5. Optics and Quantum Electronics

Academic and Research Staff

Prof. C.G. Fonstad, Prof. H.A. Haus, Prof. J. Fujimoto, Prof. E.P. Ippen, Dr. S. De Silvestri, Dr. P. Mataloni, Dr. W.Z. Lin, Dr. M. Nakazawa

Graduate Students

S. Brorson, C. Gabriel, E. Garber, W.P. Huang, J.M. Huxley, M. Islam, M. Kesler, M. Kuznetsov, M.J. Legasse, L.Y. Liu, L. Molter-Orr, M. Phillips, R.W. Schoenlein, G. Shahidi, M. Stix, N. Whitaker, J. Zayhowski

5.1 Photorefractive Effect

Joint Services Electronics Program (Contract DAAG29-83-K-0003)

Hermann A. Haus, Mary R. Phillips

The experiments with visible light or 0.85 μ light on coupled waveguides and waveguide interferometers fabricated in $LiNbO_3$ are plagued by the photorefractive effect, in particular if optical nonlinearities in these waveguides are used intentionally, as in the all-optical waveguide modulator.[1] In her experiments on optical waveguide interferometers, A. Lattes discovered a transformation from a TM-mode input to a TE-mode output on a time scale of seconds. If the input was TE no transformation occurred.

This effect was not understood on the basis of the Helwarth *et al.*[2] and A. Glass[3] models of the photorefractive effect. In her Master's thesis, M.R. Philips confirmed Lattes' findings and succeeded in explaining the phenomenon by the photogalvanic process postulated by Russian researchers.[4]

References

1. A. Lattes, H.A. Haus, F.J. Leonberger, and E.P. Ippen, "An Ultrafast All-Optical Gate," IEEE Quantum Electron. QE-19, 1718-1723, November 1983.
2. J. Feinberg, D. Heiman, A.R. Tanguay, and R.W. Hellwarth, "Photorefractive Effects and Light-Induced Charge Migration in Barius Titanate," J. Appl. Phys. 51, 1297-1305 (1980).
3. A.M. Glass, D. von der Linde, and T.J. Negran, "High-Voltage Bulk Photovoltaic Effect and the Photorefractive Process in $LiNbO_3$," Appl. Phys. Lett. 25, 233-235 (1974).
4. V.I. Belinicher, V.K. Malinovskii, and B.I. Sturman, "Photogalvanic Effect in a Crystal with Polar Axis," Sov. Phys. JETP 46, 362-366 (1978).

5.2 The Nonlinear Waveguide Interferometer

Joint Services Electronics Program (Contract DAAG29-83-K-0003)
National Science Foundation (Grant ECS83-05448)
Hermann A. Haus, Norman A. Whitaker

Nonlinear Waveguide Interferometers built in GaAs-AlGaAs are much less susceptible to photorefractive damage than in $LiNbO_3$. Further, they permit the incorporation of quantum well structures. We have, therefore, begun to build such interferometers. The main problem is to provide the *Y's* of the interferometer with sufficiently large divergence angles so that the length of the interferometer is not excessive. However, the transverse-field confinement in ridge waveguides is weak for single mode waveguides unless the "ridges" are etched quite deeply, into the lower index substrate. Under these conditions, the effective index method of mode analysis does not give reliable answers. Norm Whitaker is currently fabricating an interferometer in GaAs-GaAlAs and working on the extension of the analysis to deeply etched waveguides.

The Quantum Well nonlinearity saturates with laser intensities achievable with semiconductor lasers. Thus a nonlinear interferometer in GaAs incorporating a quantum well can be at power levels compatible with semiconductor lasers. A nonlinear interferometer in GaAs-GaAlAs incorporating a quantum well is currently in fabrication.

5.3 Quantum Noise and Quantum Nondemolition Measurement

Joint Services Electronics Program (DAAG29-83-K-0003)
National Science Foundation (Grant ECS83-10718)
Hermann A. Haus

During the author's sabbatical stay at the Nippon Telegraph and Telephone Co. he worked with the coherent optical communications group headed by Dr. Y. Yamamoto. This group is interested in achieving improved detector sensitivity using light that, impingent upon a photodetector, produces noise less than shot noise. Such light is said to be in a "squeezed state." Similar work is pursued within RLE by Professor Shapiro's group.

