Section 2 Optics and Devices

Chapter 1. Optics and Quantum Electronics

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1.1 Ultrafast Optics

1.1.1 Picosecond Optical Switching

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Project Staff

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Our research group has been studying all-optical switching with subpicosecond pulses for several years.[4] We have focused on interferometric switching using the index nonlinearity of optical materials. Lately, we have concentrated on the construction of switches using fiber interferometers because of the close to ideal behavior of optical fibers.[5] Our work is aimed at establishing a "proof of principle," exploring the requirements that must be met by the physical system in order to achieve satisfactory performance. Eventually, when quantum wells or other "engineered" materials of sufficient nonlinearity and with acceptable low linear and two-photon absorption become avail-

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[4] A. Lattes, H.A. Haus, F.J. Leonberger, and E.P. Ippen, *IEEE J. Quant. Electron.* QE-19: 1718-1723 (1983); M.J. LaGasse, D. Liu-Wong, J.G. Fujimoto, and H.A. Haus, "Ultrafast Switching with a Single-fiber Interferometer," *Opt. Lett.* 14: 311-313 (1989).

[5] M.J. LaGasse, D. Liu-Wong, J.G. Fujimoto, and H.A. Haus, "Ultrafast Switching with a Single-fiber Interferometer," *Opt. Lett.* 14: 311-313 (1989).

able, the principles demonstrated with the fiber system can be implemented in more practical systems with less "latency."

The fundamental requirement of a practical switch is that the output must be a reasonable replica of the input. By its nature, nonlinear interaction using the Kerr effect (third order nonlinearity), tends to distort the spectrum and pulse shape, the latter due to group velocity dispersion. A working switch must overcome this tendency of pulse distortion. One way to accomplish this is to use soliton-like interactions.[6] If this operating principle is chosen, the interaction region must possess negative dispersion, if the Kerr nonlinearity is positive, and vice versa. The "collisions" of the control pulses and controlled pulses must be soliton collisions or soliton-like so the pulses are not distorted if the system is not strictly a soliton system. Strict soliton collisions require the use of different frequencies for the colliding pulses, but this is sometimes an unacceptable constraint. If the colliding pulses have the same frequency, they must be distinguishable, e.g., by polarization. In general, two orthogonally polarized pulses do not interact in a distortion-free way, but distortion can be minimized if the collision is "weak." In order to achieve large effects, the collisions must be repeated several times.

This operation principle has been chosen for a switch developed in our laboratory that uses a fiber ring reflector interferometer.[7] The collisions of orthogonally polarized pulses, traveling at different velocities due to fiber birefringence, were repeated by splitting the fiber into 11 segments. In each of the segments, one collision occurred, and the effects of the collisions were cumulative. The interaction was distortion-free as anticipated. The operating principle required use of a polarization sensitive coupler. Because the coupler was not performing to specifications, the contrast ratio was not large. Yet the performance was in good agreement with theoretical predictions. The controlling pulses are eliminated by a polarizer. Figure 1 shows the intensity autocorrelation functions of the controlled pulse in the presence (the upper trace) and in the absence (the lower trace) of the controlling pulse. There is no observable distortion of the pulse.

1.1.2 Squeezing in Optical Fibers

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Squeezing of optical radiation has been pursued by many other laboratories,[8] including Professor Shapiro's group in RLE. Our group started work in this area when a proposal was made to squeeze optical pulses in a fiber ring interferometer,[9] a modification of the all-optical switch which is described in other sections of this report. The use of pulses leads to enhanced nonlinearities. A particularly attractive feature of the proposed scheme is that the pump power used in the squeezing is not wasted, because it is reused as the local oscillator power (at least in principle, if nonreciprocal couplers are used, otherwise a 6 dB loss is incurred).

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6 N.J. Doran, K.J. Blow, and D. Wood, *Proc. SPIE* 836: 238-243 (1987); M.N. Islam, E.R. Sunderman, R.H. Stolen, W. Pleibel, and J.R. Simpson, "Soliton Switching in a f1 Nonlinear Loop Mirror," *Opt. Lett.* 14: 811-813 (1989).

7 J.D. Moores, K. Bergman, H.A. Haus, and E.P. Ippen, "Optical Switching Using Fiber Ring Reflectors," *J. Opt. Soc. Am. B*, forthcoming; J.D. Moores, K. Bergman, H.A. Haus, and E.P. Ippen, "Demonstration of Optical Switching Via Solitary Wave Collisions in a Fiber Ring Reflector," *Opt. Lett.*, forthcoming.

8 M. Xiao, L. Wu, and H.J. Kimble, "Precision Measurement Beyond the Shot-Noise Limit," *Phys. Rev. Lett.* 53: 278-281 (1987); R.E. Slusher, L.W. Hollberg, B. Yurke, J.C. Mertz, and J.F. Valley, "Observation of Squeezed States Generated by Four-wave Mixing in an Optical Cavity," *Phys. Rev. Lett.* 55: 2409-2412 (1985); R.M. Shelby, M.D. Levenson, S.H. Perlmutter, R.G. DeVoe, and D.F. Walls, "Broad-band Parametric Deamplification of Quantum Noise in an Optical Fiber," *Phys. Rev. Lett.* 57: 691-694 (1986); S. Machida, Y. Yamamoto, and Y. Itaya, "Observation of Amplitude Squeezing in a Constant-current-driven Semiconductor Laser," *Phys. Rev. Lett.* 58: 1000-1004 (1987).

9 M. Shirasaki, H.A. Haus, and D.L. Wong, "Quantum Theory of the Nonlinear Interferometer," *J. Opt. Soc. Am. B* 6: 82-88 (1989); M. Shirasaki and H.A. Haus, "Squeezing of Pulses in a Nonlinear Interferometer," *J. Opt. Soc. Am. B* 7: 30-34 (1990).

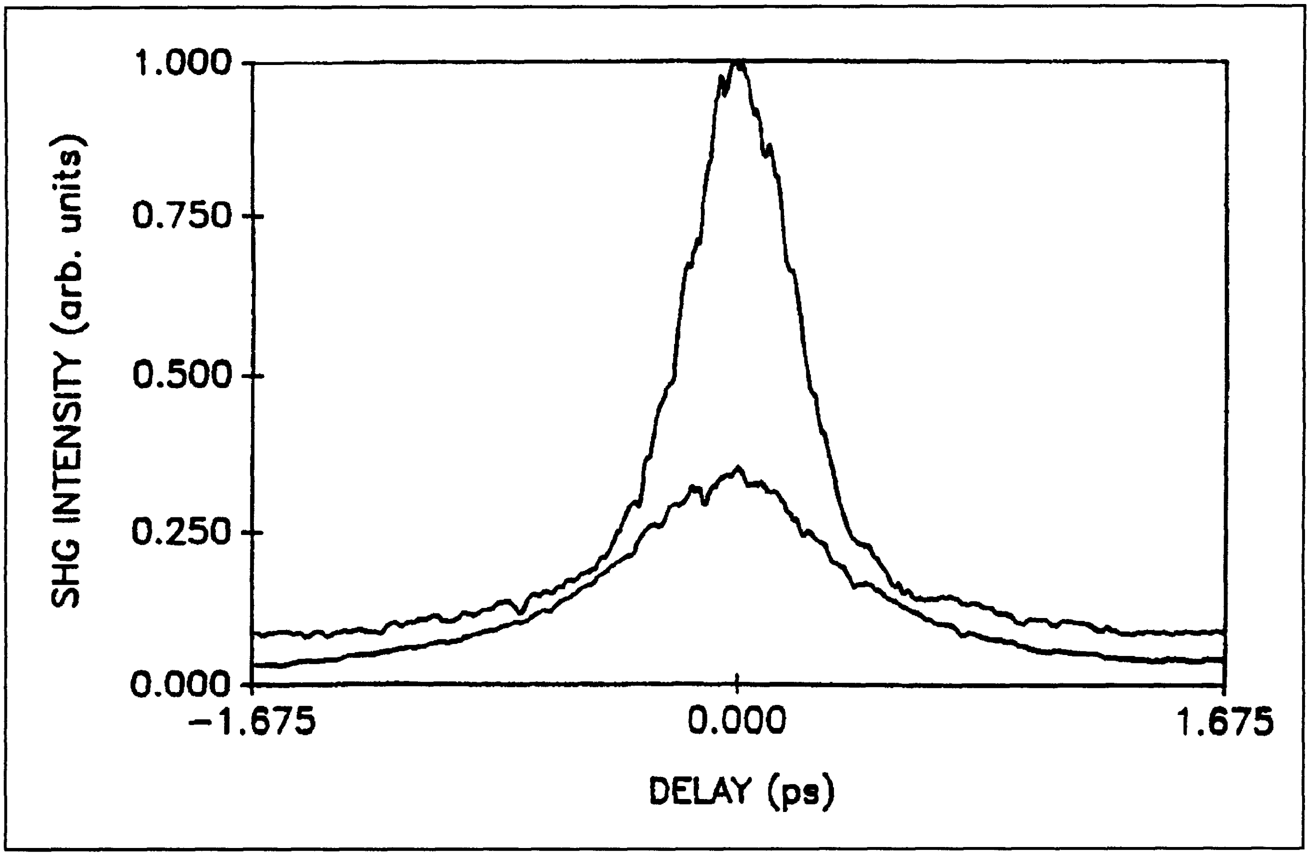

Figure 1.

Experiments using a fiber ring reflector pulse excited by a mode locked Nd:YAG laser operating at 1.3 μ have been gratifyingly successful.[10] Noise reduction greater than 5 dB below the shot noise level in the frequency regime between 40-60 kHz was observed. Figure 2 shows a histogram of noise measurements by the balanced detector. The power of the pump was set at one level and the noise was measured within 2 millisecond intervals. The phase between the squeezed radiation and the local oscillator (the recovered pump pulse) was allowed to drift randomly so that the noise level varied between its minimum and maximum value. The black columns give the shot noise calibration obtained by blocking the squeezed radiation from entering the balanced detector. The reduction below shot noise on the order of 5 db, as well as the enhancement by more than 5 db. The asymmetry is due to the unavoidable variation of squeezing phase across the pump pulse profile.

There are several reasons for the early success of the experiment. First, the threshold of Stimulated Brillouin Scattering is raised significantly by the use of pulses instead of cw excitation so that this source of classical noise is not operative. Similarly, the observation in the low frequency range of 40-60 kHz avoids the effect of Guided Acoustic Brillouin Scattering (GAWBS), which has a higher cutoff frequency. Also, the ring reflector geometry partially suppresses GAWBS at frequencies lower than the transit time of the pulse through the fiber ring. Finally, the modelocked Nd:YAG showed a noise level in the frequency range of the measurement that was only about 25 dB above the shot noise level. The balanced detector could suppress this relatively low "local oscillator" noise.

1.1.3 Quantum Theory of Solitons

Sponsors

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National Center for Integrated Photonics

[10] K. Bergman and H.A. Haus, "Squeezed Pulse Vacuum from Fiber-ring Interferometer," paper presented at OPTCON90, Boston, Massachusetts, November 4-9, 1990, paper FBB4.

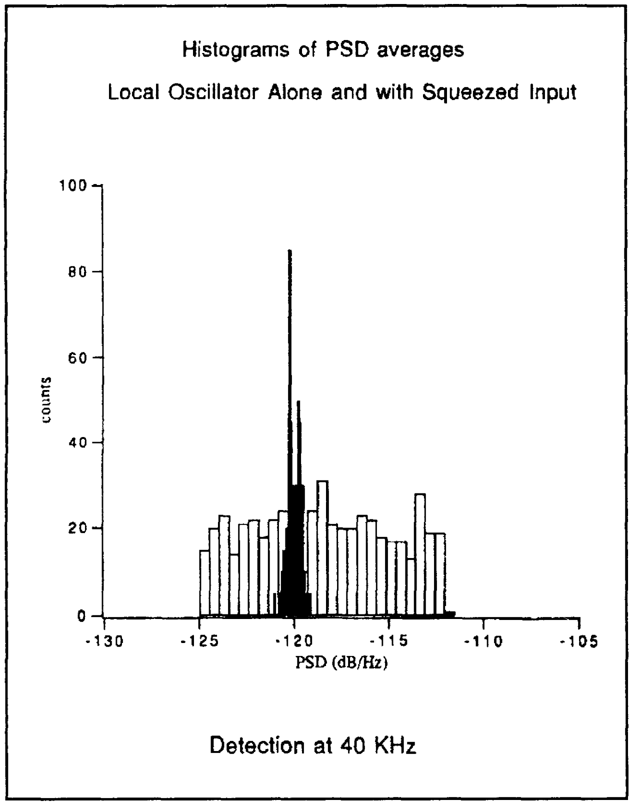

Figure 2.

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An understanding of the noise associated with soliton detection necessitates a quantum analysis of solitons, since the shot noise and the reduction below the shot noise level (squeezing), are quantum phenomena. We have pursued this kind of analysis of solitons of the Nonlinear Schrodinger Equation (NLSE), both exactly[11] and approximately.[12] The approximate analysis is based on the linearization of the NLSE and is amenable to simple interpretation. A soliton is found to have both particle and wave properties simultaneously. It is described by noncommuting momentum and position operators, on one hand, and inphase and quadrature operators (or phase and photon number operators) on the other hand. Any one of these operators can be measured with a local oscillator pulse of properly prepared temporal amplitude- and phase-profile. An extended description and analysis will appear in a chapter of the Springer-Verlag series.

1.1.4 Additive Pulse Modelocking

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Additive Pulse Modelocking (APM) is a novel scheme for the production of short pulses, particularly from solid state lasers with long gain-relaxation times.[13] These laser systems cannot be modelocked in a way analogous to the dye laser systems, in which the saturable gain and the saturable loss cooperate in the pulse shaping process.

Thus far, most APM systems employ a coupled cavity system, one cavity containing the laser medium, the auxiliary cavity containing a Kerr medium, generally a fiber. The length of the auxiliary cavity needs to be stabilized by a feedback circuit to maintain the relative phase of the pulses meeting at the coupling mirror between the two cavities.

[11] Y. Lai and H.A. Haus, "Quantum Theory of Solitons in Optical Fibers. I. Time-dependent Hartree Approximation," *Phys. Rev. A* 40: 844-853 (1989); Y. Lai and H.A. Haus, "Quantum Theory of Solitons in Optical Fibers. II. Exact Solution," *Phys. Rev. A* 40: 854-866 (1989).

[12] H.A. Haus and Y. Lai, "Quantum Theory of Soliton Squeezing: A Linearized Approach," *J. Opt. Soc. Am. B* 7: 386-388 (1990).

[13] E.P. Ippen, H.A. Haus, and L.Y. Liu, "Additive Pulse Mode Locking," *J. Opt. Soc. Am. B* 9: 1736-1745 (1989).

We have developed the criteria for self-starting of the APM modelocking process.[14] When the process is self-starting, the need for an internal modulator is obviated, not only simplifying the system, but also eliminating the competition between the modulator frequency and the pulse repetition frequency. It is this competition that can render the mode locking process unstable.

We have APM modelocked a flashlamp pumped Nd:YAG laser achieving 6 ps pulses without sacrifice of average power.[15] A diode laser pumped Nd:YAG crystal gave 2 ps modelocked pulses.[16] We have achieved APM action in a Ti:Sapphire laser in a single cavity, analogous to the system demonstrated first by Sibbett et al. Generally, it is necessary to start this system with a moving mirror in an external cavity.

These experimental results have stimulated theoretical work. The APM principle applies to any interferometric transformation of nonlinear phase modulation to nonlinear amplitude modulation. The single cavity Ti:Sapphire system operates in this way, the role of the two arms of an interferometer being played by two transverse cavity modes. A theory that considers many possible configurations that produce APM action is currently under investigation.[17]

Modelocking of a Ti:Sapphire system with a saturable absorber in the auxiliary cavity was found to be insensitive to the length of the auxiliary cavity and, therefore, did not require stabilization.[18] The scientists who discovered the phenomenon called it Resonant Pulse Modelocking (RPM).[19] The phenomenon was later explained as a form of self-stabilized Additive Pulse Modelocking. The relative phase at the coupling mirror was shown to be maintained by automatic adjustment of the carrier frequency. This theoretical explanation was confirmed experimentally. While this self-stabilization was shown to work only for absorptive nonlinearities in the auxiliary cavity, the principle is an intriguing one and deserves further investigation to determine whether it could be applied to Kerr nonlinearities as well.

