5.0 Optics and Quantum Electronics

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5.1 The Nonlinear Waveguide Interferometer

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The nonlinear optical interferometer transforms a phase modulation into an amplitude modulation. With a continuous stream of optical pulses as the "bias", control pulses can affect the passage of individual pulses. In this way one may realize any logic gate operation.[1] The throughput rate of the interferometer is determined solely by the material relaxation time and thus can be extremely high (>100 Gbit). The travel time of the pulses through the interferometer determines the delay time.

A nonlinear waveguide interferometer was built by N. A. Whitaker in GaAs, with access waveguides as originally realized in $LiNbO_3$ by Lattes et al.[1] The doped substrate provided the lower index for the guiding layer of undoped GaAs, and the lateral confinement was achieved with etched ridges. This interferometer was tested as an electrooptic device with a voltage applied to electrodes mounted for this purpose. Better than 13 db extinction ratio was realized. The nonlinear response was limited by the damage threshold at the input waveguide-interface.[2] It was found that for input intensities exceeding several Mw/cm^2 the cleaved facet exhibited damage. This was attributed to the free carrier absorption of the substrate, and could be eliminated in principle by replacing the substrate with undoped GaAlAs. Because of the findings described below, we decided to take a different approach.

An investigation by C. Gabriel on the operation of a nonlinear interferometer formed of a GaAs/AlGaAs heterostructure ridge waveguide with cleaved endfaces revealed the importance of thermal effects in determining a limit to the rate of throughput through the interferometer.[3] The (small) free-carrier absorption of the nominally undoped sample was sufficient to account for most of the nonlinear phase shift at a 100MHz repetition rate of the 1.06 micron pulse-stream. The estimated absorption coefficient was 2×10^{-4} cm^{-1}. In view of this finding we questioned the use of the bulk nonlinearity in

GaAs as a means for high-rate all-optical switching. Similar difficulties do not arise in silica fibers, and thus we decided to use fibers for all-optical nonlinear interferometers.

A particularly promising realization of the nonlinear fiber interferometer has been carried out by M. Shirasaki, a visiting researcher from Fujitsu Laboratories, and D. L. Wong, a graduate student.[4] The interferometer utilizes one single fiber in which two mutually orthogonal polarized versions of the same pulse, delayed with respect to each other, interfere under control of a cotraveling pulse (see Fig. 5.1). A probe pulse *(P)* is separated in a pulse divider *(D)* into two mutually orthogonally polarized pulses with the same power that are delayed with respect to each other and are injected into a fiber. At the fiber output they are recombined by an analogous pulse combiner arrangement. Because the two pulses travel through the fiber with subnanosecond time separations, their relative phase is insensitive to slow fluctuations of the effective index of the fiber. A control pulse *(C)* advanced by a time corresponding to the path difference in the pulse divider is similarly separated into two orthogonally polarized pulses, the second of which travels synchronously with the front probe-pulse, changing the index seen by this part of the probe pulse. As a result, the polarization of the probe pulse is changed after recombination.

