ell$ are all integral multiples of $\pi/2$, it is possible to obtain useful, relatively simple, expressions when $k\ell$ is $\pi/2$ or π, but kh_1 and kh_2 are not. More accurate currents and charges per unit length can be obtained for all arms and lengths by evaluating the first-order terms. Since they cannot all be evaluated analytically, numerical integration is necessary. The distributions of current and charge per unit length can be determined on the swept-wing structure for other than normally incident fields in the general manner described above for the orthogonal cross with equal arms.

A summary has been written[2] which reviews the coordinated application of theory and experiment to determine the induced currents and charges on circular, highly conducting cylinders in a normally incident plane-wave field in the following sequence: 1) Infinitely long cylinders with unrestricted radii. 2) Electrically thin cylinders of finite length. 3) Electrically thin crossed cylinders. 4) Tubular cylinders with unrestricted radii and finite length. 5) Crossed electrically thick cylinders.

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IV. 13 Single and Crossed Electrically Short and Thin Tubular Cylinders.

R. W. P. King, D. J. Blejer, and B. H. Sandler, Contract N00014-75-C-0648 and Grant AFOSR-76-3073; Research Unit 11.

The surface densities of current and charge induced on tubular, highly conducting cylinders and intersecting cylinders by a normally incident plane wave depend in both their axial and transverse distributions on the length and radius of the individual conductors. When $ka \leq 0.1$, the general series of transverse Fourier components is well approximated by two terms for both E- and H-polarizations. When $kh > 1$, $ka \leq 0.1$, the zero-order axial current dominates and thin-cylinder theory and junction conditions are adequate to determine the axial distributions. A paper has been written[1] in which it is shown that, as kh is reduced to satisfy the conditions $ka < kh << 1$, the magnitude of the rotationally symmetric axial current decreases to small values and the first-order axial currents together with the transverse currents dominate. All of these have nonrotationally symmetric transverse distributions. They are determined by the local incident magnetic field and are in a large measure independent of junction conditions. The paper points out the significance of the surface currents and charges on aircraft illuminated by an incident electromagnetic pulse containing low-frequency components for which the dimensions of the aircraft are electrically short. For them,

calculations of currents and charges by thin-cylinder approximations and junction conditions are inadequate and must be supplemented with currents and charges calculated from the higher-order terms in the transverse Fourier representation. The theoretical calculations and experimental data presented in this paper have been incorporated, along with the analysis of the swept-wing configuration described in the previous topic, in a comprehensive, though compact summary of the recent theoretical and experimental investigations of thin and thick cylinders and crossed cylinders.[2]

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IV. 14 Surface Currents and Charges Induced on Electrically Thick Cylinders, Crossed Cylinders, and Cylinders Crossed with Horizontal Flat Plates by an Incident Plane-Wave Field. R. W. P. King, D. J. Blejer, S.-K. Wan, R. W. Burton, M. E. Burton, T. T. Wu, and M. Krook, Contracts F29601-75-C-0119 and N00014-75-C-0648; Research Unit 11.

The problem of determining the currents and charges induced on the metal surfaces of a rocket or aircraft that is exposed to an intense

electromagnetic pulse when the structure is modeled by a thin-wire cross has been discussed under topics IV. 12 and IV. 13. The related investigation of the currents and charges on the surfaces of electrically thick crossed cylinders, a more realistic model, has been completed for the two values of electrical radius, ka = 1 and ka = 2. An experimental study was then performed to measure the surface currents and charges on a cross formed by an electrically thick vertical cylinder and a horizontal flat plate. Work in this area will be continued under a separate Grant (see the following topic).

A Final Report was prepared[1] of the results of this coordinated analytical and experimental study to determine the axial and transverse components of the surface densities of current and charge in both amplitude and phase on the several electrically thick structures. Specifically, the report contains: 1) A brief critical review of the approximations and limitations associated with the theory of thin cylinders and crossed thin cylinders with a discussion of the specific application of thin-cylinder theory to electrically thick cylinders and crossed cylinders. 2) A complete analytically based study of currents and charges on single, electrically thick, tubular cylinders in both E- and H-polarized fields. 3) An experimental study of the corresponding currents and charges on the single tubular cylinder in an E-polarized field to develop and standardize probes and techniques and to determine the degree to which the experimentally available exciting field approximates a traveling plane wave. 4) An experimental study of crossed tubular cylinders using these probes, techniques, and field. 5) An experimental study of currents and charges on a tubular cylinder with a flat plate as the cross.

This research effort has produced 6 papers--two that were reported last year, three that have been published recently, and one that has been submitted for publication. The two original papers[2,3] presented the results, respectively, of a theoretical treatment and an experimental study of the surface currents and charges induced on an electrically thick ($ka = 1$) and axially resonant ($kh = 1.5\pi$) conducting tube illuminated by an E-polarized, normally incident, plane-wave field. The first of the new articles[4] extends the theoretical and experimental work to electrically quite long tubes (kh up to 3.5π) excited by both E- and H-polarized plane-wave fields. The electrical radius remains $ka = 1$; the lengths are not restricted to those that are axially resonant. The second new paper[5] describes an experimental study of the surface currents and charges induced on crossed electrically thick conducting tubes ($ka = 1$) on a ground plane by a normally incident, approximately plane, electromagnetic wave. Two locations of the cross along the vertical cylinder ($kh_1 = 2.5\pi$ and 2π with $kh = 3.5\pi$) and three lengths of the horizontal member ($k\ell = \pi$, 1.5π and 2π) are investigated. Correlations are made between the measured data for the cross and the corresponding theoretical and measured quantities on each cylinder when isolated. The third paper in the series[6] deals with cylinders and crossed cylinders with $ka = 2$. The analytical representation for single cylinders in terms of a sum of transverse Fourier components is complicated by the existence of a propagating TE_{11} waveguide mode in the interior of the tube and requires several more terms than with $ka = 1$ in order to achieve sufficient accuracy. The final paper[7] describes the distributions of current and charge density on all of the surfaces of a cross consisting of an electrically large ($ka = 1$) tubular cylinder with a transverse plate, erected on

a ground plane and illuminated by a normally incident, approximately plane wave. In general, the currents and charges on a horizontal plate are less closely coupled to the currents and charges on the vertical cylinder than are those on a horizontal cylinder.