1.1.5 Control of Spontaneous Emission with Semiconductor Microcavities

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Optical microcavities hold technological promise for constructing efficient, high speed semiconductor lasers. One particularly interesting possiblity is the alteration of the spontaneous emission rate of the device by the presence of a cavity. This kind of alteration has previously been observed with atoms by Professor Kleppner's group in RLE, but is more difficult to achieve in a semiconductor device because the broad spontaneous emission bandwidth requires cavity dimensions on the order of a wavelength. To determine the potential feasibility and significance of spontaneous emission alteration in these devices, we have analyzed the radiation modes of oscillating dipoles in planar (one-dimensional confinement and optical-wire (two-dimensional confinement) structures.[20] We found that an idealized planar

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[14] E.P. Ippen, L.Y. Liu, and H.A. Haus, "Self-starting Condition for Additive-pulse Mode-locked Lasers," *Opt. Lett.* 15: 183-185 (1990).

[15] L.Y. Liu, J.M. Huxley, E.P. Ippen, and H.A. Haus, "Self-starting Additive-pulse Mode Locking of a Nd:YAG Laser," *Opt. Lett.* 15: 553-555 (1990).

[16] J. Goodberlet, J. Jacobson, J.G. Fujimoto, P.A. Schulz, and T.Y. Fan, "Self-starting Additive-pulse Mode-locked Diode-pumped Nd:YAG Laser," *Opt. Lett.* 15: 504-506 (1990).

[17] H.A. Haus, J.G. Fujimoto, and E.P. Ippen, "Structures for Additive Pulse Modelocking," to be submitted.

[18] U. Keller, W. H. Knox, and H. Roskos, "Coupled-cavity Resonant Passive Mode-locked Ti:sapphire Laser," *Opt. Lett.* 15: 1377-1379 (1990).

[19] H.A. Haus, U. Keller, and W. H. Knox, "A Theory of Coupled Cavity Modelocking with a Resonant Nonlinearity," submitted to *J. Opt. Soc. Am. B.*

[20] S.D. Brorson, H.Yokoyama, and E.P. Ippen, "Spontaneous Emission Rate Alteration in Optical Waveguide Structures," *IEEE J. Quant. Electron.* QE-21: 1492 (1990).

metallic mirror cavity can suppress the spontaneous emission by no more than a factor of two with respect to free space. The amount of suppression obtainable with a real dielectric stack will be even less. Theory predicts that much larger effects could be achieved by restricting the dimensionality to that of the optical wire. It has been shown that enhancement of spontaneous emission is more easily observable.[21] With GaAs quantum-wells, monolithically integrated with Fabry-Perot cavities fabricated at NEC, we have observed enhancement of emission by a factor of two and a corresponding reduction in the luminescence lifetime due to cavity effect. Future work on this topic will rely on advances in the fabrication of suitable wire or dot devices or improved resonator structures.

1.1.6 Femtosecond Studies of Superconductors

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When an ultrashort optical pulse is incident on the surface of a metal, most of its energy is absorbed directly, because of the high electron density, into the free electron gas. The resulting rise in electron temperature produces a dynamic change in reflectivity. Relaxation of this change occurs as the electrons lose energy to the lattice via phonon emission. The rate is governed by the electron-phonon coupling strength. Since the strength of the electron-phonon coupling is an important component in the BCS theory of superconductivity, we were motivated to undertake a systematic study of these dynamics in superconductors. This was done in collaboration with Professor M. Dresselhaus' group. In a series of experiments,[22] we measured λ the relaxation rate, for ten different metals (four superconducting and six not). The agreement between the values obtained and those derived from the literature is strikingly good. The advantages of our method for measuring λ compared with other techniques (e.g., tunneling or heat capacity measurements) are that: (1) it is a direct measurement, (2) it works at room temperature, and (3) it can be applied to nonsuperconducting as well as superconducting samples. In some metals for which the changes in reflectivity were otherwise too small to detect, we have also found that thin overlayers of Cu (which has d-band transitions in the visible) can be used to greatly enhance the experimental reflectivity changes without affecting the inherent relaxation rate. This extends the method to virtually any metal film.

Encouraged by the success of these results, we also performed several preliminary pump-probe reflection and transmission experiments on three high T_c thin films: $YBa_2Cu_3O_{7-x}$, $Bi_2Sr_2CaCu_2O_{8+x}$ and $Bi_2Sr_2Ca_2Cu_3O_{10+y}$.[23] Of course, we do not have a theoretical framework with which to connect our experiments to high T_c superconductivity for these materials yet. Nevertheless, in these preliminary experiments, we have observed strong changes in observed relaxation rates with changing T_c.

1.1.7 Nonlinear Dynamics in Active Semiconductor Devices

Sponsors

Joint Services Electronics Program
Contract DAAL03-89-C-0001
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National Science Foundation
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[21] H. Yokoyama, K. Nishi, T. Anan, H. Yamada, S.D. Brorson, and E.P. Ippen, TITLE? *Appl. Phys. Lett.* 57: 24 (1990).

[22] S.D. Brorson, A. Kazeroonian, J.S. Moodera, D.W. Face, T.K. Cheng, E.P. Ippen, M.S. Dresselhaus, and G. Dresselhaus, "Femtosecond Room-Temperature Measurement of the Electron-Phonon Coupling Constant λ in Metallic Superconductors," *Phys. Rev. Lett.* 64: 2172 (1990).

[23] S.D. Brorson, A. Kazeroonian, D.W. Face, T.K. Cheng, G. L. Doll, M.S. Dresselhaus, G. Dresselhaus, E.P. Ippen, T. Venkatesan, X.D. Wu, and A. Inam, "Femtosecond Thermomodulation Study of High-Tc Superconductors," *Sol. State Commun.* 74: 1305 (1990).

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Nonlinear optical effects in active waveguides not only influence the generation and propagation of ultrashort pulses in diode lasers, but they can also be applied in all-optical switching. In our laboratory, with 100 fs-duration pulses in the 800-900 nm regime (obtained by fiber compression of synch-pumped dye laser pulses) and with similar pulses in the 1.45-1.65 μm band (from an APM F-center laser), we have performed the first investigations of nonlinear dynamic behavior in both GaAlAs[24] and InGaAsP [25] devices under various excitation conditions. By varying the wavelength of the pump and probe beams, as well as injection current in our diode structures, we have studied interactions in the presence of gain, loss, or nonlinear transparency. In all cases, there is an injected carrier density on the order of $10^{18}/cm^3$, and this makes the nonlinear optical behavior considerably different from what is observed in passive devices or pure materials.

In both GaAlAs and InGaAsP devices, we have discovered a strong nonlinearity due to nonequilibrium between the carrier and lattice temperatures. Heating of the carrier gas with respect to the lattice has a recovery time on the order of 1 ps in GaAlAs and 650 fs in InGaAsP; and, since heating occurs via free electron absorption and no change in carrier number is involved, recovery is complete. This is a particularly important characteristic for all-optical switching applications. Our most recent experiments have yielded preliminary measurements of femtosecond index of refraction dynamics as well as gain changes in GaAlAs. Index changes corresponding to optical Kerr effect and nonequilibrium heating have been observed and are comparable in magnitude to those produced by population changes. During the past year, we have also used a novel means for detecting these nonlinear optical interactions by monitoring changes in diode voltage.[26] By measuring bias voltage as a function of time delay between two optical pulses passing through the diode, we can clearly identify nonlinear optical interactions that utilize active carriers. The time constants observed corroborate those obtained from pump-probe measurements of nonlinear gain.

1.1.8 Impulsive Excitation of Coherent Phonons

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We have recently reported the first observations of coherent optical phonon excitation in two opaque conducting materials, bismuth and antimony.[27] Previous experiments involving excitation of coherent phonons in transparent materials have relied upon stimulated Raman scattering as the excitation mechanism and have utilized changes in transmission for detection. In our work, we simply observe changes in sample reflectivity following absorption of a femtosecond pulse incident upon the surface. The reflectivity is observed to oscillate at the frequency corresponding to the A_{1g} mode in each case (2.9 THz in Bi and 4.5 THz in Sb), indicating that the modulation varies linearly with phonon amplitude. Both the large amplitudes of the reflectivity changes (greater than 10^{-3}) and the absence of other allowed Raman modes argue that a mechanism other than stimulated Raman scattering is the driving force. The initial phase of the oscillations (cosinusoidal rather than sinusoidal) also imply that an electronic transition is involved. Experiments are in progress to clarify the actual

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[24] M.P. Kesler and E.P. Ippen, "Subpicosecond Spectral Gain Dynamics in AlGaAs Laser Diodes," *Electron. Lett.* 24: 1102-1104 (1988).

[25] K.L. Hall, J. Mark, E.P. Ippen, and G. Eisenstein, "Femtosecond Gain Dynamics in GaAsP Optical Amplifiers," *Appl. Phys. Lett.* 56: 1740-1742 (1990).

[26] K.L. Hall, E.P. Ippen, and G. Eisenstein, "Bias-lead Monitoring of Ultrafast Nonlinearities in InGaAsP Diode Laser Amplifiers," *Appl. Phys. Lett.* 57: 129-131 (1990).

[27] T.K. Cheng, S.D. Brorson, A.S. Kazeroonian, J.S. Moodera, G. Dresselhaus, M.S. Dresselhaus, and E.P. Ippen, "Impulsive Excitation of Coherent Phonons Observed in Reflection in Bismuth and Antimony," *Appl. Phys. Lett.* 57: 1004-1006 (1990).

mechanism and to use this technique to study electron-phonon interactions. The method opens up the possibility for detailed time-domain studies of phonon dynamics on a whole class of opaque materials.

1.1.9 Observation of Third Order Optical Nonlinearity Due to Intersubband Transitions in AlGaAs/GaAs Superlattices

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Semiconductor growth techniques allow the production of superlattices designed so that the energy subband separations can be matched to a particular laser frequency. As the optical field frequency approaches the intersubband separation, the contribution to the dielectric function from the intersubband transitions grows rapidly. At resonance, the dielectric function can be modulated by as much as 10%. This large effect is primarily due to several factors:

- The very large dipole matrix element (≈ 20Å) for this transition[28] means that each oscillator will provide a substantial contribution to the change in the dielectric.
- The high doping densities possible in semiconductors allow a great number of oscillators per well ($\approx 10^{18}$ cm^{-3}).
- The narrow bandwidths possible in semiconductor superlattices permit a sharp resonance.

This potential for substantial modulations of the dielectric function has led to predictions of large optical nonlinearities when the subband separation matches the frequency of the incident laser radiation.[29] Furthermore, the nonlinearity is expected to have picosecond response times. We observed the modulation of the dielectric by measuring the nondegenerate four-wave signal. The nonlinearity is further enhanced because this process will be triply resonant for small laser difference frequencies. Since this nonlinearity results from the two-dimensional character of the electrons, it is not specific to AlGaAs/GaAs superlattices. Other materials could be used to apply this process to other wavelengths (strained layer) or to match the fundamental bandgap with the subband gap in order to enhance the nonlinearity (HgCdTe/CdTe).

Several AlGaAs/GaAs superlattices were grown to match the subband separation with that produced by a pair of CO_2 lasers. The doping level was chosen to place the Fermi level between the first and second subbands. The absolute value of $\chi^{(3)}$ for these samples was measured at $\Delta\omega$ 3.45 cm^{-1} to be 5×10^{-5} esu. By measuring $\chi^{(3)}$ at a series of difference frequencies, we estimated the intersubband relaxation time to be 3 ps. No saturation was observed for input intensities of up to 200 kW/cm^2.

The optical nonlinear susceptibility of the subband system can be readily calculated if we treat it as a two level system. Using the diagrammatic technique, we can show that

$$\chi^{(3)} = \frac{N e^4 <z>^4}{4\hbar^3}$$

$$\times \left[\frac{1}{(-\omega_2 - \Omega_{gn})} + \frac{1}{(\omega_1 - \Omega_{ng})} \right]$$

$$\times \frac{1}{(\omega_1 - \omega_2 - \Omega_{nn})} \frac{1}{(2\omega_1 - \omega_2 - \Omega_{ng})} \rho_{gg}^{(0)} \quad (1)$$

where $<z>$ is the dipole matrix element, N is the number of electrons and $\Omega_{ng} \equiv \omega_{ng} - i\Gamma_{ng}$ and $\Omega_{nn} \equiv i\Gamma_{nn}$. Γ_{ng} is the intrasubband rate. This broadening has two different components: impurity scattering and nonparabolicity. We have conducted Hall measurements and found an impurity scattering time of 10^{13} s, which corresponds to a homogeneous broadening of approximately 10 meV. The nonparabolicity is responsible for an inhomogeneous broadening of about 6 meV. Γ_{nn} is the intersubband scattering rate which is essentially the LO-phonon scattering rate. Theoretical

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[28] L.C. West and S.J. Eglash, "First Observation of an Extremely Large Dipole Infrared Transition within the Conduction Band of a GaAs Quantum Well," *Appl. Phys. Lett.* 46: 1156 (1985).

[29] S.Y. Yuen, "Fast Relaxing Absorptive Nonlinear Refraction in Superlattices," *App. Phys. Lett.* 43: 813 (1983).

predictions of 1 ps[30] for this time are close to our measured value.

Eq. (1) can be used to generate lineshapes for our samples as well as to predict absolute values for $\chi^{(3)}$. In both cases, we have obtained close agreement between theory and experiment for the values for magnitude and linewidth.[31] Since this process entails a real change in the electron population, the absorption can be very high (4000 cm^{-1}). However, the absorption can be dramatically reduced by detuning the lasers. The lineshapes show that for finite $\Delta\omega$ the maximum absolute value for $\chi^{(3)}$ is not coincident with the absorption peak. By detuning the laser frequency and operating at $\Delta\omega = 3.45\ cm^{-1}$, we can decrease the absorption while keeping the figure of merit $(\chi^{(3)}/\alpha\tau)$ constant.

1.1.10 JSEP Publications

Anderson, K.K., M.J. LaGasse, H.A. Haus, and J.G. Fujimoto. "Femtosecond Studies of Nonlinear Optical Switching in GaAs Waveguides Using Time Domain Interferometry." *SPIE 1216: Nonlinear Optical Materials and Devices for Photonic Switching* (1990).

Anderson, K.K., M.J. LaGasse, C.A. Wang, J.G. Fujimoto, and H.A. Haus. "Femtosecond Dynamics of the Nonlinear Index Near the Band Edge in AlGaAs Waveguides." *Appl. Phys. Lett.* 56: 1834-1836 (1990).

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1.2 New Ultrashort Pulse Laser Technology

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Project Staff

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1.2.1 Introduction

Ultrashort pulse laser technology is of primary importance in the study of ultrafast phenomena, to make high speed optical measurements, and in telecommunications applications. The central goals of our research program are the investigation of ultrashort pulse generation, amplification, and measurement techniques, and the development of femtosecond laser technology.

Our investigation of femtosecond technology emphasizes several topics including tunability, high repetition rate amplification, and solid state laser materials. The study of ultrafast phenomena has traditionally been limited by the availability of suitable laser sources. Tunable femtosecond lasers provide a powerful capability for time resolved spectroscopy and are especially important for time domain studies of optoelectronic devices. High peak intensity amplifiers permit the investigation of nonlinear optical effects, while high repetition rate amplifier technology permits high sensitivity measurements using signal averaging techniques. Development of solid state ultrashort pulse laser technology yields significant improvements in performance over conventional dye lasers and is an essential step in developing a compact and low cost ultrashort pulse laser technology for high performance signal processing, measurement, and instrumentation applications.