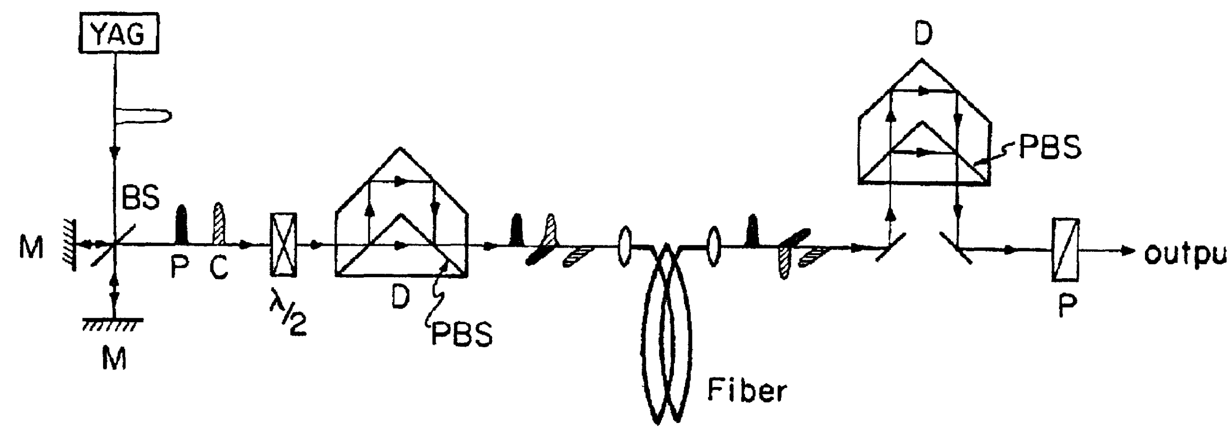

Figure 5.1. : Interferometer

In the experiment a fiber length of 400 m was used and the pulses were generated from a modelocked Nd:YAG laser operating at 1.06 microns at 100 MHz repetition rate. The interferometer was found to be extremely stable, with no feedback stabilization required. Of course, the repetition rate could be much higher, because the fiber nonlinearity is still instantaneous on a subpicosecond time scale. Because of the success of the preliminary experiments on this interferometer, we plan to explore its potentialities further in the coming year.

5.2 Picosecond Optical Signal Sampling

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Hermann A. Haus, Lynn Molter-Orr, Weiping Huang

The work on nonlinear waveguide sampling devices[5] has led into the reexamination of the theory of modecoupling and into the study of waveguide dispersion characteristics, with particular attention devoted to the single-mode nature of the guides.

The conventional theory of mode coupling was challenged by Hardy and Streifer.[6] For strong coupling these authors showed by means of an expansion in terms of normal modes that modifications are necessary in the coupling coefficients and propagation constants. We showed that such modifications are already contained in the derivation of the coupled mode theory from a variational principle for the guide-propagation constant set up for the study of traveling wave tubes in 1958.[7,8] A more subtle consequence of the revised coupled mode theory is the appearance of crosstalk in switches that is not predicted by the conventional theory. We have shown that proper modification of the coupling structure can prevent crosstalk.[8,9] In order to test the predictions of the revised coupled mode theory, they were compared with the exact analysis on a simple coupler structure. It was found that the agreement is excellent, even in the limit of rather strong coupling.[10]

Another issue in the design of nonlinear waveguides is the determination of the mode profile, and the design criteria for the "single-modedness" of a waveguide. Many analyses have appeared in the past; the approximate analyses are unsatisfactory near mode cutoff, the more accurate analyses are computation intensive. We have developed a reliable method for the evaluation of propagation constants based on a variational principle. The method requires much less computation than previous methods and will be extended to provide coupling constants for two-guide couplers.

5.3 Surface Acoustic Wave Propagation in Gratings

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Hermann A. Haus, Weiping Huang

We have begun to study higher order effects in metal-strip SAW gratings. The purpose is to develop theoretical expressions for the quadratic dependence of the frequency shift upon η/λ , where η is the thickness of the grating fingers and λ is the wavelength. This dependence is observed experimentally over and above the linear dependence and is matched with empirical coefficients. The SAW research group at the Siemens Research Laboratory in Munich is sharing with us their experimental results in an effort to arrive at a reliable theory for SAW grating resonator design.

5.4 Solitons

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Hermann A. Haus, Ling-Yi Liu, Mary R. Phillips, Kristin K. Anderson

The nonlinear fiber interferometer developed for optical switching and described in the section on the Nonlinear Waveguide Interferometer will require the use of solitons when very high throughput rates are the objective. Hence we are continuing the study of soliton propagation that was initiated with the study of the soliton laser[11] developed by Stolen and Mollenauer at AT&T Bell Laboratories. Dr. Islam is now a member of the Bell Laboratories group and the exchange of information is continuing. With Dr. Nakazawa, who was a visiting scientist from NTT, Japan, we developed the theory of the Fiber Raman Soliton Laser (FRASL) which was demonstrated by Drs. Islam and Mollenauer.[12] The theory[13] establishes limits on the obtainable pulse-width.

The nonlinear fiber interferometer uses the interaction of two orthogonally polarized fields. This effect is described by two coupled nonlinear Schrodinger equations, a phenomenon that has not been studied extensively since the first publication of the application of the inverse scattering theory to this problem.[14] We have determined the phase shift produced by two orthogonally polarized solitons passing through each other on a birefringent fiber by a perturbation analysis.[15] The full theory of soliton interactions will be the subject of continued research.

References

[1] A. Lattes, H.A. Haus, F.J. Leonberger, and E.P. Ippen, "An Ultrafast All-Optical Gate," I.E.E.E.. J. Quant. Electron. *QE-19*, 1718, (1983).

