In this annual technical report, I shall summarize the various research activities that I and my group have pursued this past year here at UCLA, in the area of the "applications of mesoscopic physics to novel correlations and fluctuations of speckle patterns: imaging and tomography with multiply scattered classical waves," and related topics, during the grant period from July 1992 to June 1993.

I shall divide the summary of my recent research activities into two categories: in section I: fundamental physics research; in section II: applied physics research.

I. RESEARCH IN FUNDAMENTAL PHYSICS

The main thrust of my recent research activities in the fundamental research category is in the general areas of mesoscopic effects in disordered semiconductors and metals and the related field of applications of mesoscopic physics to the subject matter of classical wave propagations through disordered scattering media. I will list the main research results below.

1. Fabry-Perot Interferometer with disorder: correlations and light localization: This is a research project that I performed with my former postdoc Richard Berkovits. In this project, we studied theoretically the multiple scattering effects in an optical Fabry-Perot Interferometer (FPI) containing random elastic scatterers (and its electronic equivalent of a disordered double barrier resonant tunneling device). Among many interesting correlation effects, we find an enhanced narrow transmission peak in the mirror direction due to weak localization. At frequencies near the resonance frequency, we show that the multiply scattered waves inside the FPI are in fact localized.
Our predictions may lead to realistic experimental studies of Anderson localization of light which have so far eluded physicists in recent years. Our paper on this topic has been published in Physical Review B.

2. Electron-phonon inelastic scattering rate and the temperature scaling exponent in integer quantum Hall effect: Very recently, following a suggestion by Prof. Steve Kivelson, my student Hui-Lin Zhao and I looked into the problem of the mechanisms for inelastic scattering in the quantum Hall effect. Experiments carried out by Dan Tsui's group as well as in von Klitzing's group several years ago indicated that the width of the transition region between plateaus obeys scaling relations: temperature as $\Delta E \sim T^\kappa$, with $\kappa \approx 0.42$. This temperature scaling exponent was argued to be related to the inelastic scattering rate exponent $1/\tau_{\text{in}} \sim T^p$ as $\kappa = p/2\mu$, where $\mu$ is the localization length exponent defined in $\xi_{\text{loc}} \sim \Delta E^{-\mu}$. Recent numerical simulations on short-range scattering potential models have yielded reliable values $\nu \approx 2.3 - 2.4$. Percolation arguments, which are valid for smooth potentials, in the semiclassical approximations gives $\mu = \nu + 1 = 7/3$, where $\nu = 4/3$ is the percolation length exponent ($\xi_p \sim \Delta E^{-\nu}$), very close to the numerical findings for the Anderson model numerical work which models short-range disorder potential. For diffusive electron transport in zero field in 2D, $p = 1$ was found sometime ago for electron-electron scattering by Altshuler and Aronov. If one assumes that this value is still applicable at large field, one would be led to seeming disagreement with the experimental value for $\kappa$. Fermi liquid theory would give $p = 2$, but it is valid only for ballistic transport regime, so that the factor of two should be absent in the relation between $\kappa$ and $p$. This again leads to difficulties in reconciling with the experimentally measured value for $\kappa$. We performed analytical calculations of the electron-phonon scattering rate in the semi-classical regime (smooth potential), and found that due to the high magnetic field, the linear regime ($1/\tau_{\text{in}} \sim T$) which normally applies only for $T > T_D$ (the Debye
temperature) now moves all the way down to $T \approx \hbar c/l \approx 1K$, where $l$ is the magnetic length. In contrast, the electron-electron scattering rate is still $1/\tau_{ee} \sim T^2$. This indicates that for a very wide temperature range in the smooth potential (percolation) regime, semiclassical analysis indicates that acoustic phonon scattering dominates the inelastic processes, and gives the value $p = 1$. But because of the fractal nature of percolation perimeter paths for semi-classical electrons, the relation between the inelastic length and the inelastic scattering rate $1/\tau_{in}$ is $L_{in} \sim \tau_{in}^{1/D_H}$, where $D_H = 7/4$ is the fractal dimension of the perimeter ("Hull") of the percolation clusters. In the semi-classical picture, the electron wavefunction decays only through tunneling events at the saddle points between percolation clusters, thus the correct crossover criterion between localized versus extended transport regimes is $L_{in} \approx \xi_p$, which separates the regime of transport where coherent, successive (sequential), tunneling dominates (the localized bahavior) and the regime where electron experiences dephasing while orbiting on a percolation perimeter such that the sample's resistance is the classical addition of the various saddle point resistances (the extended behavior). These considerations lead to the result $\kappa = 7/3$, as is found experimentally. We also have argument suggesting that this phoenomenon of the high temperature linear law for electron-phonon scattering rate being pushed down from $T_d$ to $\hbar c/l \sim 1K$ is quite general, and in fact holds even for short range scattering potential. This can explain the seemingly universal value for $\kappa$ for both short-range scatterers and smooth random potentials.