1.2.2 Ultrashort Pulse Generation in Titanium Sapphire

The $Ti:Al_2O_3$ laser is an important model system for investigating ultrashort pulse generation in solid state lasers. The properties of $Ti:Al_2O_3$ are especially attractive for ultrafast spectroscopy. $Ti:Al_2O_3$ features a tuning range from 700 nm to 1100 nm with room temperature operation, high thermal conductivity, and high energy storage.[32] The broad gain bandwidth of this material makes it an ideal crystal for the generation and amplification of femtosecond pulses. The tuning range is particularly suited for studies of GaAs and AlGaAs-based opto-electronic devices. In addition, amplification and frequency conversion techniques can be developed to produce tunable ultraviolet pulses for femtosetcond UV spectroscopy. For these reasons, the investigation of ultrashort pulse generation in $Ti:Al_2O_3$ has emerged recently as an active and promising area of research.

Working in collaboration with Professors E.P. Ippen and H.A. Haus in RLE and Dr. P.A. Schulz of MIT Lincoln Laboratory, we have recently developed a new modelocking technique for ultrashort pulse generation in $Ti:Al_2O_3$.[33] This modelocking technique has been termed Additive Pulse Modelocked (APM) because pulse shaping is produced by coherent field addition.[34] Additive Pulse Modelocking in $Ti:Al_2O_3$ is significant because it was the first demonstration of self-starting passive modelocking without the need for active gain or loss modulation. Short pulses can be generated with a significant reduction in cost and complexity over previous approaches.

The APM laser generates short pulses using an external cavity containing a Kerr medium (a single mode optical fiber of appropriate length), which has an intensity dependent index of refraction. The external cavity functions as a nonlinear Fabry Perot with an intensity dependent reflectivity. If the external cavity length is interferometrically controlled relative to the main cavity, it is possible to operate the external cavity as a fast saturable absorber. Pulses as short as 1.4 ps have been generated directly from the $Ti:Al_2O_3$ laser. Using an intracavity prism pair with negative group velocity dispersion to remove pulse chirp and produce pulse compression resulted in bandwidth limited pulses of 230 fs.[35] Pulses of similar duration can also be achieved by external dispersion compensation by a diffraction grating pair.[36]

During the last year, our research has focused on understanding the starting dynamics of the APM modelocking.[37] Studies of starting dynamics provide an approach for investigating the mechanisms of the pulse formation process. Our investigations demonstrate that the nonlinear external cavity produces pulse shaping by a fast saturable absorber like action. These studies provide important design criteria for optimizing the laser system as well as for generalizing the APM technique to other solid state laser materials.

1.2.3 Additive Pulse Modelocking in Diode Pumped Nd:YAG and Nd:YLF

The objective of this program was to demonstrate the extension of self-starting Additive Pulse Modelocking techniques developed in $Ti:Al_2O_3$ to other solid state laser materials. The diode pumped Nd materials are especially attractive since they can be engineered into a compact and low cost ultrashort pulsed laser technology.

Additive pulse modelocking was studied in Nd:YAG and Nd:YLF.[38] Theoretical studies by E.P. Ippen and H.A. Haus suggest that gain cross section is an important parameter in determining

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[32] P.F. Moulton, "Spectroscopic and Laser Characteristics of $Ti:Al_2O_3$," *J. Opt. Soc. Am. B* 3: 125-133 (1986).

[33] J. Goodberlet, J. Wang, J.G. Fujimoto, and P.A. Schulz, "Femtosecond Passive Modelocked $Ti:Al_2O_3$ Laser with a Nonlinear External Cavity," *Opt. Lett.* 14: 1125-1127 (1989).

[34] E.P. Ippen, H.A. Haus, and L.Y. Liu, "Additive Pulse Modelocking," *J. Opt. Soc. Am. B* 6: 1736-1745 (1989).

[35] J. Goodberlet, J. Jacobson, G. Gabetta, P.A. Schulz, T.Y. Fan, and J.G. Fujimoto, "Ultrashort Pulse Generation with Additive Pulse Modelocking in Solid States Lasers," OSA Meeting, 1990, paper MB1.

[36] J. Goodberlet, J. Jacobson, J. Wang, J.G. Fujimoto, T.Y. Fan, and P.A. Schulz, "Ultrashort Pulse Generation with Additive Pulse Modelocking in Solid State Lasers: $Ti:Al_2O_3$, Diode Pumped Nd:YAG and Nd:YLF," Springer Series in Chemical Physics 53, *Ultrafast Phenomena VII*, eds. C.B. Harris, E.P. Ippen, G.A. Mourou, and A.H. Zewail (New York: Springer-Verlag, 1990).

[37] J. Goodberlet, J. Wang, J.G. Fujimoto, and P.A. Schulz, "Starting Dynamics of Additive Pulse Mode Locking in the $Ti:Al_2O_3$ Laser," *Opt. Lett.* 15: 1300-1302 (1990).

[38] J. Goodberlet, J. Jacobson, J. Wang, J.G. Fujimoto, T.Y. Fan, and P.A. Schulz, "Ultrashort Pulse Generation with Additive Pulse Modelocking in Solid State Lasers: $Ti:Al_2O_3$, Diode Pumped Nd:YAG and Nd:YLF," Springer Series in Chemical Physics 53, *Ultrafast Phenomena VII*, eds. C.B. Harris, E.P. Ippen, G.A. Mourou, and A.H. Zewail (New York: Springer-Verlag, 1990); J. Goodberlet, J. Jacobson, J.G. Fujimoto, P.A. Schulz, and T.Y. Fan, "Self Starting Additive Pulse Modelocked Diode Pumped Nd:YAG Laser," *Opt. Lett.* 15: 504-506 (1990).

whether self-starting APM can be achieved in a given laser.[39] The gain cross sections of Nd:YAG and Nd:YLF are comparable to Ti:Al_2O_3. In addition, these solid state laser materials have absorption peaks which can be pumped by commercially available high power laser diode arrays.

Figure 3 shows a schematic diagram of our Additive Pulse Modelocked diode pumped Nd:YAG and Nd:YLF laser design. Three diode arrays are used as the pump source. The main laser cavity consists of a high reflector, a folding mirror, and an output coupler. The external cavity consists of a beam splitter, an optical fiber, and a retroreflecting mirror. The cavity length is 1.1 m corresponding to a 136 MHz repetition rate. In Nd:YAG, durations of 1.7 ps were obtained with a spectral bandwidth of 0.67 nm.[40] To date, these are the shortest pulses produced directly from an Nd:YAG laser. In Nd:YLF, chirped pulses of 2.0 ps with a bandwidth of 0.8 nm were generated.[41]

These results demonstrate that Additive Pulse Modelocking can be scaled to lower power systems such as diode pumped solid state lasers. Pulse durations are generated which are significantly shorter than possible by previous techniques. Finally, diode pumped solid state lasers can be engineered into a compact and low cost ultrashort pulse technology.

1.2.4 New Modelocking Technology

Recently, ultrashort pulse generation in Ti:Al_2O_3 has become an area of investigation being pursued actively by several research groups. In addition to Additive Pulse Modelocking, a variety of techniques have been explored including active modelocking, passive modelocking with a saturable absorber dye,[42] passive modelocking using a semiconductor saturable absorber in an external cavity,[43] and self modelocking in a single cavity.[44] The result of these studies suggests that it is possible to develop new approaches for ultrashort pulse generation in a variety of solid state laser systems.

One of the key concepts which has emerged is the use of intracavity all-optical switching or modulation to modelock a laser. Solid state lasers permit the generation of high intracavity powers. For pulses in the subpicosecond range, the intracavity intensities can be in excess of $\sim$ 100 KW. This is sufficient to achieve appreciable nonlinear phase shifts in bulk materials such as glass or bulk Ti:Al_2O_3 using the Kerr effect or nonlinear index of refraction.

The problem of modelocking a solid state laser can thus be related to all-optical switching. Furthermore, intracavity pulse compression is possible by incorporating negative group velocity dispersion in the laser cavity and using this in conjunction with nonlinear self phase modulation. Working in collaboration with Professor H.A. Haus and E.P. Ippen, we have developed a closed form analytical theory to predict the operation of modelocked solid state lasers with intracavity self phase modulation and dispersion.[45] Experimental studies using

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39 E.P. Ippen, L.Y. Liu, and H.A. Haus, "Self-starting Condition for Additive-pulse Modelocking of an Nd:YAG Laser," *Opt. Lett.* 15: 553 (1990).

40 J. Goodberlet, J. Jacobson, J.G. Fujimoto, P.A. Schulz, and T.Y. Fan, "Self Starting Additive Pulse Modelocked Diode Pumped Nd:YAG Laser," *Opt. Lett.* 15: 504-506 (1990).

41 J. Goodberlet, J. Jacobson, J. Wang, J.G. Fujimoto, T.Y. Fan, and P.A. Schulz, "Ultrashort Pulse Generation with Additive Pulse Modelocking in Solid State Lasers: Ti:Al_2O_3, Diode Pumped Nd:YAG and Nd:YLF," Springer Series in Chemical Physics 53, *Ultrafast Phenomena VII*, eds. C.B. Harris, E.P. Ippen, G.A. Mourou, and A.H. Zewail (New York: Springer-Verlag, 1990).

42 N. Sarukura, Y. Ishida, H. Nakano, and Y. Yamamoto, "CW Passive Mode Locking of a Ti:sapphire Laser," *Appl. Phys. Lett.* 56: 814-815 (1990).

43 U. Keller, W.H. Knox, and H. Roskos, "Coupled-cavity Resonant Passive Mode-locked Ti:sapphire Laser," *Opt. Lett.* 15: 1377-1379 (1990).

44 D.E. Spence, P.N. Kean, and W. Sibbett, "60-fsec Pulse Generation from a Self-mode-locked Ti:sapphire Laser," *Opt. Lett.* 16: 42-44 (1991).

45 H.A. Haus, J.G. Fujimoto, and E.P. Ippen, "Structures for Additive Pulse Modelocking," submitted to *J. Opt. Soc. Am.*

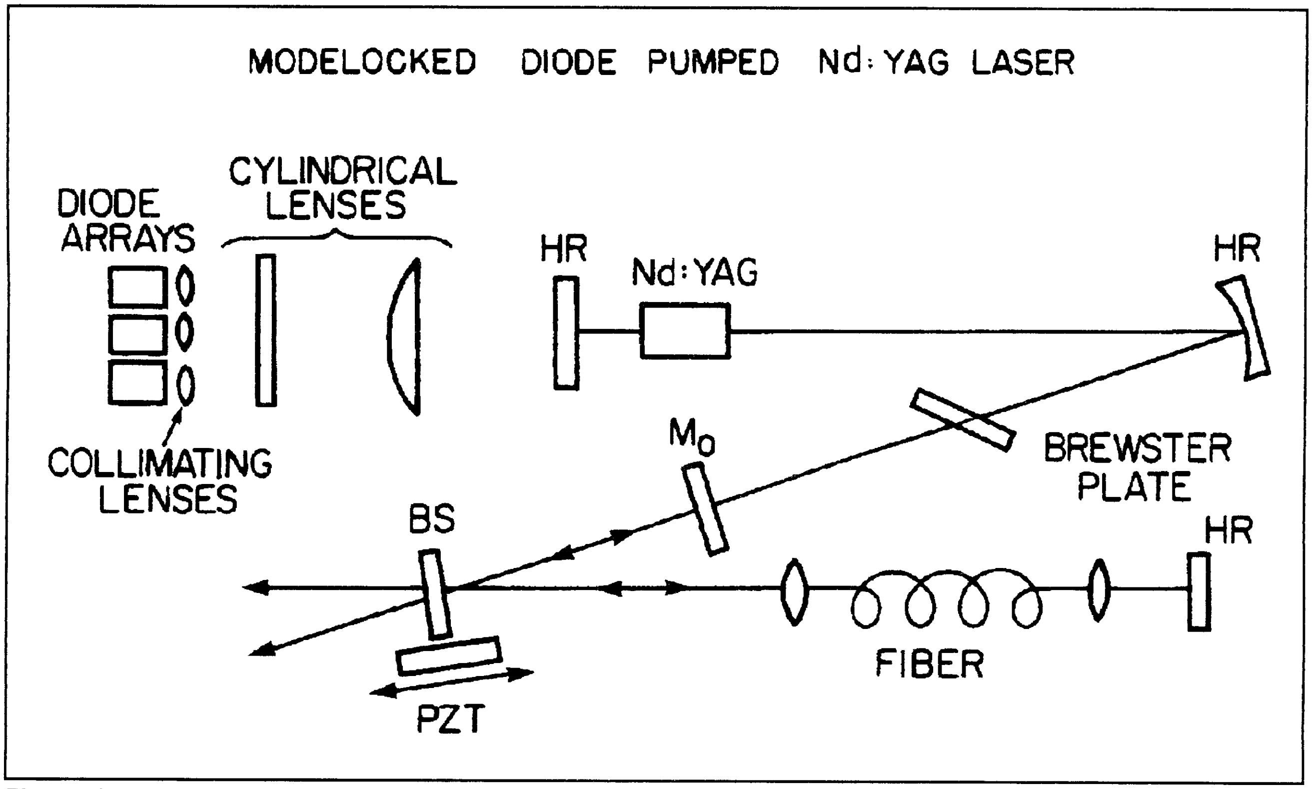

Figure 3. Additive Pulse Modelocked diode pumped Nd:YAG laser. Pulse durations of 1.7 ps were generated using a passive nonlinear external cavity. These are the shortest pulses generated in a YAG laser to date.

different modelocking techniques in $Ti:Al_2O_3$ are currently in progress.

The objective of our studies is to develop approaches for passive modelocking using different types of nonlinear intracavity all optical modulators. These techniques would represent a significant improvement over current APM which uses optical fibers and requires interferometric cavity length control. If successful, these new modelocking techniques could be applied to a wide range of solid state lasers to generate ultrashort pulses with superior performance and reduced cost compared to previous techniques. The development of low cost laser sources would represent a significant advance for engineering and commercial applications of ultrashort pulse technology and high speed optical measurement.

1.2.5 Multistage High Repetition Rate Femtosecond Amplifiers

Currently, dye laser systems and flowing dye amplifiers are the most widely used technology for ultrashort optical pulse generation. We are continuing our research on dye based systems in order to enhance our experimental facilities for investigating ultrafast phenomena. We have recently completed the development of a multistage, high repetition rate, dye amplifier which may be used for a variety of ultrafast studies in materials and devices.

Our femtosecond pulse laser system is based on a colliding-pulse modelocked ring dye laser (CPM).[46] The CPM generates 35 fs pulses at a wavelength of 630 nm. The advantage of the CPM laser is that it produces extremely short pulse durations. However, since the CPM uses passive modelocking with saturable absorber dyes, the output is not tunable in wavelength. This trade off between short pulse duration and wavelength tunability is typical of ultrafast laser systems, and

[46] 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).

much of our work focuses on the development of new ultrafast generation techniques to achieve tunable sources.

In order to generate high intensities necessary for studies of nonlinear processes or frequency conversion and pulse compression, the femtosecond pulses generated by our CPM are amplified by a copper vapor laser pumped dye amplifier.[47] The copper vapor laser amplifier operates at 8 kHz repetition rate. The high repetition rate permits the use of lock-in detection and signal averaging to achieve high sensitivity experimental measurements. We have recently completed the development of a novel multistage copper vapor laser pumped amplifier system.[48]

The amplifier system has been designed with modular construction and in a flexible arrangement so it can be configured for amplification, white light continuum generation, or ultrashort pulse compression. The system generates femtosecond pulses with 20-30 μJ pulse energy with pulse durations of 50 fs corresponding to peak intensities in excess of 100 MW.

When an intense ultrashort optical pulse is focused into a material with an intensity dependent index of refraction, self phase modulation effects can be used to broaden the spectrum of the pulse. In the high intensity limit, the spectral broadening becomes very pronounced and a broadband white light continuum is generated with wavelengths ranging from 400 nm to greater than 900 nm.[49] The technique thus provides a source of tunable femtosecond light for experimental studies.

Although continuum generation has been widely used experimentally, the physical origins of the process are not well understood. We are currently investigating the nonlinear frequency modulation and beam propagation effects associated with high peak intensity pulses. These investigations are important because they suggest other techniques for nonlinear frequency generation. In preliminary work, we have observed that the continuum is generated coherently, and that, by using negative group velocity dispersion, it is possible to compress selected wavelength regions of the continuum to less than 20 fs. This represents a powerful new capability for ultrafast spectroscopy.