[2] N.A. Whitaker, "All-Optical Signal Processing in Semiconductor Waveguides," Ph.D. Thesis, Dept. Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

[3] M.C. Gabriel, H.A. Haus, and E.P. Ippen, "Thermal Index Changes by Optical Absorption in Group III-V Semiconductor Waveguides," J. Lightwave Tech. *LT-4*, 1482, (1986).

[4] H.A. Haus, M. Shirasaki, and D. Liu Wong, "A Nonlinear Fiber Interferometer and Logic Gate," to be presented at CLEO '87, Baltimore, Maryland, April 27, 1987.

[5] L.A. Molter-Orr, H.A. Haus, and F.J. Leonberger, "20 GHz Optical Waveguide Sampler," I.E.E.E.. J. Quant. Electron. *QE-19*, 1877 (1983).

[6] A. Hardy and W. Streifer, "Coupled Mode Theory of Parallel Waveguides," J. Lightwave Tech. *LT-3*, 1135 (1985).

[7] H.A. Haus, "Electron Beam Waves in Microwave Tubes," Proceedings of the Symposium on Electronic Waveguides, Polytechnic Institute of Brooklyn, April 1958.

[8] H.A. Haus, W.P. Huang, S. Kawakami, and N.A. Whitaker, "Coupled-Mode-Theory of Optical Waveguides," J. Lightwave Tech. *LT-5*, 17, (1987).

[9] H.A. Haus, "Coupled-Mode Theory Revisited," S.P.I.E. Conference on Fiber Optics, Optoelectronics and Laser Applications in Science and Eng., Cambridge, Mass., September 1986, Paper no. 70417.

[10] J.P. Donnelly, H.A. Haus, and L.A. Molter, "Cross Power and Cross Talk in Waveguide Couplers," submitted for publication to J. Lightwave Tech.

[11] L.F. Mollenauer and R.H. Stolen, "The Soliton Laser," Opt. Lett. *9*, 13, (1984).

[12] M.N. Islam and L.F. Mollenauer, "Fiber Raman Amplification Soliton Laser," 14th International Quantum Electronics Conference, San Francisco, Calif., June 1986.

[13] H.A. Haus and M. Nakazawa, "Theory of the Fiber Raman Soliton Laser," J. Opt. Soc. Am. B (accepted for publication).

[14] S.V. Manakov, "On the Theory of Two-Dimensional Stationary Self-Focusing of Electromagnetic Waves," Sov. Phys. JETP *38*, 248, (1974).

[15] H.A. Haus, "Collisions of Orthogonally Polarized Solitons," Quantum Electronics and Femtosecond Optics, M.I.T., R.L.E. Memo No. 9, Cambridge, Mass., 1987.

5.5 Analysis and Characterization if III-V Guided Wave Optics Rib Waveguide Couplers

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Nadir Dagli, Clifton G. Fonstad, Jr., Hermann A. Haus

Rectangular waveguides and couplers are being analyzed as part of a program to make efficient multiple waveguide optical switches and modulators capable of operating at very high data rates. In these studies III-V compound semiconductors were used and the fabrication, characterization and modeling of waveguide devices were undertaken. In this context a new technique was developed to model open guided wave structures. The technique is basically a mode-matching technique which results in a microwave equivalent circuit for the geometry under consideration. In order to accurately describe open guided wave structures, contributions from the continuum spectra as well as the guided spectra should be taken into account. This is difficult, however, because in the model expansions, the continuum set is represented as integrals and such integral terms are not suitable for an equivalent circuit representation. Usually these terms are converted into summations by artificially bounding the structure with conducting boundaries. In our work these terms are discretized by converting integrals into summations using suitable basis function expansions. This results in a transmission line representation for all regions, even those where there are no guided modes. Therefore, it is possible to analyze structures where there are no guided modes in the outer regions, situations which cannot be analyzed with simple approximate techniques such as the effective dielectric constant method. The resulting model is modular, and, consequently, the method can be used to analyze a wide variety of rectangular dielectric waveguides. Because of modularity, it is possible to divide a complex structure into a cascade of dielectric steps and uniform regions. Steps are modeled as a transformer network and uniform regions as uniform transmission lines.

A general computer program was developed to analyze open guided wave structures. The structure under consideration can be a single guide or multiple coupled waveguides with nonidentical widths and spacings. The geometry of the waveguides can be either ideal with vertical sidewalls or more complex with non-ideal sidewalls like the sloped sidewalls produced with chemical etching techniques. Results indicate that convergence of propagation constant values is very fast as the number of discretized continuum modes is increased. Results of this method were compared with the results of other mode matching techniques for rectangular fibers, rib guides, strip guides and channel guides. Agreement is excellent and the required computational effort is less than that of the other techniques. Using this technique universal design curves were generated and plotted for the design of rib guides. Results demonstrate that when there are well guided modes in the slabs, the contribution from the continuous spectra is very small even for structures with large discontinuities.