The nonlinear interferometric all-optical modulator first realized by our group[1] is a candidate, at least in theory, for the achievement of such squeezed states. In its ideal lossfree form it can be shown to be an apparatus for a quantum nondemolition measurement of photon number.[2] Successive measurements on a wavepacket produce the same measured value of the photon number, hence the "nondemolition" designation.

References

1. A. Lattes, H.A. Haus, F.J. Leonberger, and E.P. Ippen, "An Ultrafast All-Optical Gate," IEEE J. Quantum Electron. QE-19, no. 11, 1718-1723, November 1983.
2. N. Imoto, H.A. Haus, and Y. Yamamoto, "Quantum Nondemolition Measurement of the Photon Number Via the Optical Kerr Effect," Phys. Rev. A 32, no. 4, 2287-2292, October 1985.

5.4 Picosecond Optical Signal Sampling

National Science Foundation (Grant ECS83-10718)

Hermann A. Haus, Wei Ping Huang, Lynne A. Molter-Orr

Coupled pairs of waveguides have device applications that have been extensively exploited in the past. We have pursued investigations of multiple coupled waveguides and shown that they offer interesting novel applications.[1,2] A properly designed array of N parallel waveguides is capable of collecting coherent input excitations in N-waveguides into a single output waveguide.[2] The question arises whether such waveguides arrays permit parameter adjustment by the $\Delta\beta$ principle first proposed by Kogelnik and Schmidt for the coupled waveguide pair. We have shown that this is indeed possible.[3]

The coupled mode analysis of multiple waveguides can be interpreted by analogy with the paraxial wave equation. Since the physical intuition and the store of solved problems built up for this equation is considerable, such an analogy can prove very useful. It has been proposed previously by Kapon,[4] but was not carried out correctly. In a paper accepted for publication we have set up the correct formalism.[5]

Recently the coupled-mode approach has been criticized by Hardy and Streifer.[6] In particular they challenged the symmetry of the coupling of guides of different cross sections or index distributions. The symmetry assumption underlies all previous work utilizing the coupled mode formalism. We have shown the symmetry of the coupling coefficients is a matter of proper choice of the mode amplitudes and, thus, previous work using the symmetry condition maintains it's generality.[7]

References

1. H.A. Haus and L. Molter-Orr, "Coupled Multiple Waveguide Systems," IEEE J. Quantum Electron. QE-19, no. 5, 840-844, May 1983.
2. H.A. Haus, L. Molter-Orr, and F.J. Leonberger, "Multiple Waveguide Lens, Appl. Phys. Lett. 45, no. 1, 19-21, July 1984.
3. L.A. Molter-Orr and H.A. Haus, "Multiple Coupled Waveguide Switches Using Alternating $\Delta\beta$ Phase Mismatch," Appl. Opt. 24, 1260-1264, May 1985.
4. E. Kapon, J. Katz, and A. Yariv, "Supermode Analysis of Phase-Locked Arrays of Semiconductor Lasers," Opt. Lett. 10, 125-127, April 1984.
5. S. Kawakami and H.A. Haus, "Continuum Analog of Coupled Multiple Waveguides," IEEE/OSA J. Lightwave Technol., LT-4, 160-168, February 1986.

6. A. Hardy and W. Streifer, "Coupled Mode Theory of Parallel Waveguides," IEEE/OSA J. Lightwave Technol. LT-3, 1135-1146, October 1985.
7. H.A. Haus, W.P. Huang, S. Kawakami, and N.A. Whitaker, "Coupled Mode Theory of Optical Waveguides," IEEE/OSA J. Lightwave Technol., submitted for publication.

5.5 Studies of Surface Acoustic Wave Propagation in Gratings

National Science Foundation (Grant ECS82-11650)
Dong-Pei Chen, Hermann A. Haus, John Melngailis

The analysis of metal-strip SAW gratings and transducers has been carried out deriving all pertinent transducer parameters from one single set of coupled mode equations via the use of a variational principle.[1] A sign mistake in the reflection coefficient due to the mass loading of the transducer finger that appeared in the literature was found and corrected. This sign reversal changes the criterion for reflection-free metal finger design. The reflection can be eliminated even for solid (as opposed to split) fingers for a special choice of metal thickness and metalization ratio. This can double the working frequency of transducers for a given resolution limit of fabrication.