1.3 Femtosecond Processes in Electronic Materials

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1.3.1 Studies in Metals and Semiconductors

Advances in high speed electronic and optoelectronic devices require an understanding of the fundamental electronic processes in their constituent materials. The ultimate speed limit for new devices arises from the dynamics of electrons in electronic and optoelectronic materials. Our program focuses on femtosecond studies of electron dynamics in semiconductors and metals. Currently, femtosecond optical measurement techniques are the only methods that allow the direct measurement of ultrafast processes. The temporal resolution of our laser systems is fast enough to resolve the fundamental scattering processes in semiconductors, which occur typically on a 100 fs time scale. In contrast, the electron density in metals is very high so electronic scattering events can occur in 10 fs or less. This is near the limit of the current state-of-the-art femtosecond measurement technology. Our studies of electron dynamics in metals represent some of the first femtosecond experiments performed on these systems.

Working in collaboration with researchers at the General Motors Research Laboratories, we have investigated the dynamics of image potential states

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

[48] M. Ulman, R.W. Schoenlein, and J.G. Fujimoto, "Cascade High Repetition Rate Femtosecond Amplifier," paper presented at the Annual Meeting of the Optical Society of America, Orlando, Florida, October 15-20, 1989.

[49] F.L. Fork, C.V. Shank, C. Hirlimann, R. Yen, and W.J. Tomlinson, "Femtosecond White-light Continuum Pulses," *Opt. Lett.* 8: 1 (1983).

in metals.[50] An image potential state occurs in a metal when an electron outside the surface of the metal is bound state to its image charge in the bulk. Electrons in the image potential state form a Rydberg series as a two-dimensional electron gas analogous to quantum well systems in semiconductors. The electrons relax by tunneling from the image potential state back to the bulk states. The investigation of image potential states is thus an important approach to understanding ultrafast electron dynamics in metals.

In order to study femtosecond image potential dynamics, we have developed new measurement techniques which combine photoemission spectroscopy with femtosecond optics. An ultrashort pump pulse is used to prepare the excited state while a delayed pump pulse is used to photoionize the state. The photoemitted electrons are energy analyzed as function of delay between the pump and probe pulses. This permits a transient measurement of photoemssion spectra on the time scale of 10 fs.

Using these techniques, we have performed a comprehensive investigation of the image potential states in Ag. These studies are of interest because they permit us to test theoretical predictions of image potential dynamics. Relaxation dynamics of the n = 1 and n = 2 states on the 100 and 111 surfaces were studied. The dynamics of the image potential state have been measured as a function of time and electron energy. The lifetime of the n = 1 state on Ag(100) was 25 ± 10 fs. To our knowledge, this measurement represents the highest time resolution photoemission measurement to date.[51] Systematic measurements of lifetimes of different states in the Rydberg series on different surfaces have been performed and compared to theoretical descriptions of the image potential dynamics based on tunneling and many particle models.[52]

We are continuing our work on femtosecond carrier dynamics in semiconductors. We have established a collaborative program with condensed matter theorists from the University of Florida.[53] Our objective is to combine state-of-the-art experimental and theoretical techniques to investigate fundamental excited carrier dynamics in technologically relevant compound semiconductors and quantum confined structures. Within this collaborative program, we have begun to develop a comprehensive model for carrier dynamics in the GaAs and AlGaAs semiconductors. This will result in a powerful tool for the prediction of nonequilibrium behavior in a variety of new materials.

Research at MIT focuses on femtosecond experimental studies in GaAs and AlGaAs, while our collaborators at the University of Florida perform theoretical investigations of carrier dynamics using full band structure and ensemble Monte Carlo techniques. The Monte Carlo simulation is used to find the electron and hole distribution functions by developing a correspondence with experimentally measured differential transmission pump probe data. These studies show that it is essential to include collisional broadening during photoexcitation and the effects of hole scattering in the theoretical model.[54] The combination of theoretical and experiment studies provided the first direct evidence for hole redistribution on a femtosecond time scale.

Our work on ultrafast processes in metals and semiconductors provides fundamental information on the ultimate limits of high speed electronic and optoelectronic devices. Many new devices depend on quantum transport effects in semiconductors; femtosecond technology has the highest temporal resolution for investigating these processes in optoelectronic materials.

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[50] R.W. Schoenlein, J.G. Fujimoto, G.L. Eesley, and T.W. Capehart, "Femtosecond Studies of Image-potential Dynamics in Metals," *Phys. Rev. Lett.* 61: 2596 (1988).

[51] R.W. Schoenlein, J.G. Fujimoto, G.L. Eesley, and T.W. Capehart, "Femtosecond Dynamics of the n = 2 Image-potential State on Ag(100)," *Phys. Rev. B* 41: 5436 (1990).

[52] R.W. Schoenlein, J.G. Fujimoto, G.L. Eesley, and T.W. Capehart, "Femtosecond Relaxation Dynamics of Image-potential States," *Phys. Rev. B,* forthcoming.

[53] D.W. Bailey, C.J. Stanton, K. Hess, M.J. LaGasse, R.W. Schoenlein, and J.G. Fujimoto, "Femtosecond Studies of Intervalley Scattering in GaAs and $Al_xGa_{1-x}As$," *Solid State Electron.* 32:1491 (1989).

[54] D.W. Bailey, C.J. Stanton, and K. Hess, "Numerical Studies of Femtosecond Carrier Dynamics in GaAs." *Phys. Rev. B,* forthcoming; C.J. Stanton, D.W. Bailey, and K. Hess, "Femtosecond Pump, Continuum-probe Nonlinear Absorption in GaAs," *Phys. Rev. Lett.* 65: 231 (1990).

1.3.2 Four Wave Mixing and Information Storage in Photorefractive Crystals

Photorefractive materials such as $BaTiO_3$, SBN, and $LiNbO_3$ present large optical nonlinearities that are attractive for applications in optical devices based on four-wave mixing processes.[55] Although the response times of these crystals are typically in the millisecond range, they provide an important model system for the design of phase conjugation, optical processing, and optical logic techniques. Working in collaboration with investigators from Tufts University, we have performed the first four-wave mixing experiments in $BaTiO_3$ using femtosecond optical pulses.[56]

These investigations explore the factors which determine the temporal broadening of optical signals in four wave mixing. Studies were performed using 40 fs pulse durations from a CPM dye laser. Different phase conjugation geometries were examined including the ring resonator as well as the two beam coupling geometry. A surprising discovery was that temporal signals are influenced only by material dispersion effects and that pulse durations of 40 fs could be preserved in the four wave mixing process. Since four wave mixing in $BaTiO_3$ occurs via the photorefractive effect, these studies determine the transient behavior of scattering from volume index photorefractive gratings.

Four wave mixing in $BaTiO_3$ is a well established approach for encoding image and phase conjugation information. We have extended these concepts and demonstrated the encoding of temporal information using a two beam four wave mixing approach. Our experiments are closely related to femtosecond holography which uses holographic recording to store transient femtosecond images.[57] In our approach, however, the temporal behavior of a signal pulse can be encoded geometrically onto the volume photorefractive grating which is written in the $BaTiO_3$ crystal. Subsequently, this temporal signal can be read out by diffracting as probe pulse from the volume grating. These investigations suggest a new approach for encoding and reconstructing high speed optical information. Extensions of these techniques using acousto-optic modulators or other programmable volume diffraction devices could make possible the generation of programmable optical pulse trains at THz repetition rates.

1.4 Femtosecond Studies of Waveguide Devices

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1.4.1 Time Domain Interferometry

Investigations of nonresonant nonlinear processes in semiconductors are directly relevant to the development of high-speed all-optical switching devices and the optimization of high speed modulation performance in diode lasers. In particular, the characterization of the nonlinear index of refraction, n_2, and its dynamics is key to the development of such fast devices.[58] Various techniques have been used to measure intensity dependent index changes, such as fringe shift

[55] M. Cronin-Golomb, B. Fischer, J.O. White, and A. Yariv, "Theory and Applications of Four-wave Mixing in Photorefractive Media," *IEEE J. Quant. Electron.* QE-20: 12 (1984).

[56] L.H. Acioli, M. Ulman, E.P. Ippen, J.G. Fujimoto, H. Kong, B.S. Chen, and M. Cronin-Golomb, "Femtosecond Two Beam Coupling and Temporal Encoding in Barium Titanate," paper to be presented at CLEO '91, Baltimore, Maryland.

[57] J.A. Valdmanis, H. Chen, E.N. Leith, Y. Chen, J.L. Lopez, "Three Dimensional Imaging with Femtosecond Optical Pulses," *CLEO Technical Digest,* p. 54, paper CTUA1 (1990).

[58] S.W. Koch, N. Peyghambarian, and H.M. Gibbs, "Band-edge Nonlinearities in Direct-gap Semiconductors and Their Application to Optical Bistability and Optical Computing," *J. Appl. Phys.* 63: R1 (1989); G.I. Stegeman, E.M. Wright, N. Finlayson, R. Zanoni, and C.T. Seaton, "Third Order Nonlinear Integrated Optics," *J. Lightwave Tech.* 6: 953 (1988).

interferometry,[59] Mach-Zehnder interferometry,[60] four wave mixing,[61] nonlinear waveguide couplers,[62] and nonlinear Fabry-Perots.[63]

Our group has recently developed a novel technique for performing highly sensitive nonlinear index measurements.[64] This technique is called time division interferometry or TDI and uses a single waveguide with time division multiplexing to perform transient pump probe interferometric measurements of n_2. A pump and time delayed probe pulse are coupled into a waveguide structure. The transient phase shift of the probe pulse produced by the pump is measured by interfering the probe with a time division multiplexed reference pulse. The femtosecond transient behavior of the nonlinear index can be measured by varying the delay between the pump and probe pulses. The TDI technique reduces parasitic contributions from thermal and acoustic effects and achieves a measurement sensitivity of $\lambda/500$ without active length stabilization of the interferometer. Active stabilization increases the sensitivity by over an order of magnitude.

Using this technique, we have performed the first direct measurements of the nonresonant nonlinear index in AlGaAs.[65] We have recently extended these investigations to explore other nonlinear optical waveguide materials. Working in collaboration with investigators at MIT Lincoln Laboratories and Bellcore, we are studying multiple quantum well waveguides and polydiacetylene waveguides.

Many of these new materials have highly anisotropic nonlinear optical properties. In order to address this issue, we have developed variations of our original time division interferometry approach which permit measurement of the different tensor components of the third order nonlinear susceptibility tensor $\chi^{(3)}$ that contribute to the nonlinear index n_2. These studies should permit a comprehensive characterization of the the nonlinear index and its dynamics in a wide range of materials systems.

1.4.2 Time Domain Optoelectronic Diagnostics

In addition to measuring nonlinear properties, it is also possible to develop time domain diagnostics for linear device properties. Since femtosecond pulses have a spatial extent smaller than most waveguide longitudinal dimensions, the impulse response of the waveguide can be measured. The impulse response contains information on linear absorption, group velocity and dispersion and permits a complete characterization of the linear properties of optical guided wave devices.[66]

Nonlinear effects other than the nonlinear index of refraction n_2 can also be studied using time domain techniques. The nonlinear two photon

[59] Y.H. Lee, A. Chavez-Pirson, S.W. Koch, H.M. Gibbs, S.H. Park, J. Morhange, A. Jeffrey, N. Peyghambarian, L. Banyai, A.C. Gossard, and W. Wiegmann, "Room-temperature Optical Nonlinearities in GaAs," *Phys. Rev. Lett.* 57: 2446 (1986).

[60] D. Cotter, C.N. Ironside, B.J. Ainslie, and H.P. Girdlestone, "Picosecond Pump-probe Interferometric Measurement of Optical Nonlinearity in Semiconductor-doped Fibers," *Opt. Lett.* 14: 317 (1989).

[61] W.K. Burns and N. Bloembergen, "Third-harmonic Generation in Absorbing Media of Cubic or Isotropic Symmetry," *Phys. Rev. B* 4: 3437 (1971).

[62] P. Li, K. Wa, J.E. Sitch, N.J. Mason, J.S. Roberts, and P.N. Robson, "All Optical Multiple-quantum-well Waveguide Switch," *Electron. Lett.* 21:27 (1985); R. Jin, C.L. Chuang, H.M. Gibbs, S.W. Koch, J.N. Polky, and G.A. Pubanz, "Picosecond All-optical Switching in Single-mode GaAs/AlGaAs Strip-loaded Nonlinear Directional Couplers," *Appl. Phys. Lett.* 53:1791 (1988).

[63] Y.H. Lee, A. Chavez-Pirson, S.W. Koch, H.M. Gibbs, S.H. Park, J. Morhange, A. Jeffrey, N. Peyghambarian, L. Banyai, A.C. Gossard, and W. Wiegmann, "Room-temperature Optical Nonlinearities in GaAs," *Phys. Rev. Lett.* 57: 2446 (1986).

[64] M.J. LaGasse, K.K. Anderson, H.A. Haus, and J.G. Fujimoto, "Femtosecond All-optical Switching in AlGaAs Waveguides Using a Single Arm Interferometer," *Appl. Phys. Lett.* 54: 2068 (1989).

[65] M.J. LaGasse, K.K. Anderson, C.A. Wang, H.A. Haus, and J.G. Fujimoto, "Femtosecond Measurements of the Nonresonant Nonlinear Index in AlGaAs," *Appl. Phys. Lett.* 56: 417 (1990).

[66] K.K. Anderson, J.J. LaGasse, H.A. Haus, and J.G. Fujimoto, "Femtosecond Time Domain Techniques for Characterization of Guided Wave Devices." *Mat. Res. Soc. Symp. Proc.* 167: 51 (1990).

absorption β is an important limiting process for all-optical switching since it produces excited carriers which limit the recovery times of the index nonlinearity.[67] We have performed measurements of β and the associated carrier dynamics for AlGaAs waveguide devices.[68] Coupled with measurements of linear properties and nonlinear index, this constitutes a complete characterization of the waveguide device. This information can be used to calculate the all-optical switching behavior and determine figures of merit for all-optical switching.

With development of new tunable femtosecond laser sources, time domain device diagnostics can become a viable approach for characterizing optoelectronic waveguide devices. The passively modelocked $Ti:Al_2O_3$ laser is particularly suited for this application since it is a solid state laser which features tunability over the wavelength range from 700 nm to greater than 1000 nm. The improved performance of this laser over existing femtosecond dye lasers will permit us to investigate a broader range of guided wave devices. As described previously, another part of our research program focuses on the development of new femtosecond solid state laser technology. Since low cost, compact femtosecond technology is a major limiting factor in commercial applications, our program concept is to simultaneously address the issues of ultrashort pulse laser develop and applications. Time domain device diagnostics are particularly attractive since they can be applied to investigate processes which cannot be studied using continuous wave techniques.

1.5 Laser Medicine

Sponsors

Medical Free Electron Laser Program
Contract N00014-86-K-0117
National Institutes of Health
Grant 5-RO1-GM35459

Project Staff

Professor James G. Fujimoto, Michael Hee, David Huang, Jyhpyng Wang

1.5.1 Optical Coherent Reflectometry

Optical coherence domain reflectometry (OCDR) is a new optical ranging method that uses short coherence length light sources and interferometric detection to determine the time-of-flight delay of light reflected from a sample.[69] It is the optical analog of ultrasound, but offers higher resolution and noncontact measurement. The coherent detection techniques used in OCDR also offer inherently superior signal to noise ratio compared to other optical ranging methods, including femtosecond ranging techniques we have previously utilized in biological measurements.[70] The high detection sensitivity of OCDR allows us to measure weak backscattered signal from biological systems, not only in the transparent media of the eye, but also in turbid tissues. Additionally, OCDR employs a compact continuous wave laser diode source and can be easily engineered into compact and reliable clinical instruments. We believe that OCDR is a promising technique for many applications in laser microsurgery and medical diagnostics.

Working in collaboration with investigators at the Massachusetts Eye and Ear Infirmary and the Wellman Laboratories of the Massachusetts General Hospital, we have developed an experimental OCDR system to investigate optical

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67 K.W. DeLong, K.B. Rochford, and G.I. Stegeman, "Effect of Two-photon Absorption on All-optical Guided-wave Devices," *Appl. Phys. Lett.* 55: 1823 (1989).