Once the equivalent circuit parameters for a waveguide are developed the extension of the analysis to couplers is very easy and requires very little additional computation. Both directional couplers and three guide couplers have been analyzed. Propagation constant values of the supermodes of the structure were calculated and using these values, transfer lengths were determined. The results of these theoretical predictions were experimentally verified by measurements on rib waveguides and multiple coupled guides in GaAs. These devices are produced with chemical etching techniques, and hence have sloped sidewalls. Furthermore, they are very tightly coupled. Experimentally determined transfer lengths on directional couplers and three guide couplers of various dimensions are in excellent agreement with the theoretical predictions. Other approximate techniques either cannot analyze such devices at all or are not accurate enough. Such an accurate technique is very important in the design of integrated optical switches, modulators, power dividers and combiners.

5.6 Multiple Quantum Well Heterostructures and Diode Laser Arrays

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Elias Towe, Clifton G. Fonstad, Jr.

Our program on (Al,Ga)As/GaAa quantum well heterostructures has progressed to the point where we can now routinely grow very high quality single and multiple quantum well structures. We have been able to achieve the high optical optical layers we need for laser structures by a careful attention to the growth conditions. A feature that we have found to be instrumental in obtaining high luminscent efficiency from our layers was the incorporation of a superlattice buffer layer before growing the device structures.

Broad area lasers with the typical dimensions of 400 μm $\times$ 210μm $\times$ 100μm fabricated from our best multiple quantum well laser structure exhibited measured threshold current densities of around 220 A/cm^2. This value is comparable to those reported in the literature for state-of-the-art devices of similar structures grown by molecular beam epitaxy.

We have also recently developed a novel type of diffraction-coupled phase-locked laser array, the mixed-mode phase-locked (M^{2}PL) laser. This new device has the usual parallel-element array of lasers but it incorporates a section in the middle of the device where the modes are unguided. This middle section forms the mode-mixing region and allows the modes in the individual elements to couple and mix by diffraction, thus establishing a common phase for all the elements. Stable, single-lobe far-field patterns are routinely obtained from these devices. For a seven-element array, patterns as narrow as 2° have been measured and up to 60 m W has been obtained in a single peak.

For the M^2PL lasers which have been studied thus far, the mode-mixing region has been 75 μm long and the guiding regions on either side of it have been approximately 100 μm long. The individual array element ridge guides and the mode-mixing region are photolithographically defined and wet chemically etched. The guides are aligned so that the etched regions between them are v-shaped; the top metallization forms Schottky contacts on the lightly-doped AlGaAs regions between the guides and ohmic contacts to the ridges themselves. Each guide is 3.0 μm wide and the center-to-center spacing is 7.0 μm.

At the present time analytical models for the new device are being developed so that design curves for the optimal mode-mixing region length can be determined and the device performance can be optimized.

Publications

Dagli, N. and C.G. Fonstad, "Microwave Equivalent Circuit Representation of Rectangular Dielectric Waveguides," Appl. Phy. Lett. *49*, 308 (1986).

Dagli, N. and C.G. Fonstad, "A New Method of Analyzing and Modeling Integrated Optoelectronic Components," Digest of the 1987 I.E.E.E. Microwave and Millimeter-Wave Monolithic Circuits Symposium, in press.

Towe, E. and C.G. Fonstad, "Mixed-Mode Phase-Locked Quantum Well Laser Arrays," Technical Digest of the I.E.E.E. International Devices Meeting, 1986, p. 626.

5.7 Femtosecond Laser Systems and Pulse Generation

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James G. Fujimoto, Erich P. Ippen

During the past year we have focused on two principle areas of ultrashort pulse generation: the development of a high repetition rate femtosecond laser source and amplifier and the development of a wavelength tunable femtosecond laser system. These new systems provide capabilities for the measurement of ultrafast phenomena in a wider variety of physical systems with greater sensitivity than previously possible.

Our high repetition rate femtosecond laser amplifier consists of a colliding pulse modelocked (CPM) ring laser with a copper vapor laser pumped amplifier. The CPM laser uses passive modelocking with an intercavity dispersion compensating prism arrangment similar to that demonstrated by Fork et al. at AT&T Bell Laboratories.[1] The laser operates at 625 nm and can produce pulse durations as short as 35 fs. The laser output consists of a train of .1 nJ pulses at a 100 MHz repetition rate. The high repetition and short pulse duration of this system make it ideal for time resolved studies requiring extremely high temporal resolution and sensitivity.