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IV. 15 Currents and Charges on Cylinders in a Parallel-Plate Transmission Line. R. W. P. King, S.-K. Wan, D. J. Blejer, T. K. Sarkar, T. T. Wu, and M. Krook, Grant AFOSR-76-3073 and Contract N00014-75-C-0648; Research Unit 11.

An experimental study of the electric-field distribution of the model EMP simulator is partially complete. The simulator, a parallel-plate structure between two tapered sections has been designed for use at single frequencies or with an electromagnetic pulse such as might actua lly illuminate an aircraft. Such a pulse consists of an essentially plane, traveling wave front with the mutually perpendicular electric and magnetic vectors transverse to the direction of propagation. It is the purpose of this study to determine how effectively the parallel-plate structure is able to simulate such a plane-wave field by repeating the surface current and charge measurements on cylinders and crossed cylinders described under the previous topic but with the superstructure present. A comparison of the two data should provide direct evidence about the efficacy of the model simulator as a generator of traveling plane waves since the corner reflector antenna used in the earlier measurements has been shown to generate an approximately plane wave from a sufficient distance. Special attention will be directed to the distribution of charge density on the illuminated side of each cylinder since this is particularly sensitive to the nature of the incident wave front.

Measurements of the magnitude and phase of the electric field have been taken on the surface of the ground plane, the underside of the parallel-plate section, and in the three-dimensional region comprising

the working volume. They give a detailed account of the important electromagnetic characteristics of the simulator, namely, the traveling- and standing-wave components of the field, the surfaces of constant phase, and an approximation of the radiated power. It remains to integrate the three sets of measured data of the electric field in the simulator to achieve a complete plot of the field throughout the region.

Measurements have also been made of the surface density of outside charge on a tubular cylinder located in the working volume of the model simulator. It was found that the charge density on the illuminated side ($\theta = 0^{o}$) shows the opposite result, namely, that the charge density for the case of the monopole and corner reflector better approximates the theoretical values. The explanation for this effect is that the standing-wave pattern in the working volume of the simulator causes significant variations in the magnitude and phase of the field along the surface of the cylinder. A detailed study of these effects awaits the complete representation of the field.

The severity of the departure from ideal plane-wave excitation depends on the location of the obstacle in the working volume. By comparing measurements of the charge density on cylinders at other locations in the working volume with the theoretical curves, one can determine the ideal location for an obstacle.

Finally, a separate theoretical study of the currents on thick intersecting cylinders is planned. An attempt will be made first to model the thick cylinders by bodies of revolution. This would be achieved by expanding the current in the circumferential direction in a Fourier series and in the longitudinal direction as piecewise continuous functions.

This technique would then be extended to the crossed cylinder configuration.

IV. 16 Theoretical and Experimental Study of the Ferrite Rod Antenna.

D. V. Giri, Contract N00014-67-A-0298-0005 and the Microwave Physics Branch, Ballistic Research Laboratories, U.S. Army Aberdeen Proving Ground, Maryland; Research Unit 11.

This research project was completed some time ago. A paper has recently been presented[1] on the results. A condensed version of the Conference summary is reproduced below for the reader's benefit.

Electrically small, circular loop antennas with permeable cores have been used extensively in radio receivers. More recently, the radiating properties of loop antennas with spherical ferrite cores have been studied both experimentally and theoretically by several researchers. Loop antennas with cylindrical cores, however, have not been used as transmitting elements--possibly because of the lack of sufficient theoretical and experimental information. This then provided the motivation for this investigation which addresses the problem of electrically small, driven loop when it is loaded by a ferrite cylindrical core of finite length.

A theory was first developed[2] to treat the electrically small loop antenna loaded by an infinitely long, homogeneous, isotropic, but lossy, ferrite rod. Using a boundary-value approach, an explicit expression for the magnetic current in the form of an inverse Fourier integral was derived and computed numerically. The magnetic current was found to

consist of a transmission and a radiation part. The theory was then extended to treat practical, finite ferrite rods by two different approaches.[3] The first method made use of the analogy between the ferrite rod antenna and the conducting cylindrical dipole antenna to derive an integral equation for the magnetic current on an infinitely permeable ferrite antenna. By letting $h \to \infty$, the integral equation is shown to be consistent with the earlier results for the infinite antenna. Appropriate corrections to the integral equation were then made by treating the ferrite as an imperfect magnetic conductor, and an approximate, three-term expression for the current was obtained. The second, more rigorous method obtains two coupled integral equations in terms of the tangential electric field and the tangential electric surface current from independent treatments of the interior (ferrite) and exterior (free space) problems. The coupled equations were then solved numerically by the moment method. Finally, the results of the two theories were compared with experimental measurements made on eleven different antenna configurations. The agreement was good for all cases with discrepancies occurring only very close to the driving point.

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