68 K.K. Anderson, M.J. LaGasse, H.A. Haus, and J.G. Fujimoto, "Femtosecond Studies of Nonlinear Optical Switching in GaAs Waveguides Using Time Domain Interferometry," SPIE OE LASE '90, Los Angeles, California, January 14-19, 1990; *Proceedings, Nonlinear Optical Materials and Devices for Photonic Switching* 1216: 2 (1990).

69 R.C. Youngquist, S. Carr, and D.E.N. Davies, "Optical Coherence Domain Reflectometry: a New Optical Evaluation Technique," *Opt. Lett.* 12: 158 (1987).

70 D. Stern, W.Z. Lin, C.A. Puliafito, and J.G. Fujimoto, "Femtosecond Optical Ranging of Corneal Incision Depth," *Invest. Ophthamol. Vis. Sci.* 30: 99 (1989).

ranging in biological systems.[71] The system employs a Michelson interferometer with a short coherence length light source (AR coated laser diode at 830 nm) and optical heterodyne detection to achieve a ranging resolution of 10 μm and detection sensitivity of 1 part in 10^{10} (100 dB SNR). The high ranging resolution is obtained because interference fringes are observed only when the two interferometer arms are length matched to within the coherence length of the light source. Noise reduction is achieved by phase modulating the reference arm of the interferometer with a piezoelectrically actuated end mirror at a frequency range at which optical and mechanical noise is low. The light power incident on the biological sample is 7 μW, considerably lower than the safety limit for intraocular applications. This system has been used to demonstrate measurements of both eye structures and turbid tissue samples.

1.5.2 Optical Diagnostics in Ophthalmology

The transparent media of the eye offers unique accessibility to optical diagnostic methods, and we have focused our investigations on applications in the eye that require the high ranging resolution possible with optical coherence domain reflectometry (OCDR). Specifically, we have demonstrated potential applications to corneal measurements in keratorefractive surgeries and retinal measurements which may be useful for the diagnosis of glaucoma and other retinal diseases.

The ability of excimer lasers to remove corneal tissue in submicron increments has led to interest in the use of these lasers for keratorefractive surgeries.[72] In this procedure, the curvature or refractive power of the cornea is altered surgically to achieve refractive correction without the need for external lenses. To exploit the potential for micron-precision ablation control in laser surgery, a precise method for monitoring the excision depth is needed. We have demonstrated in vitro measurements of excimer laser corneal excision depth using OCDR.[73] The corneal thickness in excised and intact areas were determined by the optical delay between reflection peaks at the air/cornea and cornea/aqueous medium boundaries. We have found that OCDR has sufficient sensitivity to detect rough ablated surfaces even in the presence of a precorneal tear film.

Changes in retinal thickness accompany a variety of retinal diseases. In glaucoma, elevated intraocular pressure produces a gradual loss of the retinal nerve fiber layer that may eventually lead to blindness.[74] Currently, there is no reliable diagnostic tool for the in situ evaluation of retinal nerve fiber loss. Changes in visual function and retinal appearance can occur only in late stages in glaucoma and intraocular pressure itself is not a reliable indicator of disease progression.[75] We have demonstrated in vitro measurements of retinal thickness with OCDR. Retinal thickness was determined by the optical delay between reflections at the vitrious medium/retina and retina/choroid boundaries. Potentially, serial measurements of retinal thickness with OCDR is an accurate method for diagnosing the progress of glaucoma and in selecting the proper treatment regimen.

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[71] D. Huang, J. Wang, C. P. Lin, C. A. Puliafito, and J.G. Fujimoto, "Micron-resolution Ranging of Cornea and Anterior Chamber by Optical Reflectometry," submitted to *Invest. Ophthalmol. Vis. Sci.*

[72] D.S. Aron-Rosa, C.F. Boerner, M. Gross, J.C. Timsit, M. Delacour, and P.E. Bath, "Wound Healing Following Excimer Laser Radial Keratotomy," *J. Cataract Refract. Surg.* 14: 173-179 (1988); J. Marshall, S. Trokel, S. Rothery, and R.R. Krueger, "Photoablative Reprofiling of the Cornea Using an Excimer Laser: Photorefractive Keratectomy," *Lasers Ophthalmol.* 1: 21 (1986).

[73] D. Huang, C.P. Lin, J. Wang, J.G. Fujimoto, and C.A. Puliafito, "High Resolution Measurement of Corneal and Anterior Eye Structure Using Optical Coherence Domain Reflectometry," paper presented at the Association for Research in Vision and Ophthalmology Annual Meeting, Sarasota, Florida, April 1990; *Invest. Ophthal. Vis. Sci.* 31: 244 (1990).

[74] H.A. Quigley and E.M. Addicks, "Quantitative Studies of Retinal Nerve Fiber Layer Defects," *Arch. Ophthalmol.* 100: 807 (1982).

[75] H.A. Quigley, E.M. Addicks and W.R. Green, "Optic Nerve Damage in Human Glaucoma: III Quantitative Correlation of Nerve Fiber Loss and Visual Field Defect in Glaucoma, Ischemic Neuropathy, Papilledema, and Toxic Neuropathy," *Arch. Ophthalmol.* 98: 1564 (1980).

1.5.3 Fiber Optic Integrated Reflectometer

A clinically viable optical reflectometer must be integrated into diagnostic instruments and laser delivery systems and be able to acquire data on the time scale of target motion. We are developing a fiber optic integrated reflectometer in collaboration with Eric Swanson in Group 67 at MIT Lincoln Laboratory. This system will employ modular fiber optic components and a detection scheme capable of high speed data acquisition rate. The system is based on a fiber Michelson interferometer with a superluminescent diode light source (830 nm). Modulation of the interference signal is provided by a combination of piezoelectric fiber length modulation and high speed scanning of the reference arm end mirror. This novel modulation technique allows arbitrary adjustment of signal bandwidth and therefore permits tradeoffs between signal-to-noise ratio and data acquisition rate to be examined. The system has achieved signal-to-noise ratio of 90 dB at a detection bandwidth of 4 kHz. This bandwidth supports scanning data aquisition rate in excess of 1 cm/s, allowing the measurement of thin structures such as cornea and retina without significant motion error. In vitro measurement of cornea thickness has been demonstrated using this system, which will be adapted to a slitlamp biomicroscope for measurements of intraocular structures in vivo.

1.5.4 Variable Pulse Duration Laser

In recent years, laser induced optical breakdown has become an important technique for intraocular surgery.[76] Current clinical systems employ either Q-switched nanosecond pulses or mode-locked picosecond pulse trains. These laser sources generate a single pulse or a pulse train that produces collateral damages through cavitation and shockwave production. This treatment is limited to applications far away from sensitive structures such as the retina and cornea. The use of single picosecond or femtosecond pulses can result in more precise incisions with reduced collateral damage. Shorter pulse duration lowers the threshold energy for optical breakdown and allows the use of less energetic pulses.

We have performed studies of optical breakdown using single 40 ps Nd:YAG laser pulses. Time resolved measurement techniques were used in a comprehensive study of the temporal and spatial dynamics of plasma formation, shock wave, and cavatation processes that accompany optical breakdown.[77] Tissue effects were investigated using corneal endothelium in vitro.[78] Comparison of tissue effects with physical measurements suggests that endothelial cell damage is mediated by shock wave and cavitation precesses while incisions confined to the focal region of the laser beam are produced by the laser-induced plasma. Systematic studies were performed to determine the energy scaling behavior of the tissue effects and to quantify the minimum "safe" distance for clinical photodisruption near sensitive areas. Tissue damage range was found to vary with the cube root of the pulse energy. Picosecond and nanosecond optical breakdown results in comparable damage if the same amount of energy is involved. The minimum damage range of 100 μm was achieved with 8 μJ picosecond pulses.

We have studied corneal excisions generated with nanosecond, picosecond, and femtosecond pulses.[79] Compared with nanosecond pulses, picosecond and femtosecond pulses produced much smoother excision edges and less damage to the adjacent tissue. Pulses shorter than 1 ps produced additional strand-like collateral damage that may be caused by nonlinear processes other than optical breakdown. Because the use of femtosecond pulses is compromised by nonlinear propagation effects, our studies suggest that pulse duration in the 1 to 100 ps range is likely to be optimal for the construction of a precision laser scalpel.

In order to study the optimal pulse duration for a laser scalpel, we have constructed a solid state

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[76] F. Fankhauser, P. Rousel, J. Steffen, E. Van der Zypen, and A. Cherenkova, "Clinical Studies on the Efficiency of High Power Laser Radiation upon Some Structures of the Anterior Segment of the Eye," *Int. Ophthalmol.* 3: 129-139 (1981).

[77] B. Zysset, J.G. Fujimoto, and T.F. Deutsch, "Time-resolved Measurements of Picosecond Optical Breakdown," *Appl. Phys. B* 48: 139-147 (1989).

[78] B. Zysset, J.G. Fujimoto, C.A. Puliafito, R. Birngruber, and T.F. Deutch, "Picosecond Optical Breakdown: Tissue Effects and Reduction of Collateral Damage," *Lasers Surgery Med.* 9: 193-204 (1989).

[79] D. Stern, R.W. Schoenlein, C.A. Puliafito, E.T. Dobi, R. Birngruber, and J.G. Fujimoto, "Corneal Ablation by Nanosecond, Picosecond, and Femtosecond Lasers at 532 and 625 nm," *Arch. Ophthalmol.* 107: 587-592 (1989).

laser system which features high pulse energy and variable pulse duration. The system consists of a high power modelocked Nd:YLF laser, a pulse stretching/compression stage, and a Nd:Phosphate glass regenerative amplifier.[80] Variable pulse duration is achieved using an optical pulse compression/stretching technique.[81] A pulse train from the modelocked Nd:YLF laser is first sent through a long optical fiber. Frequency dispersion and self-phase modulation in the fiber produce a linear frequency chirp and stretch the laser pulse, which is subsequently amplified and compressed by a grating pair. Varying the distance between the grating pair changes the pulse duration.

This system can produce pulse duration from 100 to 1 ps with energies up to 1 mJ. The variable pulse duration system will permit a wide range of studies in laser tissue interaction as well as photochemical and photobiological reactions.

1.6 The MIT Short-Wavelength Laser Project: A Status Report

Sponsors

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Project Staff

Professor Peter L. Hagelstein, Dr. Santanu Basu, Martin H. Muendel, John Paul Braud, Daniel Tauber, Sumanth Kaushik, James G. Goodberlet, Kathryn M. Nelson, Janet L. Pan, Michele M. Bierbaum

1.6.1 Introduction

During the past several years, short-wavelength laser research has advanced to the point where many laboratories around the world have been able to observe stimulated emission in the EUV and soft x-ray regimes. While the use of these lasers in applications is an area of current research, progress has been hindered in most cases by high system cost, low shot rate, and poor beam quality. The resolution of such issues is our principal concern as we seek to develop new EUV lasers.

In this effort, we have chosen to use a Ni-like collisional excitation scheme at low Z; Table 1 lists laser wavelengths and other relevant atomic physics parameters. A solid target will be irradiated by a series of pump pulses,[82] and gain is predicted to appear on the second and following pulses after the plasma is formed. A cavity having a round-trip time equal to the interval between pump pulses would be used to provide feedback synchronous with gain formation.

The experimental facility which we are developing consists of a pump laser system, a target chamber, an automatic target alignment system, and appropriate EUV diagnostics.[83] The pump laser itself is based on a mode-locked, Q-switched Nd:YLF laser which produces a string of 70-100 ps pulses separated by 3.5 ns. Five pulses from this oscillator are amplified in a Nd:glass preamplifier to a total energy of 100 mJ. Final amplification is carried out in a pair of multipass, zig-zag, Nd:glass slabs to produce two beams, each delivering a total of 5 J.

This report describes some of the ongoing and recently completed work associated with this project. Although it will take several months to make our first gain measurements, we have made progress in a number of areas; these are the subjects of the various sections of this report.

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[80] L. Yan, J.D. Lin, P.T. Ho, C.H. Lee, and G.L. Burdge, "An Active Modelocked Continuous Wave Nd:Phosphate Glass Laser and Regenerative Amplifier," *IEEE J. Quant. Electron.* 24: 418 (1988).

[81] W.J. Tomlinson, R.H. Stolen, and C.V. Shank, "Compresson of Optical Pulses Chirped by Self-phase Modulation in Fiber," *J. Opt. Soc. Am. B* 1: 139 (1984).

[82] P.L. Hagelstein, "Short Wavelength Lasers: Something Old Something New," *Proceedings of the OSA Meeting on Short Wavelength Coherent Radiation: Generation and Applications,* eds. R.W. Falcone and J. Kirz, 1988.

[83] P.L. Hagelstein, J.P. Braud, K. Delin, C. Eugster, S. Kaushik, A. Morganthaler, M.H. Muendel, L. Balents, T. Farkas, T. Hung, and K. Lam, *RLE Progress Report No. 130,* Res. Lab. Electron., MIT, 1988, pp. 48; P.L. Hagelstein, S. Basu, M.H. Muendel, S. Kaushik, D. Tauber, J.P. Braud, and A.W. Morganthaler, *RLE Progress Report No. 132,* Res. Lab. Electron., MIT, 1989, pp. 86; S. Basu, M.H. Muendel et al, "Development of the Tabletop 194 Å Laser in Ni-like Mo," Paper QTuD2, presented at CLEO/IQEC, Anaheim, California, 1990.

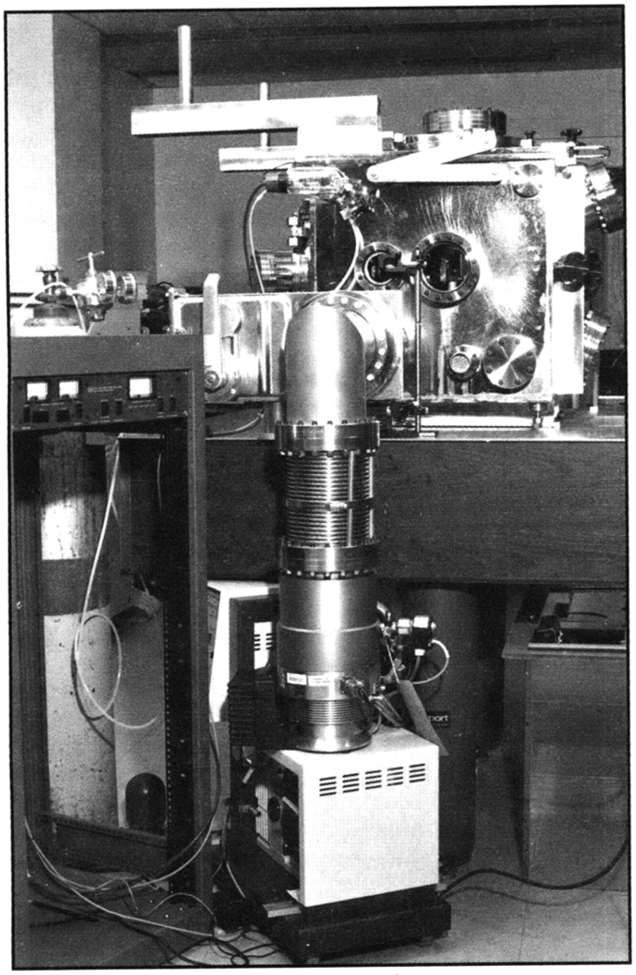

Figure 4. X-ray laser target chamber.

1.6.2 Kinetics of Transiently Pumped Laser Plasmas

Project Staff

Professor Peter L. Hagelstein

In our earlier publication on this approach,[84] we used the numerical simulation tools LASNEX, YODA and XRASER to model the hydrodynamics and laser kinetics. We found that, in contrast to the high-Z systems which have been studied at Lawrence Livermore National Laboratory and elsewhere, low-Z Ni-like systems do not develop significant laser gain under steady-state conditions. The reason is that at low Z, the temperature at which nickel-like ions occur is too low to allow significant excitation of the 4d. Our proposed solution to this problem is to use a low-density transient plasma in which the Ni-like ions are produced at low density and at a temperature matched for 3d-4d electron-collisional excitation. Under these conditions, the Ni-like ions will occur only transiently, since the high temperature will cause the ionization to proceed much further than Ni-like sequence.