For many experiments, however, it is desirable to generate pulses of higher intensity. For these applications the output of the CPM laser can be amplified in a high repetition rate amplifier.[2] Our system uses a copper vapor laser operating at an 8 kHz repetition rate as the pump source for a dye amplifier. Using a 6 pass configuration in a thin gain jet, we have obtained gains of greater than 10^4 corresponding to single pulse energies of 2 2μJ with output pulse durations as short as 50 fs. The peak intensities are greater than 10^8 W, sufficient for most nonlinear optical experiments involving pump-probe or transient four wave mixing techniques. In addition, these amplified pulses can be used to generate a broadband femtosecond continuum via self-phase-modulation. This continuum provides a broadband wavelength probe suitable for the measurement of transient absorption or reflectivity lineshape on a femtosecond time scale. The high repetition rate of this system permits the use of lock-in detection techniques and single averaging so that very high sensitivity measurements are possible. Changes in optical properties as small as 1 part in 10^5 - 10^6 are detectable.

Our second major topic of research in ultrashort pulse generation involves the development of a tunable femtosecond laser system for wavelengths in the visible and near IR. This system is based on a Nd dye laser. The Nd μ m at a repetition rate of 80 MHz. These pulses are compressed by using self-phase-modulation in a single mode optical fiber followed by a diffraction grating dispersive delay line. Pulse durations as short as 5-10 ps may be obtained with CW average powers as high as 3 W. Using a nonlinear second harmonic crystal (KTP), output powers of $\sim$1 W are generated at 532 nm with pulse durations of less than 5 ps. This source is then used to pump a synchronously modelocked tunable dye laser. Since no passive modelocking dyes are used the wavelength of the dye laser may be tuned over the bandwidth of the dye. Using rhodamine 6G we have generated pulses as short as 300 fs tunable over a range of λ = 580 to 625 nm. Further wavelength tunability may be accomplished by changing the dye and laser mirrors. Tuning of the laser output between 580 and 850 nm should be possible.

Shorter pulse durations may be generated by cavity dumping the synchronously pumped dye laser and using an addition stage of optical fiber pulse compression. Pulse durations of less than 50 fs have been demonstrated using this technique in the visible.[3] Tunable femtosecond sources are extremely important since they allow the investigation of transient processes associated with different energy level or resonance behavior in materials. The visible and near IR wavelength region is especially important for studies in electronic and optoelectronic semiconductors such as GaAs.

References

[1] J.A. Valdmanis, R.L. Fork, and J.P. Gordon, "Generation of Optical Pulses as Short as 27 Femtoseconds Directly from a Laser Balancing Self-Phase Modulation, Group-Velocity Dispersion, Saturable Absorption, and Saturable Gain," Opt. Lett. *10*, 131 (1985).

[2] W.H. Knox, M.C. Downer, R.L. Fork, and C.V. Shank, "Amplified Femtosescond Optical Pulses and Continuum Generation at 5-kHz Repetition Rate," Opt. Lett. *9*, 552 (1984).

[3] J.D. Kafka and T. Baer, "Generation of Tunable Femtosecond Pulses," Technical Digest of the Conference on Lasers and Electro-Optics, Baltimore, Maryland, May 1985, Paper ThZZ5-1.

5.8 Femtosecond Carrier Dynamics in GaAs

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National Science Foundation (Grant ECS 85-52701)

Erich P. Ippen, James G. Fujimoto

The investigation of transient behavior of excited carriers in GaAs is relevant to electronic and optoelectronic devices which will require high speed nonequilibrium carrier phenomena. The recent advent of new and more versatile femtosecond laser generation techniques provide opportunities for the investigation of transient scattering relaxation and transport processes which occur on the femtosecond time scale.