Our paper on this subject has just received very favorable referee reports from the Physical Review Letters, and we expect it to be published in this journal soon.

3. Transmission and reflection correlations of second harmonic waves in non-linear random Media: Since about two years ago, I started to work on the generalization of my earlier work on speckle correlations to treat the case of non-linear optical
systems, motivated by discussions with Prof. Lagendijk of University of Amsterdam. I obtained very nice theoretical results for the correlation functions, which have recently been successfully measured in the Amsterdam experimental group. So we have just submitted to Physical Review Letters a joint theory/experiment paper, in which we present the first measurement and theoretical analysis of the first-kind correlations ($C^{(1)}$) in both transmission and reflection geometries of second harmonic light generated inside a (powder) random medium, as a function of the angle of the incoming and outgoing light. The random medium consists of scattering particles with a non-linear susceptibility. We obtained the striking theoretical result, which are verified nicely by experiment, that correlations in reflection of the second harmonic light depend mainly on the sample thickness $L$, in sharp contrast to the correlations in reflection of the fundamental light in the linear scattering regime, which mainly depend on the mean free path $l$. We also find the interesting result that memory effect in non-linear optics corresponds to $2\Delta \theta_{\text{in}} = \Delta \theta_{\text{out}}$, where $\Delta \theta_{\text{in}}$ is the angular shift in the incoming fundamental light, and $\Delta \theta_{\text{out}}$ is that in the outgoing second-harmonic light.

II. RESEARCH IN THE APPLIED PHYSICS AREAS

Since a couple of years ago, I have also started conscientiously a program to work on some applied physics problems. One of the motivations is that I find particular satisfaction when my research can have a real potential of being useful to society, rather than just for intellectual curiosity. Another motivation is a realization that more and more, the US research emphasis will shift to more applied areas, as the industrial competition with Japan and Europe intensifies. This new direction (on a part time basis) was also prompted by the apparent potential usefulness in my earlier work on speckle pattern correlations, which have obvious consequences in the field.
of diffusive light imaging and nondestructive acoustic evaluations. The following is a brief account of some of the main results I have obtained recently. They are mainly in two areas: (i) transport in mesoscopic electronic devices; (ii) imaging with multiply scattered light or acoustic waves.

1. **Far-infrared photon-assisted transport through quantum point contact devices:** Another topic that is motivated from Prof. Hu’s experimental work is the applicational possibilities of using quantum point contact devices as new far-infrared photon detectors. In a recent preprint submitted to the Physical Review B, we analyze theoretically the phenomenon of photon-assisted quantum transport in split-gate quantum point contact devices. Both the transverse and longitudinal polarization configurations for the AC photon field are considered. We predict that ministeps should appear in the drain/source conductance vs. gate voltage relation, as well as in the $I - V_{DS}$ curve in the nonlinear regime, for a quantum point contact irradiated with a coherent far-infrared radiation. The width of the ministeps is proportional to the radiation frequency, and the height of the ministeps is a function of the radiation power. We then calculate the current responsivity for this photon-assisted process in the limit of a small radiation signal, and show that it is quite comparable to the quantum efficiency $e/h\omega$ at and above 1 $THz$.