The simulations suggested that this approach is basically sound, and we have proceeded to build up an experimental effort to demonstrate the scheme. Further theoretical studies, however, have revealed a very interesting effect: the ion temperature in a plasma pumped by multiple pulses can be very low.[85] During the first pulse, the ions are heated since most of the plasma formation takes place at high density, and the electron-ion coupling times are quite short. After the plasma has expanded and the second pulse arrives, the laser radiation is absorbed at high density, and electron thermal conduction provides a mechanism to heat the electron distribution at low density. At low density the ions couple only weakly to the electrons, and as a result the ion temperature remains quite low; LASNEX calculates an ion temperature of less than 10 eV while the electrons are above 250 eV.

We had not previously appreciated the dramatic disparity in electron and ion temperatures which could be achieved with multiple pulses. This appears to be a new and very interesting regime for x-ray laser physics. Additionally, we note that our earlier estimates of gain in Nd-like ions[86] were low since we had assumed a high value for the ion temperature (ion Doppler broadening dominates the laser line profile). In a plasma pumped by a burst of pulses, if the ion temperature is really below 10 eV, then the Doppler broadening will be reduced by a significant factor (5 or so), and the Nd-like scheme becomes very attractive as a low-intensity means to obtain gain near 100Å and below.

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84 P.L. Hagelstein, "Short Wavelength Lasers: Something Old Something New," *Proceedings of the OSA Meeting on Short Wavelength Coherent Radiation: Generation and Applications,* eds. R.W. Falcone and J. Kirz, Cape Cod, Massachusetts, 1988.

85 S. Kaushik, S. Basu and P. Hagelstein, "Design Studies of the MIT 194 Å Ni-like Mo Laser," CLEO/IQEC '90, Anaheim, California, 1990.

86 P.L. Hagelstein, "Short Wavelength Lasers: Something Old Something New," *Proceedings of the OSA Meeting on Short Wavelength Coherent Radiation: Generation and Applications,* eds. R.W. Falcone and J. Kirz, 1988.

Z	ΔE(3d-4d)	λ_L(Å)	Ω(3d-4d)	f_L(4p-4d)
32	59	748	0.79	0.29
34	98	468	0.51	0.27
36	143	342	0.37	0.25
38	194	271	0.29	0.23
40	250	224	0.24	0.22
42	311	191	0.20	0.20
44	377	167	0.17	0.19
46	449	148	0.15	0.17

Table 1. Atomic physics parameters for $3d^{10}\,{}^1S_0 - 3d^9 4d\,{}^1S_0$ excitation and 4d-4p laser transitions. The 3d-4d excitation energies are in eV, and the 3d-4d collision strengths are near threshold distorted wave values. Based on new extrapolations, we have revised the estimate of the line in Mo to 191Å. (Second International Conference on X-ray Lasers, York, England, September 1990.)

It may be possible that some of the interesting effects reported by Hara are due to low ion temperature, since his group is working in a very similar regime. Additionally, Boehly has reported positive results from double pulse experiments in Ne-like titanium; it would be interesting to see if the ion temperature is low in these experiments.

We note in closing this section that the use of 2 μm for pumping would result in a higher electron temperature relative to the incident intensity; frequency downconversion of the pump could be done efficiently to produce such radiation.

1.6.3 Nd:Glass Power Amplifier

Project Staff

Martin H. Muendel

Final amplification of the pump laser beam is provided by a pair of zig-zag Nd:glass slab amplifiers operating in parallel.[87] A slab design was chosen in favor of the more traditional rod or disk designs because it offers a much higher repetition rate; this feature occurs because both the cooled surface area is increased and the zig-zag geometry cancels out thermal distortion of the beam to first order. Other groups have built similar slab lasers but have generally run them Q-switched, at very high average power; by contrast, we are operating with short, mode-locked pulses at very high peak powers and are therefore intensity-limited as a result of nonlinear self-focusing in the glass. Our slab is therefore designed to be wider and shorter than others, and it is pumped more strongly (at levels up to 0.4 J/cm^3) so as to minimize the B integral for a given net gain. Vacuum spatial filters, apodizing, and relay imaging are also used to help suppress the self-focusing. The required overall gain of 50-100 requires the use of three passes at a gain of 4-5 per pass; we do this in three geometrically distinct passes angled to overlap within the slab. Because our average power requirements are not stringent, we cool the slabs with air rather than liquid and thus avoid problems with phosphate glass solubility and sealing of the pump cavity.

The first head has been completed and tested. It has demonstrated a single-pass gain of over six with uniformity of better than 10% across the width of the slab and virtually perfect uniformity across the thickness. Experiments have been done with simmering and prepulsing the flashlamps, and improvements in the storage efficiency of up to 15% have been seen as a result; the highest measured storage efficiency was over 4%. A rectangular apodized beam with a fill factor of about 75% was injected into the slab and shown to propagate without significant diffractive degradation, and the apodizer image was relayed through the slab and shown to be largely undistorted. Finally, the behavior of the beam was observed as a function of the slab thermal loading: at the slab's maximum repetition rate of .5 Hz (> 1000 W input power), no beam distortion was observed. Focusability of the beam was found to be better than twice diffraction limited at up to full input power. Following installation of some remaining optical components in the amplifier chain, the system will be ready for full-scale operation.

[87] M.H. Muendel and P.L. Hagelstein, "Short-pulse Glass Slab Amplifier," paper presented at *Lasers '90*, San Diego, California, December 1990; M.H. Muendel and P.L. Hagelstein, "High Repetition Rate, Tabletop X-Ray Lasers," *Proc. OE-Laser '90, SPIE Proc.* 1229: 87 (1990).

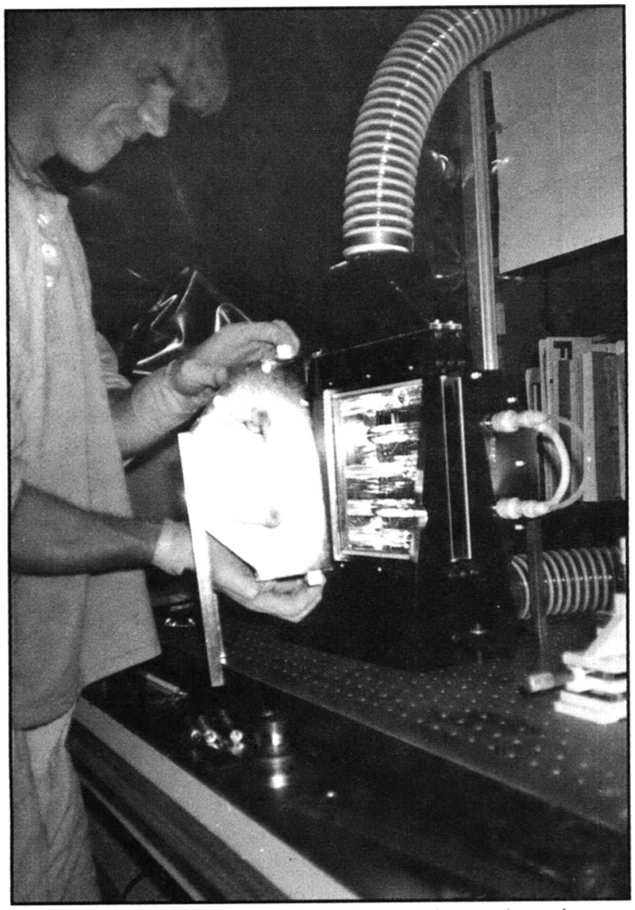

Figure 5. Martin Muendel examines the zig-zag amplifier which he built.

1.6.4 EUV Laser Diagnostics

Project Staff

Dr. Santanu Basu, Professor Peter L. Hagelstein

We are developing two primary laser diagnostics. The first instrument, based upon a flat-field Harada grating, will be run in a number of modes: (1) as a time-resolved (fast diode, 1-GHz transient digitizer) single-channel monochromator, (2) as a time-gated (MCP) spectrograph, and (3) as in (2) but with an image-plane slit to check for angular collimation.

The second instrument would be based on our novel high-resolution, single-element holographic toroidal grating, which will be sufficiently stigmatic to provide 2-D imaging capability between 100-300Å, at a resolution of one part in 5000 or higher.[88] Such a grating could be run in any of the three modes described above, as well as in a fourth, spatial-imaging mode.

1.6.5 Whispering-Gallery Cavities for Short Wavelength Lasers

Project Staff

John Paul Braud, Kathryn M. Nelson

Whispering-gallery optics is based on the principle of using a concave surface to deflect light through a large total angle by means of a series of many glancing-incidence reflections. Because whispering-gallery mirrors (WGMs) offer potentially high reflectivities at short wavelength, they have been suggested for use in x-ray laser cavities.[89] Unfortunately, the simplest resonator geometries—those employing cylindrical or spherical mirrors—have cavity modes whose behavior is poorly suited for use with typical x-ray laser amplifiers.

As a beam propagates along the surface of a WGM, its transverse structure evolves in a manner determined by the local curvatures of the surface. This evolution is highly astigmatic, i.e., the beam profile in the direction normal to the surface behaves very differently from that in the direction tangent to the surface. The fact that the normal and tangential structures evolve differently is not necessarily a major issue. The real problem is in the behavior of the normal structure: for mirrors of any reasonble size, a round geometry leads to unacceptably large beam divergence.[90]

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[88] P.L. Hagelstein, "Design of a Nearly Stigmatic Toroidal Spectrometer," submitted to *Appl. Opt.*

[89] J. Bremer and L. Kaihola, "An X-Ray Resonator Based on Successive Reflections of a Surface Wave," *Appl. Phys. Lett.* 37(4): 360-362 (1980). Erratum: 37(11): 1051 (1980); A.V. Vinogradov, N.A. Konoplev, and A.V. Popov, "Broad-band Mirrors for Vacuum Ultraviolet and Soft X-Ray Radiation," *Sov. Phys. Dokl.* 27(9): 741-742 (1982); A.V. Vinogradov, V.F. Kovalev, I.V. Kozhevnikov, and V.V. Pustovalov, "Diffraction Theory For Grazing Modes in Concave Mirrors and Resonators at X-Ray Wavelengths: II," *Sov. Phys. Tech. Phys.* 30(3): 335-339 (1985).

[90] J.P. Braud and P.L. Hagelstein, "Whispering-Gallery Laser Resonators—Part I: Diffraction of Whispering-Gallery Modes," *IEEE J. Quantum Electron.*, April, 1991, forthcoming.

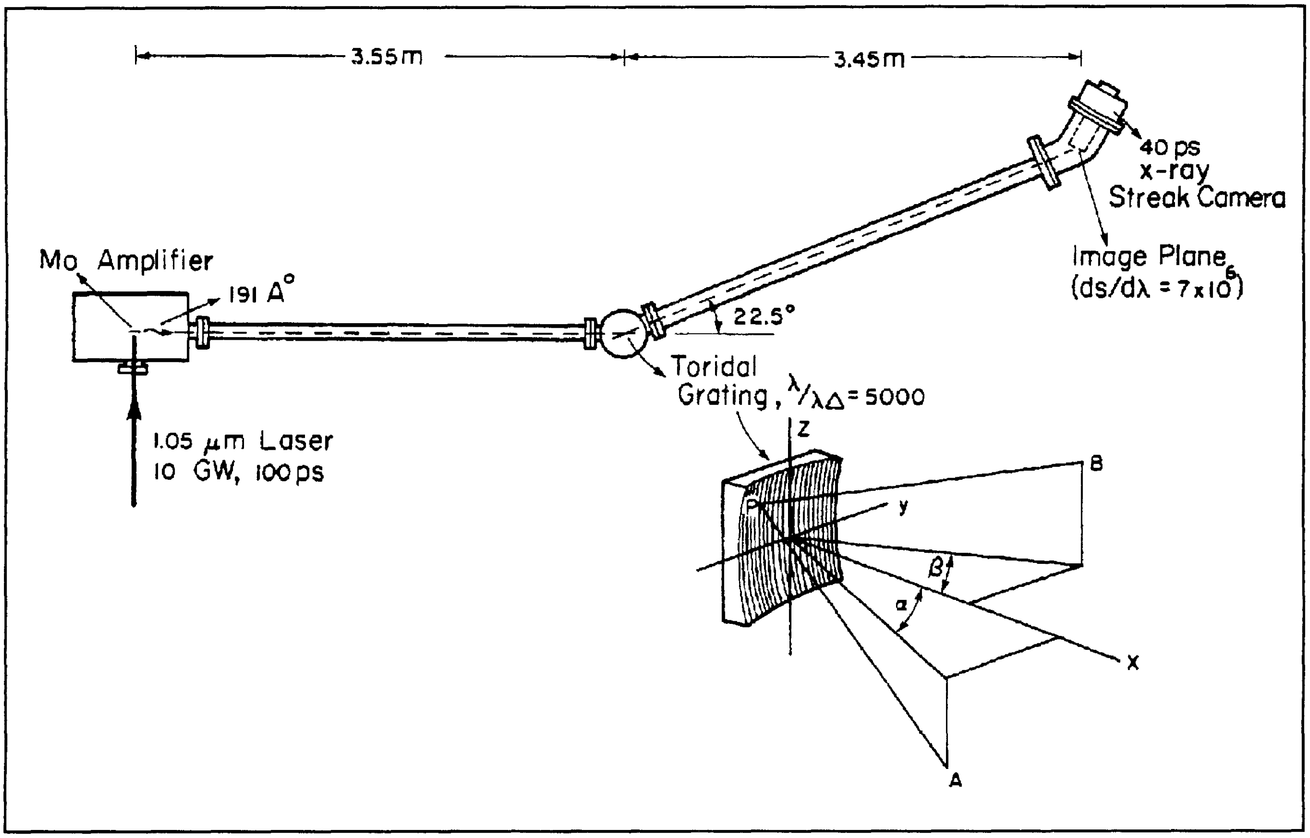

Figure 6. Holographic toroidal grating spectrometer.

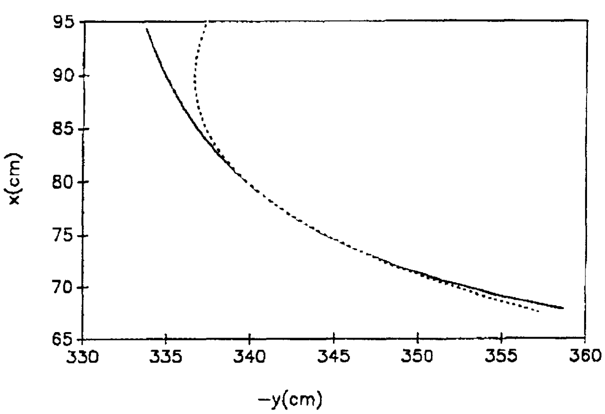

Figure 7. Solutions near image plane for meriodional (solid line) and sagittal (dashed line) imaging.

The beam divergence problem can be ameliorated by using an elongated beam path.[91] Selection of a particular shape for the beam path, however, only partially determines the required mirror shape. At each point along the beam path, the mirror surface looks locally toroidal, with two different curvatures for the directions along the beam and orthogonal to the beam. The desired beam path fixes the curvature along the beam, but the remaining curvature is determined by considerations of how the tangential beam structure should evolve.

[91] J.P. Braud, "Adiabatic Whisper-Gallery Cavities for EUV and Soft X-Ray Laser Cavities," *Proceedings of the International Conference on Lasers '89*, eds. D.G. Harris and T.M. Shay, Society for Optical and Quantum Electronics (McLean, Virginia: STS Press, 1990), pp. 37-39.

The resulting aspheric mirror shapes, although simple to describe in terms of their curvatures, are not at all like those encountered in conventional optics, and their construction appears to present a significant challenge.

As a typical example, we are interested in mirrors for which the "principal" radius of curvature, that along the direction of the beam path, takes the form $R(s) = R_0(1 - s/s^*)^{3/2}$, where s denotes length along the beam path, and where R_0 and s^* are constants; this form appears to be particularly effective in reducing the beam divergence. On the other hand, the evolution of the transverse beam structure is simplest when the the "transverse" radius of curvature Q(s) is chosen so as to keep the product R(s)Q(s) constant; this requires $Q(s) = Q_0(1 - s/s^*)^{-3/2}$. Such a mirror is illustrated in figures 8, 9, and 10.