The scattering mechanisms of optically excited carriers in GaAs and AlGaAs were investigated using pump and probe measurement of transient absorption saturation.[1–5] Pulses as short as 35 fs at 625 nm (2 eV) were generated by our CPM dye laser and used to excite carriers and investigate their subsequent scattering out of their initial optically excited states. A two component relaxation process was observed with an initial relaxation occurring on a time scale comparable to the pulse duration and a slower ~1 ps relaxation corresponding to a cooling of the excited carrier distribution to the lattice temperature. New measurement techniques using varying pulse duration, chirp and polarization were developed to investigate the dynamics of the initial femtosecond relaxation process. Measurements performed in GaAs at carrier densities ranging from 10^{17} to 10^{18} cm^{-3} indicated the presence of an initial relaxation process with a 30 to 13 fs relaxation time. These measurements are significant because they suggest the presence of an extremely rapid carrier density dependent relaxation mechanism for highly excited carrier in the GaAs. In addition, these results demonstrate the measurement of transient processes on a time scale as short as 10 femtoseconds, comparable to or less than the incident laser pulse duration.

Additional measurements of carrier relaxation have been performed in Al_{χ} $Ga_{1-\chi}$ As with varying mole fraction compositions of Al. Changing the semiconductor composition produces changes in the energy band gaps and allows an investigation of the effects of excited carriers with different excess energies in the conduction and valance bands. As the mole fraction of Al is increased the direct energy band gap at the Ga point increases as well as the indirect gaps to the *X* and *L* valleys. As the band gap is increased, a dramatic decrease in the rate of carrier scattering out of the initial optically excited states is observed. Scattering times of 13 fs, 20 fs, 80 fs, 130 fs, and 300 fs are observed for mole fractions χ= 0, \, 0.1, \, 0.2, \, 0.3, and 0.4, respectively. The observed change in carrier scattering rate may be attributed to a number of possible factors including the generation of carriers with less excess energy and decreased effective temperature, changes in allowable scattering states, changes in screening effects, as well as possible changes in intervalley scattering rates.

While these measurements permit the investigation of extremely rapid scattering processes, in order to describe more fully the relaxation of the excited carriers it is necessary to perform measurements at multiple excitation and probe wavelengths. These investigations have only recently been made possible through the development of high sensitivity, high repetition rate, femtosecond amplified pulse sources. We have extended our preliminary investigations in GaAs and AlGaAs using femtosecond pump and continuum probe absorption saturation measurements.[5] Our preliminary experimental results provide evidence for transient nonthermal carrier distributions occuring on a time scale of several tens of femtoseconds. These processes are observed as transient spectral hole burning and correspond to the excited electrons and holes before they reach a quasi-thermal distribution. In addition to transient, continuum probe measurements demonstrate that carriers excited high into the band in GaAs are scattered to energies several hundred MeV away within a time scale of several tens of femtoseconds. The scattering dynamics of highly excited carriers and the possibility of anisotropic excitation in *k* space or ballistic transport are relevant to high speed devices fabricated in these materials systems.

Additional experiments are planned using our tunable femtosecond dye laser source to investigate processes such as intervalley scattering in GaAs and GaAlAs. The role of $\Gamma - X$ and $\Gamma - L$ scattering is particularly important since it produced the negative differential resistivity observed in these materials. In addition, we are currently investigating techniques for the measurement of real space transport phenomena and tunneling in these systems. The use of quantum wells for the generation and detection of excited transient carriers is being studied as a possible technique for investigating transport phenomena on the submicron scale.

References

[1] R.W. Schoenlein, W.Z. Lin, J.G. Fujimoto, and G.L. Eesley, "Femtosecond Studies of Nonequlibrium Electronic Processes in Metals," in *Ultrafast Phenomena V*, edited by G. R. Fleming and A. E. Siegman. New York: Springer-Verlag, 1986.

[2] W.Z. Lin, J.G. Fujimoto, E.P. Ippen, and R.A. Logan, "Femtosecond Carrier Dynamics in GaAs," Appl. Phys. Lett. *50*, 124, (1987).

[3] W.Z. Lin, J.G. Fujimoto, E.P. Ippen, and R.A. Logan, "Femtosecond Studies of Absorption Saturation Dynamics in GaAs," Technical Digest of the 14th International Conference on Quantum Electronics, San Francisco, Calif., 1986, p. 50.

[4] W.Z. Lin, J.G. Fujimoto, E.P. Ippen, and R.A. Logan, "Femtosecond Carrier Dynamics in GaAs and $Al_\chi Ga_{1-\chi}As$" presented at Lasers '86, Orlando, Florida, November 1986.

[5] W.Z. Lin, R.W. Schoenlein, S.D. Brorson, J.G. Fujimoto, and E.P. Ippen, "Femtosecond Carrier Thermalization in GaAs and AlGaAs," 15th International Conference on Quantum Electronics, Baltimore, Maryland, April 1987, paper TuJJ2.