2. **Photon Migration Distributions in Mutiple Scattering Media:** Another area of applied physics research that I have been working in is to apply concepts from my previous work on understanding the correlations properties of multiply scattered light speckle patterns to see if it is possible to perform imaging in biological tissue systems using diffusive red or infra-red light. In a new paper submitted for the proceedings of the SPIE conference, we study the photon migration path distributions in biological tissue and other multiple scattering media. We derive analytical expressions for the so called “banana” shape regions where photon fluence densities are concentrated, in
both infinite medium and semi-infinite medium, for the point source/detector configuration. Our theory is based on a perturbation technique, which yield exact closed form expressions for the photon path distribution functions. These results are compared with Monte Carlo simulation studies. We are still working hard in this general area, now trying to figure out ways to maximize the intensity of perturbed diffuse light due to the introduction of defects (such as a tumor) into a multiple light scattering system (such as a human tissue system), which absorbs and scatters light (diffusively) more than the surrounding tissues. If our efforts are successful, we can hope to propose new setups to optically detect millimeter size tumors in human tissues. This could be a very big prize!

The above summarizes the various research activities that I and my group have pursued this past year. I hope they are satisfactory to the requirement of the guidelines of the DOE granting agency. On the next page, I shall list all the papers (published as well as preprints) that I have published from the research projects that I have performed during this granting period.
PUBLICATIONS FROM RESEARCH ACTIVITIES BETWEEN 7/92 TO 6/93


STATEMENT OF RESEARCH PLANS FOR THE NEW DOE GRANT PERIOD

Shechao Feng

July 1992 – June 1993

During the upcoming new year, we plan to pursue research in the following few areas, under DOE funding:

1. In the upcoming year I would like to start a new program to study the dynamics and noise spectra of a driven single flux line in superconductors; in particular to investigate the possible instabilities and avalanche-type behavior in such a system. This project will be with Chao Tang from NEC and my former postdoc Leo Golubovic, and our focus will be on the low temperature dynamics of single flux lines in superconductors near the depinning transition (corresponding to the critical current $j_c$). Our new feature is the realization that Lorentz force produced by a driving current is confined near the sample surfaces, both near and above the depinning threshold, unlike the standard approach to depinning transition where a bulk force is applied. We expect to find a novel instability of the flux line motion at large driving currents, such that at driving forces $F$ exceeding a threshold which corresponds to applied current density reachable in experiments, the flux line speed reaches a terminal value, independent of $F$. This corresponds to turbulent generation of flux lines near the sample surfaces, with enhanced fluctuations and dissipations. We also would like to study the power spectra of the voltage noise (or the noise of the end point velocities of the flux line) generated by the moving flux line in the presence of random pinning forces. We have preliminary results that show that the noise spectra have a rich set of behaviors: $\omega^{1/2}$ at low frequency, $\omega^{-1/2}$ at intermediate frequency, and $\omega^{-3/2}$ at high frequencies. We would like to interpret the low frequency spectrum as coming from classical uncorrelated fluctuations (at large length scales); the intermediate frequency spectrum as due to conventional critical dynamics of the depinning transition,
whose exponents have been studied very recently by Parisi, Natterman, and Daniel Fisher. The $\omega^{-3/2}$ behavior may be interpreted as due to avalanches similar to that in self-organized critical phenomena.

2. We will continue to study the problem of applying mesoscopic theoretical techniques for acoustical non-destructive evaluations of cracks and other defects in materials containing already many cracks which scatter sound wave strongly, i.e. in the multiple scattering limit. We plan to perform extensive numerical simulations, taking into account realistic material parameters, to make study if our method will work for real systems. Such effort is currently under way.

3. We have also recently started a new effort to study the problem of light multiple scattering and reflection from random rough surfaces. This problem is of technological importance in the field of remote sensing as well as surface characterization. Our focus is on the relation of correlation functions of the reflected speckle patterns and the enhanced backscattering peak. Our method will be using perturbation theory on relatively smooth surfaces.