The variational approach to coupled mode theory used on the SAW analysis has also been employed to settle a controversy as to the proper derivation of the coupling coefficients for optical waveguide couplers.[2]

References

1. D.-P. Chen and H.A. Haus, "Analysis of Metal-Strip SAW Gratings and Transducers," IEEE Trans. Sonics Ultrason. SU-32, no. 3, 395-408, May 1985.
2. H.A. Haus, W.P. Huang, S. Kawakami, and N.A. Whitaker, "Coupled Mode Theory of Optical Waveguides," IEEE/OSA J. Lightwave Technol., accepted for publication.

5.6 Solitons

Joint Services Electronics Program (Contract DAAG29-83-K-0003)
Hermann A. Haus, Masataka Nakazawa

The soliton laser uses index modulation, rather than absorption modulation, for modelocking and pulse shortening. This fact opens up new possibilities for the generation of short pulses that in addition can be made to assume a standard shape. We have developed a theory of the soliton laser as realized by Dr. L.F. Mollenauer and Dr. R.H. Stolen at AT&T Bell Laboratories.[1]

There are other realizations of a soliton laser such as the Raman fiber ring soliton laser proposed by Dr. M. Nakazawa. During Dr. Nakazawa's stay we have developed a theory of the laser and its tuning characteristic.[2] Interestingly, the frequency of the laser can be changed by a change of the ring roundtrip time that can be adjusted by variable distance between the fiber input and output ends.

References

1. H.A. Haus and M.N. Islam, "Theory of the Soliton Laser," IEEE J. Quantum Electron. QE-21, no. 8, 1172–1188, August 1985.
2. H.A. Haus and M. Nakazawa, "Theory of the Fiber Raman Soliton Laser," J. Opt. Soc. Am. B, submitted for publication.

5.7 Ultrashort Pulse Generation

Joint Services Electronics Program (Contract DAAG29-83-K-0003)
National Science Foundation (Grant ECS84-06290)
Erich P. Ippen, James G. Fujimoto

Femtosecond pulses are generated in our laboratory at a high repetition rate (100 Mhz) by a colliding-pulse-modelocked (CPM) ring dye laser and then amplified to high power, at a lower repetition rate, in an Nd:YAG-laser-pumped dye amplifier chain. This system is the workhorse of our program in femtosecond spectroscopy to date, and methods for extending its capabilities are currently being investigated. During the past year several significant improvements have been implemented.

By incorporating a set of four prisms into the CPM laser (in a dispersion-compensating arrangement originally demonstrated by Fork *et al.*[1] at AT&T Bell Laboratories), we have been able to reduce the minimum output pulse duration from about 55 fsec to 35 fsec. Even more important, for many spectroscopic applications, this makes it possible to vary the output pulse duration continuously from 35 to 200 fsec. With a second set of four prisms external to the laser we can tailor the output pulses for either minimum or desired frequency chirp. These new features allow us to distinguish between electric field correlation and intensity correlation effects in pump-probe experiments and thereby identify coherence artifacts that may otherwise be confused for physical phenomena.

For high power experiments, our signal averaging capability has been enhanced by upgrading the Nd:YAG system to improve beam quality and increase repetition rate from 10 to 20 Hz. High gain and pulse durations well under 100 fs have now also been achieved at the slightly longer wavelength of operation caused by insertion of the prisms in the oscillator.