5.9 Femtosecond Spectroscopy of Electronic and Optical Materials

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National Science Foundation (Grant ECS 85-52701)

James G. Fujimoto, Erich P. Ippen

Complementing our research in the area of ultrashort pulse generation, we are investigating femtosecond time resolved spectroscopic techniques and measurements in a variety of materials and systems which are relevant to electronic, optoelectronic, and all-optical signal processing.

In addition to studies of semiconductors, we are also investigating transient processes in metals. Because of their inherent high densities, many of the transient processes occuring in these systems are extremely rapid, occuring on a femtosecond time scale. In contrast to semiconductors, changes in optical properties associated with metallic systems can be extremely small. Thus, transient spectroscopy on metals has been only recently possible through the development of high sensitivity techniques. Using transient reflectivity and photoemission, it is possible to generate and investigate nonequilibrium electron heating. If the incident pulse duration is shorter than or comparable to the electron-phonon energy transfer time, electron temperatures far in excess of lattice temperature may be generated. Experiments in noble metals allow measurements of the transient electron temperature through optical transitions from the *d* bands. Our experiments demonstrate the generation of nonequilibrium temperatures in the electron gas which relax to the lattice temperature on a time scale of ~1ps.[1-3] In addition, we have performed pump-probe time-of-flight measurements to investigate electronic heat transport phenomena in thin gold films of varying thickness.[1-3] Subpicosecond thermal transport times are observed in 1000-2000Å thick samples demonstrating the presence of nonequilibrium electronic heat transport with a velocity of $\sim 10^8$ cm/sec. These measurements of the first observations are nonequilibrium electronic transport phenomena in metals. Extensions of these techniques to semiconductor-metal interfaces will be of potential importance in investigating transport phenomena in electronic materials and devices. In addition, the generation of transient high temperature electrons in metals without the presence of lattice melting is relevant to transient high current devices as well as transient high current photoemission and electron beam sources.

Organic polymers are another potentially interesting material system for time resolved spectroscopy. In particular, the polydiacetylenes are a potentially important material for applications in all-optical signal processing because of their high nonlinear susceptibilites $X^{(3)} > 10^{-9}$ *esu* and rapid response speeds. We have performed pump-probe measurements of transient excited state dynamics in these systems and observed relaxation times as short as ~ 100fs.[4] In addition to exhibiting high nonlinear susceptibility, the polydiacetylenes also provide an important model to test the role of electron localization to quasi-one-dimensional systems. Investigations of transient dynamics associated with the excited states of these systems should provide important information on the nature of the elementry excitations in polydiacetylene as well as the limitations of these materials for high speed optical signal processing.

References

[1] R.W. Schoenlein, W.Z. Lin, J.G. Fujimoto, and G.L. Eesley, "Femtosecond Studies of Nonequilibrium Electronic Processes in Metals," In *Ultrafast Phenomena V*, edited by G.R. Fleming and A.E. Siegman. New York: Springer-Verlag, 1986, p. 260.

[2] S.D. Brorson, J.G. Fujimoto, and E.P. Ippen, "Femtosecond Nonequilibrium Electronic Heat Transport in Thin Gold Films," Technical Digest of the Picosecond Electronics and Optoelectronics Conference, Incline Village, Nevada, January 1987, p. 136.

[3] R.W. Schoenlein, W.Z. Lin, S.D. Brorson, E.P. Ippen, and J.G. Fujimoto, "Femtosecond Transient Electron Heating in Metals," 15th International Quantum Electronics Conference, Baltimore, Maryland, April 1987, paper TuDD4.

[4] J.M. Huxley, J.G. Fujimoto, E.P. Ippen, G.M. Carter, and P. Mataloni, "Femtosecond Absorption Saturation Dynamics in Polydiacetylene," Conference on Lasers and Electro-Optics, Baltimore, Maryland, April 1987, paper ThF2.

5.10 Short and Ultrashort Pulse Laser Medicine

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U.S. Navy - Office of Naval Research (Contract N00014-86-K-0117)

James G. Fujimoto, Erich P. Ippen

Two years ago we initiated a new program to investigate the applications of short and ultrashort pulsed lasers to laser medicine. This research is being conducted in collaboration with investigators at the Massachusetts Eye and Ear Infirmary and the Wellman Laboratory of the Massachusetts General Hospital. The objectives of our program are to develop and apply new time resolved spectroscopic and diagnostic techniques for the study of physical processes relevant to laser medicine as well as to investigate laser tissue interaction produced by pulsed radiation.