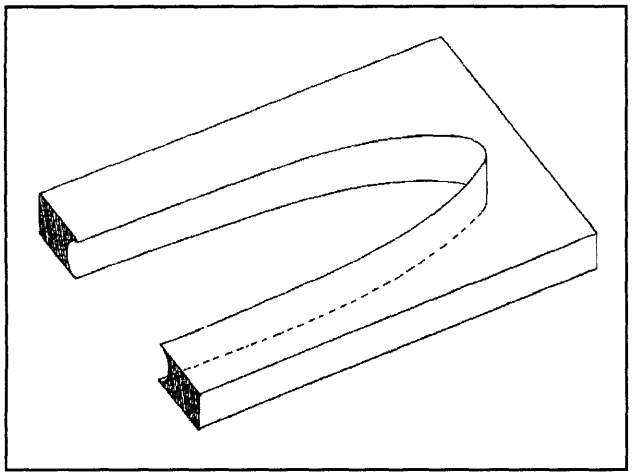

Figure 8. Sketch of the overall shape of a prototypical elongated whispering-gallery mirror.

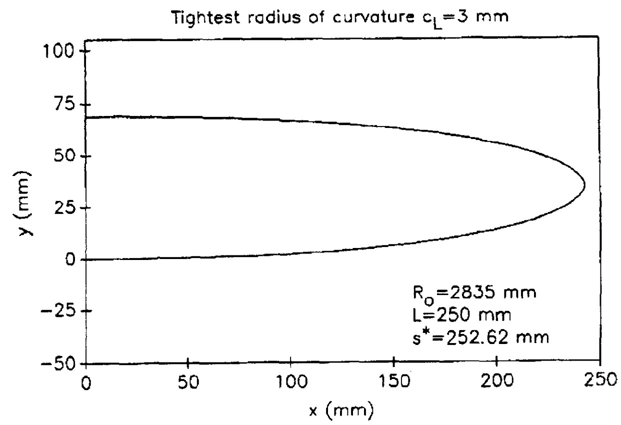

Figure 9. Prototypical elongated whispering-gallery mirror: shape of the beam path, or of the mirror as viewed from above.

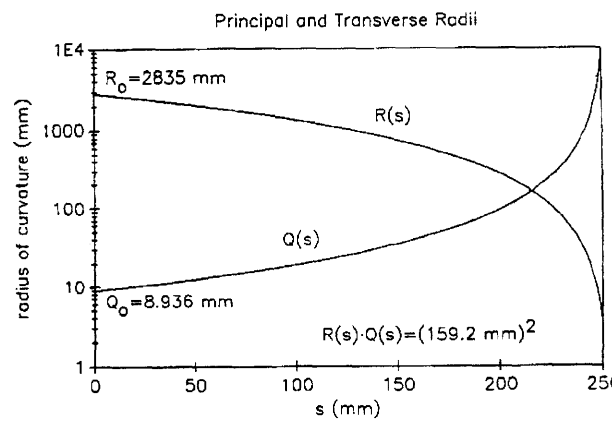

Figure 10. Prototypical elongated whispering-gallery mirror: plots of the radii of curvature. Here s = 0 corresponds to the mirror entrance, and s = 250 mm corresponds to the apex.

1.6.6 Unstable Resonators for EUV Lasers

Project Staff

Dr. Santanu Basu, John Paul Braud, Professor Peter L. Hagelstein

We are investigating the possible implementation of unstable resonators in our Ni-like Mo laser, based on multilayer mirrors[92] and on whispering-gallery mirrors.[93] In the short wavelength region, the unstable geometry has three potential advantages over other resonators. These include: (1) efficient output coupling based on diffraction rather than on transmission, (2) rapid spatial mode formation, and (3) large fractional output coupling.

A 56.3-cm long negative branch confocal strip unstable multilayer mirror resonator has been designed[94] with a magnification of 3.6, which should be capable of producing saturated output in a low divergence beam at 191Å. Fabrication of mirrors will involve growing reflective multi-layers on two concave mirror substrates of radii of curvature 24 cm and 88 cm and cutting out strips of 0.5 mm and 1.8 mm width respectively. The resonator design also makes use of two new features of this laser system: (1) the nearly constant electron density in the gain region parallel to the target surface due to one-sided illumination, and (2) synchronous amplification due to the use of a series of short pulses separated by the cavity round trip time.

1.6.7 Frequency Upconversion of EUV Radiation

Project Staff

Martin H. Muendel, Professor Peter L. Hagelstein

The advent of laser sources in the EUV and soft x-ray regimes suggests the extension of many optical laser techniques and applications to shorter wavelengths. In particular, the prospect of frequency mixing in the EUV is of special interest to our group, both for the production of a bright tunable coherent source for applications as well as for achieving shorter wavelength by means of frequency doubling.

Un-ionized matter is highly absorbing in the EUV. Efficient frequency conversion in the EUV requires low loss, and we have concluded that a low density plasma will probably be most conducive to the mixing process. This conclusion immediately rules out frequency doubling, since parity selection rules cannot be satisfied in isolated ions which are found in such plasmas.

Therefore, our approach is to study four-wave mixing in which two EUV beams are combined with an intense third optical beam to generate harder EUV radiation at roughly twice the frequency of the initial EUV beams.[95] Since it is unlikely that ions can be found with two connected transitions at the same energy (to within a few linewidths), it may not be practical to carry out four-wave mixing experiments with only one EUV laser and one optical laser. Our choice of ion was initially motivated by the hope of developing a scheme in which only a single EUV laser frequency would be required.

We have studied a four-wave mixing process in which a final frequency ω_4 is generated as $\omega_4 = \omega_1 + \omega_2 - \omega_3$, where ω_1 and ω_2 correspond to x-ray laser photons with roughly equal energies, or possibly the same energy, and ω_3 to an optical photon. This difference process is used rather

[92] S. Basu and P.L. Hagelstein, "Unstable Resonators for XUV Lasers," Paper CThO6, Conference on Lasers and Electro-Optics, Anaheim, California, 1990.

[93] J.P. Braud, "Whisper-Gallery Mirrors as Unstable Resonators for Short Wavelength Lasers," paper presented at CLEO,IQEC, Anaheim, California, 1990.

[94] S. Basu and P.L. Hagelstein, "Design Analysis of a Short Wavelength Laser in an Unstable Resonator Cavity," *J. Appl. Phys.* 69(4): 1853-1861 (1991).

[95] M.H. Muendel and P.L. Hagelstein, "Four-Wave Frequency Conversion of Coherent Soft X-rays," submitted to *Phys. Rev. A,* 1990; M.H. Muendel and P.L. Hagelstein, "Analysis of a Soft X-ray Frequency Doubler," *Proceedings of the International Conference on LASERS '89,* eds. D.G. Harris and T.M. Shay, 1990; M.H. Muendel, P.L. Hagelstein, and L.B. Da Silva, "Predicted Four-Wave Mixing Rates for Neonlike Yttrium X-Ray Laser Radiation in a Sodiumlike Calcium Plasma," submitted to *Phys. Rev. A,* 1991.

than the straight sum process because in positively dispersive media such as plasmas, only difference processes can be phasematched noncollinearly.

As an example, we have studied conversion in a plasma of Na-like K;[96] and more recently, we have examined conversion of the radiation of a particular x-ray laser (the Ne-like Y laser) at 155Å to yield 78Å using a Na-like Ca plasma.[97] The results indicate that frequency upconversion is somewhat more difficult in the EUV range than in the optical regime since $\chi^{(3)} \sim 1/w^4$ off-resonance; practically speaking, this translates into a more stringent requirement on the degree of resonance than at longer wavelengths. Nevertheless, where resonances can be found, efficient frequency conversion is possible.

As an example, we plot in figure 11 the expected conversion for the Na-like Ca scheme as a function of the optical photon wavelength, assuming that both x-ray photons are at 155Å and that the input laser intensities are 10^{14} W/cm^2. In the neighborhood of the resonance peaks, the conversion is seen to be considerable.

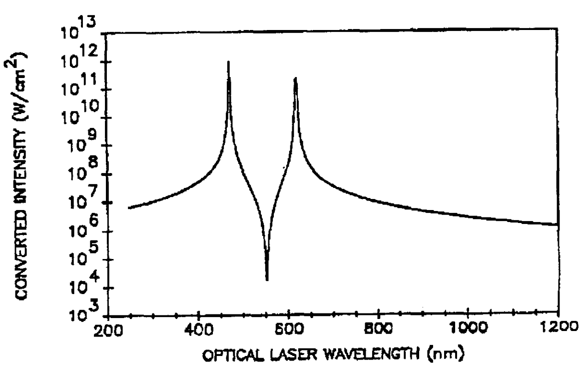

Figure 11. Non-phase-matched conversion as a function of optical laser wavelength, assuming x-ray wavelength 155Å and input intensities of 10^{14} W/cm^2.

1.6.8 X-Ray Detection Based on the MQW Nonlinearity

Project Staff

Dr. Santanu Basu

Great progress has been made during the past several years in the development of quantum well technology for optical nonlinear elements for communications, switching, and computation. In one approach, carriers produced from the absorption of one optical beam are able to alter the optical constants in the vicinity of the exciton absorption peaks, and modulate a second beam which in incident on the MQW structure. We considered the possibility that carriers could also be produced by EUV and x-ray radiation and provide a new x-ray/optical nonlinearity which could serve as the basis for a new class of x-ray detectors.[98]

We initiated a study on x-ray induced nonlinearities in quantum well structures in 1988 and proposed a planar detector scheme and a microetalon scheme for single x-ray photon detection.[98] Since then we have investigated simple designs of quantum well based detectors[99] which can be easily fabricated and can detect a flux of longer-wavelength EUV and soft x-ray radiation incident on the detector.

Once a single x-ray photon is absorbed in the quantum well, carriers are generated by inner-shell photoionization, Auger ionization, followed by collisional ionization. This carrier generation process is estimated to take place within a few picoseconds. The carriers interact with the lattice, losing energy to optical phonons.

The density of electron-hole pairs, N_c generated due to a flux of N_X x-ray photons absorbed in the material may be approximated as $N_c = N_X\eta/h$, where h is the total thickness of the quantum wells and barriers, which is chosen to be equal to the x-ray absorption depth. The average number of e-h pairs created by a single absorbed x-ray photon is $\eta = E_X/E_{eff}$. E_X is the incident x-ray energy, and E_{eff} is the effective bandgap for carrier

[96] M.H. Muendel and P.L. Hagelstein, "Four-Wave Frequency Conversion of Coherent Soft X-rays," submitted to *Phys. Rev. A,* 1990; M.H. Muendel and P.L. Hagelstein, "Analysis of a Soft X-ray Frequency Doubler," *Proceedings of the International Conference on LASERS '89,* eds. D.G. Harris and T.M. Shay, 1990.

[97] M.H. Muendel, P.L. Hagelstein, and L.B. Da Silva, "Predicted Four-Wave Mixing Rates for Neonlike Yttrium X-Ray Laser Radiation in a Sodiumlike Calcium Plasma," submitted to *Phys. Rev. A,* 1991.

[98] C. Eugster and P.L. Hagelstein, "X-ray Detection Using the Quantum Well Exciton Nonlinearity," *IEEE J. Quantum Electron.* QE-26: 75 (1990).

[99] S. Basu, "Possibility of X-ray Detection Using Quantum Wells," *IEEE J. Quantum. Electron.,* forthcoming.

production, which includes the phonon energy and the residual carrier energy and is estimated to be 4.68 eV.

For small carrier densities, the change in optical susceptibility is free of saturation effects, and the total absorption coefficient, $\alpha(E, N_c)$ can be well approximated by a linear function in the electron-hole pair density, N_c. For detection of x-rays, the probe beam will be tuned to near the exciton resonance, and the probe signal will be most affected by the change in the exciton resonace by x-ray generated carriers. We calculate a 1% change in the probe beam in a reflection geometry for an incident flux of 12 x-ray photons per μm^2.

Our analysis showed for the first time that the change in the optical susceptibility is significant enough to construct sensitive time and spatially resolved x-ray detectors. We also investigated a one-dimensional x-ray detector based on Nomarski interference technique. We showed that the time response of a quantum well detector may be diffusion limited to 50 ps by limiting its lateral dimension. Very large area detectors (six inches in diameter) could be made by growing GaAs based quantum wells on Si. Finally, quantum wells may be configured into a two-dimensional array of optical waveguides, in which longer interaction lengths will give rise to higher sensitivity.

1.6.9 Downconversion of 2ω ND:YLF Radiation

Project Staff

James G. Goodberlet, Michele M. Bierbaum

A novel x-ray susceptibility of multiple quantum wells (MQW) has been proposed.[100] In this detection scheme, incident x-ray radiation will locally change the carrier density in a MQW device. This results in a change in the real and imaginary pails of the material's refractive index. The change in optical index is largest at the material's exciton binding energy and can be observed, via phase or amplitude detection schemes, with an optical probe phase which is tuned to the exciton peak.

The proposed MQW x-ray detector requires a tunable probe source. For high temporal resolution, the optical probe should be a source of short pulses, 50 ps, which are produces synchronously with the x-ray emission. This will allow delaying of probe pulses through the x-ray pulses. The optical probe should also have adequate energy for detection purposes.

We have selected an optical parametric amplifier (OPA) as the probe source for an x-ray detector. The OPA has been selected because it meets the above requirements for an optical probe, and also because of its apparent ease of use. Namely, the OPA can be optically pumped with the same source that produces x-rays. The proposed scheme is pictured in figure 12.

For our experiments, x-rays will be generated in a plasma created by a high power, amplified Nd:YLF laser. A portion of the Nd:YLF beam will be frequency doubled to 525 nm which will then pump the OPA. The OPA will down convert the 525 nm to an unused idler frequency and a tunable signal frequency at ~ 850 nm. The 850 nm output will then be used to probe the exciton peak in GaAs multiple quantum wells.

Our strongest requirement is that the OPA have enough conversion efficiency to support adequate

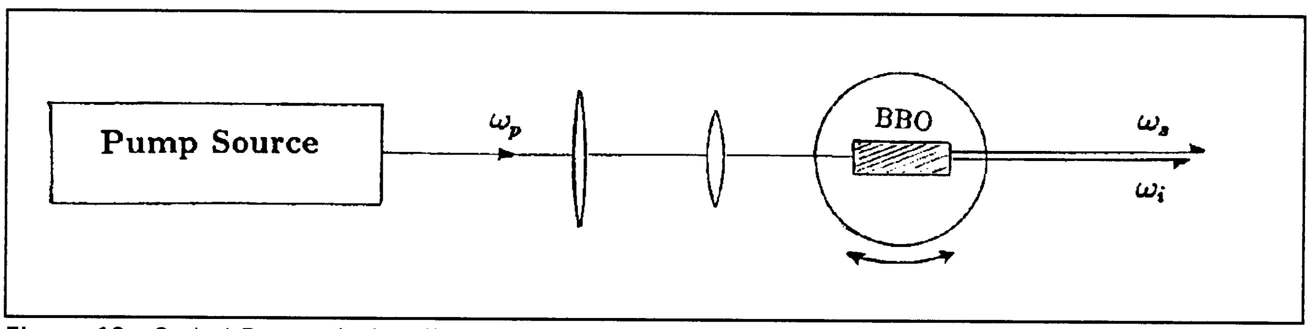

Figure 12. Optical Parametric Amplifier: The pump source provides radiation at ω_p which is focused with a beam reducing telescope into the non-linear crystal BBO. Frequency conversion occurs in the crystal and provides desired signal ω_s and unused idler ω_i outputs.

[100] C. Eugster and P.L. Hagelstein, "X-ray Detection Using the Quantum Well Exciton Nonlinearity," *IEEE J. Quantum Electron.* QE-26: 75 (1990).

probe energy or intensity at the signal wavelength. In the low conversion limit, the exponential single pass gain is proportional to crystal length and the square of the crystal's effective nonlinear coefficient. A review of currently available nonlinear crystals revealed the beta-barium borate (BBO) provides the highest conversion efficiency for our application. Figure 13 shows results of a numerical simulation of OPA conversion in the high gain regime.