One area of interest has been the study of laser induced optical breakdown produced by a pulsed nanosecond or picosecond laser sources. This type of laser-tissue interaction is an important therapeutic technique in ophthalmic laser surgery for the surgical incision of interocular structures which are nominally transparent to the laser wavelength. We have investigated the transient processes associated with optical breakdown using pump and probe techniques.[1] These processes include plasma formation, acoustic shock wave generation and propagation, and cavititation. These types of phenomena are also present in pulsed laser interaction with pigmented structures and are relevant to the therapeutic process of pulsed laser surgery. Additional investigations are aimed at determining laser parameters including intensity, pulsed duration, and pulse profile which can better channel the laser radiation into the desired physical process.

As an example to demonstrate the control of laser parameters to produce a desired effect, we have performed investigations of thermal diffusion in retinal damage using a novel interferometric exposure technique.[2] A Michaelson interferometer was used to generate a sinusoidal fringe exposure pattern on the retina and exposures were made for differing laser intensity and exposure time. Exposures at durations comparable to the thermal relaxation time produced spatially confined lesions following the periodicity of the exposure pattern, while those at much longer durations resulting in significant diffusion of the thermal damage beyond the primary targeted regions. This exposure technique is interesting because the sinusoidal exposure pattern is itself an eigenfunction of thermal diffusion equation. In addition, the role of thermal diffusion can be assessed directly from the opthalmascopic and histologic appearances of the lesions. This technique can thus be used to study thermal diffusion and other transport phenomena occurring in laser-tissue interactions.

The use of laser pulses for medical diagnostics has also been under investigation. We have demonstrated the first application of femtosecond optical ranging in biological systems. This technique is analogous to radar or ultrasound except that short pulses of light are used instead of radio or acoustic waves. Using pulsed durations of 70 fs, we have performed measurements of corneal thickness in rabbit eyes in vivo as well as epidermal structure in human skin in vitro.[3] We are currently investigating the application of these techniques to study the cornea profile alterations produced by UV excimer laser ablation as well as processes which produce changes in scattering structure in the cornea such as cataract formation.

Finally, we are investigating the biological aspects of laser-tissue interaction in the femtosecond regime. We have performed the first study of retinal damage thresholds and mechanisms produced by exposure to high intensity femtosecond laser pulses.[4–5] This research was conducted in collaboration with Dr. R. Birngruber of the University of Munich. Retinal damage thresholds were evaluated using 80 fs pulses at 625 nm in chinchilla gray rabbits. ED_{50} injury thresholds of 0.75 mJ and 4.5 mJ were measured using fluorescein-angiographic and opthalmoscopic visibility criteria. Ultra-structural studies including light and electron microscopy were performed on selected lesions. Results suggest that the primary deposition of energy in the retinal occur in melanin even for pulses of this short duration. However, in contrast to laser injury produced by longer pulses, exposures of up to 20 χ threshold in the 50-100 μJ range did not produce significantly more severe lesions or hemorrhage. This suggests the presence of a nonlinear damaging limiting mechanism.

References

[1] J.G. Fujimoto, W.Z. Lin, E.P. Ippen, C.A. Puliafito, and R.F. Steinert, "Time-Resolved Studies of Nd:YAG Laser Induced Breakdown: Plasma Formation, Acoustic Wave Generation, and Cavitation," Invest. Ophthal. Vis. Sci. *26*, 1171, (1985).

[2] J.M. Krauss, C.A. Puliafito, W.Z. Lin, and J.G. Fujimoto, "Interferometric Technique for Investigation of Laser Thermal Retinal Damage," Invest. Ophthal. Vis. Sci. (in press).

[3] J.G. Fujimoto, S. DeSilvestri, E.P. Ippen, C.A. Puliafito, R. Margolis, and A. Oseroff, "Femtosecond Optical Ranging in Biological Systems," Opt. Lett. *11*, 150 (1986).

[4] R. Birngruber, C.A. Puliafito, A. Gawande, W.Z. Lin, R.W. Schoenlein, and J.G. Fujimoto, "Femtosecond Retinal Injury Damage Studies," Invest. Ophthal. Vis. Sci., Suppl. *27*, p. 314 (1986).

[5] R. Birngruber, C.A. Puliafito, A. Gawande, W.Z. Lin, R.W. Schoenlein, and J.G. Fujimoto, "Femtosecond Retinal Injury Study," Technical Digest of the Conference on Lasers and Electro-Optics, San Francisco, Calif., June 1986, p. 152.