The graph shows an optimal conversion length of $\sim$ 20 mm at an pump intensity of 4 GW/cm^2. The graph shows that with proper crystal length and pump intensity, all the input radiation can be converted to signal and idler radiation. The OPA should then provide adequate probe intensity at 850 nm. Preliminary experiments are presently being conducted.

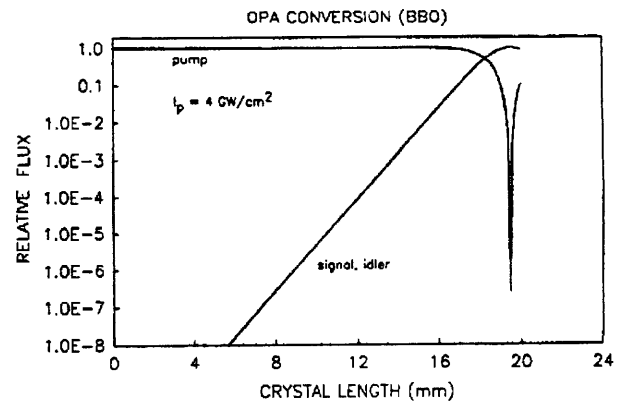

Figure 13. OPA Conversion. Results of numerical simulations in the high gain regime show that an optimal crystal length, or pump intensity, exists for complete conversion of incident pump radiation.

1.7 Generalizing Hydrodynamic Transport in Semiconductor Device Modeling

Sponsor

Columbia University
Contract P0163103

Project Staff

Sumanth Kaushik, Professor Peter L. Hagelstein

The advent of very large scale integrated circuits with submicron features has necessitated the reexamination of semiconductor transport models. The presence of hot electrons, ballistic electrons and large spatial gradients in the carrier concentration (and correspondingly large electrostatic fields) have led to the failure of conventional semiconductor transport models. Two distinct approaches to modeling the physics relevant to transport in submicron devices appear in the literature. The first approach has been to modify the standard drift-diffusion model by including additional moments of the Boltzmann transport equation (BTE). These additional moments (usually energy balance and energy flux equations) when solved together with the standard drift-diffusion equation form what is commonly referred to in the literature as the hydrodynamic model of semiconductor transport. The second approach has been to use Monte Carlo methods to stochastically solve the BTE. The latter approach is generally the most accurate method for solving transport problems in submicron devices. However, stochastic methods are not well suited for boundary value problems and, in addition, the calculations are usually computationally intensive; therefore they are not ideal for design applications.

From the viewpoint of computational complexity, hydrodynamic models are relatively straightforward to implement and are reasonably fast. In addition, boundary conditions appear naturally within the framework of the model. Despite a sizable amount of literature on the application of hydrodynamic models to device modeling, a systematic study of moment expansion methods does not exist. The focus of our research has been the development of a hydrodynamic model of semiconductor transport in which the number of moments retained in the moment expansion is an arbitrary, user supplied parameter. To date, we have adapted an algorithm due to Eddington from the field of radiation transfer to solve an infinite set of moment equations. By constructing a distribution function as an expansion over a large set of basis functions and using the moments to determine the coefficients of expansion, we are seeking an alternative to Monte Carlo methods for physical device modeling applications.

1.8 Hydrodynamic Calculations

Project Staff

Ann W. Morganthaler

An important adjunct to experiments attempting to create a plasma source of coherent x-rays will be the numerical simulation of the behavior of such a plasma. With a sophisticated, non-equilibrium, two-dimensional code which includes calculations of the transition rates between the various species in this plasma, it should be possible to accurately predict plasma temperatures, densities etc., and therefore to predict gain. These hydrodynamic calculations should then greatly aid in optimizing the shape and composition of the x-ray targets which produce the plasma.

The hydrodynamic codes utilize an implicit Lax-Wendroff-type scheme rather than the usual explicit schemes for which the maximum time step size is severely limited. A fourth-order implicit scheme is being developed, as are codes which include realistic physical modeling rather than the very simple equations of state often used. Electron transport equations will be derived using a series of moment equations, eliminating the need for traditional flux-limited computation. The mesh will ultimately be non-uniform and adaptive, greatly reducing the number of grid points necessary for a realistic calculation. Our goal is to create hydrodynamic models which will give useful design information for the x-ray laser in a minimum amount of computation time.

1.9 Infrared Laser Studies

Project Staff

Janet L. Pan

We are exploring possibilities for new lasers operating in the thermal infrared (2-10 microns). We have investigated the trends in the future of research and applications of coherent radiation product ion in this regime. We have looked at frequency up and down conversion, free electron lasers, gas lasers, and semiconductor and other solid state lasers in this regime.

At present, we are exploring the advantages and limitations of semiconductor quantum dot lasers. At present, the common semiconductor lasers, such as the lead salt or GaSb ones, are limited to low temperature operation because of large Auger recombination rates at these infrared wavelengths. We explored the effects of reduced dimensionality on this Auger rate. Initial calculations indicate that the bound-to-bound Auger rate can be eliminated because of the discrete nature of the energy spectrum in a quantum dot. Practical considerations, such as fabrication tolerances, reduced mometum matrix elements, and the availability of materials with properties that sufficiently emulate a quantum dot, are being considered.

1.10 Approximations to the Single Photon Exchange Interaction

Project Staff

Professor Peter L. Hagelstein, Isaac L. Chuang

Self-energy corrections for highly-stripped and highly charged ions have proven to be difficult to calculate, primarily because of the lack of well-developed systematic methods for evaluating the relevant Feynman diagrams accurately in a nonperturbative scheme. Presently, Lamb shifts for high-Z one-electron systems are calculated using variants of Brown's method which rely heavily on properties of the Dirac-Coulomb Green's function. We have derived an alternative approach based on a generalized partial-wave decomposition which is valid for general potentials (including those for multi-electron atoms).[101] Our approach leads to a numerical technique for obtaining systematic approximations for non-separable matrix elements of the photon exchange operator with full retardation, in terms of a summation of matrix elements of operators which are separable in radial coordinates.

The single photon exchange operator including full retardation in the Feynman Gauge is given by

$$V(\omega; r_1, r_2) = \frac{2}{\pi}[\alpha_1\alpha_2 - I]\int_0^\infty \frac{1}{\omega + k}\,\frac{\sin(k|r_1 - r_2|)}{|r_1 - r_2|}\,dk. \qquad (1)$$

Low momentum simplification and angular decomposition of this approximation lead directly to the Coulomb interaction (and Breit interaction, in the Coulomb gauge). Unfortunately, direct angular decomposition of this operator does not result in terms which are easily separable into radial and angular coordinates. The use of this operator directly in place of the Coulomb and Breit interaction in atomic physics calculations would lead to a theory in which nonseparable 2-D radial matrix elements would appear.

However, our technique makes this new approach computationally practical. The basic idea is to expand the nonseparable photon exchange operator with full retardation in terms of a series of closely related separable operators. This idea may be summarized by the approximation

[101] P.L. Hagelstein, "On the Partial-Wave Method for Self-Energy Calculations in Non-hydrogenic Ions," *Proceedings of the First International Conference on Coherent Radiation Processes in Strong Fields,* Catholic University, Washington D.C., June 1990.

$$V(\omega; r_1, r_2) \approx \tag{2}$$

$$\frac{2}{\pi}\sum_i a_i(\omega)[\alpha_1\alpha_2 - I]\int_0^\infty \frac{k}{b_i^2(\omega) + k^2}\,\frac{\sin(k\,|\,r_1 - r_2\,|\,)}{|\,r_1 - r_2\,|}\,dk.$$

The key point of this expansion is that each term in the summation is easily and accurately evaulated in terms of 1-D radial integrals.

Easily accessible numerical algorithms such as ours, which allow the use of the photon exchange operator with full retardation, promise to have a significant impact on atomic physics calculations. Additionally, the new class of algorithms we are developing will allow computations to be done accurately which have historically been deemed impractical.

Currently, we are in the process of systematically quantifying numerical sources of error, in preparation for detailed calculations of self-energy corrections for non-hydrogenic systems, beginning with Li-like, Na-like, and Cu-like systems. Our experience thus far indicates that it may be feasible to maintain 10-digit accuracy throughout our calculations.[102]

1.11 Coherent Neutron Transfer Reactions

Sponsor

U.S. Department of Energy
Grant DE-FG02-89-ER14012

Project Staff

Professor Peter L. Hagelstein

In last year's report, we described the status of coherent fusion theory and the depp reaction scenario. In analyzing this scenario, we have found a new mechanism for resonantly transferring energy between nuclear systems and macroscopic systems.[103] Although not widely appreciated, it appears that standard quantum mechanics predicts the possibility of phonon-induced removal and capture on neutrons from nuclei.

The arguments leading to this conclusion are straightforward; if we consider the coherent transfer of neutrons from deuterium, or the coherent capture of a neutron by proton, then we may describe the transition hamiltonian through

$$\hat{H}_{pd} =$$

$$-\sum_j \int\int \hat{\Psi}_n^\dagger(r_1)\hat{\Psi}_p^\dagger(r_2)\mu_j \bullet B(r_j)\hat{\Psi}_d(r_1, r_2)d^3r_1d^3r_2$$

$$-\sum_j \int\int \hat{\Psi}_d^\dagger(r_1, r_2)\mu_j \bullet B(r_j)\hat{\Psi}_n(r_1)\hat{\Psi}_p(r_2)d^3r_1d^3r_2$$

where the capture or removal is driven by a magnetic dipole transition. The field operators for the protons and deuterons are given by

$$\hat{\Psi}_p(r) = \sum_i \sum_\alpha \hat{b}_{p,\alpha}(i)\phi_p(r - \hat{R}_i)\chi_\alpha^{1/2}$$

and

$$\hat{\Psi}_d(r_1, r_2) = \sum_i \sum_\alpha \hat{b}_{d,\alpha}(i)\phi_d(r_1 - \hat{R}_i, r_2 - \hat{R}_i)\chi_\alpha^1$$

where $\hat{R}_i$ is a center of mass nucleon position operator which is a function of the lattice mode amplitude operators

$$\hat{R}_i = R_i^o + \sum_m \hat{q}_m u_m(i)$$

Of course the lattice itself differs before and after the transfer by one nucleon, and hence the lattice position operator differs before and after the reaction.

The transition operator is observed to be a highly nonlinear function of the phonon mode amplitudes; if sufficient excitation of a small subset of the phonon modes occurs, then it is possible that the lattice energy can be transferred to and from the nuclear system. One condition that the transition operator produce a large associated matrix element is that the positions of the proton and nucleon within the lattice coincide briefly micro-

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102 P.L. Hagelstein, I.L. Chuang, "Approximations to the Single Photon Exchange Interaction with Full Retardation," submitted to *J. Phys. B.*, April 1991.

103 P.L. Hagelstein, "Coherent Fusion Mechanisms," *Proceedings of the Conference on Anomalous Processes in Deuterated Metals*, Brigham Young University, Salt Lake City, Utah, October 1990; P.L. Hagelstein, "Coherent Neutron Transfer Reactions," submitted to *J. Fusion Tech.* (1991).

scopically to within fermis; this occurs repeatedly for certain lattice motions, and if the process is repeated at enough sites over suffcient vibrational cycles, then a transfer may occur.

This mechanism results in a theory for energy generation in which neutrons are promoted to lattice Bragg states from "donor" nuclei due to coherent lattice excitation; and the coherently captured on "acceptor" nuclei through a reverse version of the coherent process. The mechanism is illustrated in figure 14.

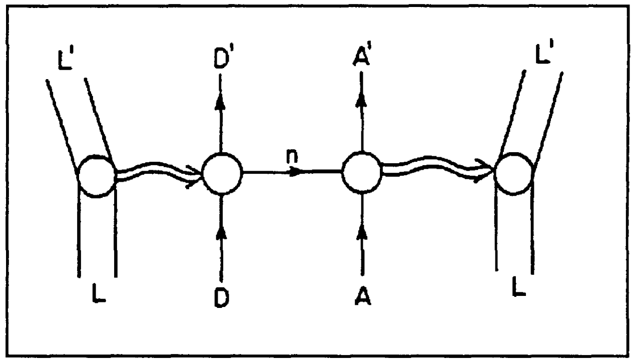
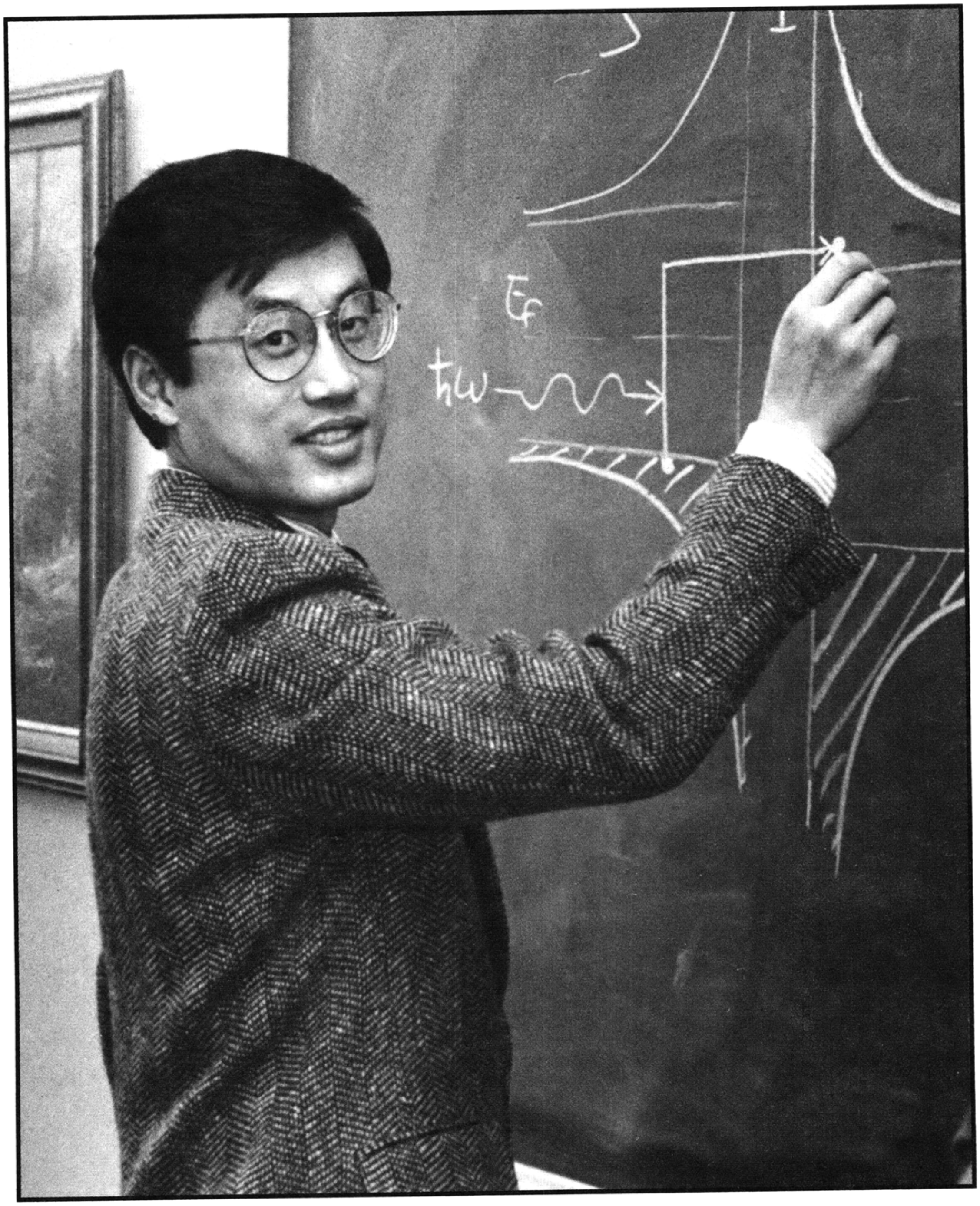


Figure 14. General neutron transfer reaction from donor to acceptor nuclei.



Professor Qing Hu explains the phenomenon of photon-assisted tunneling in superconducting tunnel junctions to graduate students.