In addition to continuing research on our 20 Hz femtosecond laser system, we have recently begun the construction of a new CPM ring dye laser and amplifier system which will operate with intermediate gains but high repetition rate.[2] The dye amplifier uses a copper vapor laser operating at an 8 kHz repetition rate as the pump source. Femtosecond pulses generated by the ring dye laser are amplified by successive passes through a pumped gain jet. Using a 6 pass configuration, we have obtained gains of > 10^4 corresponding to single pulse energies of $\sim$ 1 μJ at 635 nm. For pulse durations of 35–55 fs, this corresponds to peak intensities of > $10^8 W$. These intensities are sufficient for most nonlinear optical experiments including the generation of a broadband femtosecond continuum. The high repetition rate of this system allows the use of lock-in detection techniques and signal averaging so that very high sensitivity measurements are possible and changes in optical properties as small as one part in 10^5–10^6 are measurable on a femtosecond time scale. This system thus has complementary capabilities to our high power Nd:YAG pumped femtosecond amplifier; together these two laser facilities provide the basis for a wide range of femtosecond research.

During the past year we have also succeeded in developing a tunable femtosecond system for the wavelength range 780–860 nm, important for GaAs studies. This was accomplished by fiber compression of pulses from a near infrared dye laser. The laser was a cavity-dumped OX750 dye laser, synchronously pumped by a modelocked Krypton ion laser and yielding output pulses of 15 nJ and 8 ps. These pulses were compressed by passage through 35 m of polarization preserving fiber and a grating pair (in double-pass configuration). With four birefringent plates inside the dye laser to insure transform-limited operation, compression factors of 15–20 and pulse durations of 400–500 fs were obtained.

References

1. R.L. Fork, O.E. Martinez, and J.P. Gordon, "Negative Dispersion Using Pairs of Prisms," Opt. Lett. 9, 150–152 (1984).
2. 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, 552–554 (1984).

5.8 Femtosecond Spectroscopy

U.S. Air Force – Office of Scientific Research (Contract AFOSR-85-0213)
Joint Services Electronics Program (Contract DAAG29-83-K-0003)
International Telephone and Telegraph, Inc.
Erich P. Ippen, James G. Fujimoto

The dynamics of excited carriers in GaAs are of fundamental importance to both electronic and optical devices, and ultrashort light pulses provide a means for studying them. With the femtosecond facility in our laboratory, we have therefore begun a program to investigate the scattering, relaxation, and transport processes that occur on the fastest timescale. Initial experiments were performed using pulses from our CPM laser and thin films of GaAs. With pump and probe pulses at λ = 625 nm, we observe absorption saturation high above the bandgap.

Experimental results show an initial rapid recovery time that, even at excitation densities of less than 5 x 10^{18} cm^{-3}, is not clearly resolved by 35 fs-duration pulses and is thus less than 30 fs. The change in amplitude of this component with carrier density is consistent with a very rapid initial relaxation whose rate increases with increasing carrier density. Measurements made as a function of pulse duration (which help separate rapid response from coherent artifact) also indicate the presence of an ultrafast process. Further recovery of the absorption saturation occurs with a longer ~ 1.5 ps time constant. These initial results seem to be consistent with an interpretation assuming an initial femtosecond redistribution of excited carriers in the bands followed by a picosecond cooling of the carrier distribution to the lattice. Plans in progress include measurements as a function of polarization and pulse-chirp as well as variation of material properties and sample structure.

In addition to studies of semiconductors, we are also continuing research on femtosecond nonequilibrium processes in metals.[1] Using transient reflectivity and photoemission measurements, it is possible to generate and investigate nonequilibrium electron temperatures in metals which occur on a time scale comparable to or faster than the electron-phonon energy transfer time of ~ 1 ps. Experiments in progress are aimed at the investigation of nonequilibrium electron heat diffusion and excited electron transport in metals. Future extensions of these studies may provide an approach for the characterization of high speed transport and electrical phenomena in devices.

Ultrashort pulses now also make it possible to excite and probe the dynamic behavior of molecular and solid state systems on a timescale that is comparable not only to energy relaxation and dephasing times but also to the fundamental period of the excitation. With pulse durations of less than 100 fs, vibrational motion at frequencies up to 200 cm^{-1} can be observed. In collaboration with Prof. Keith Nelson's group we recently demonstrated what we believe are the first time-resolved measurements of optic phonon oscillation and decay on a femtosecond timescale.[2] In a series of experiments, decay rates of vibrational and translational optic phonons in perylene crystals were measured in the temperature range 20–300° K.

Another area of investigation is femtosecond spectroscopy of organic polydiacetylenes. These materials are potentially important for applications in all optical signal processing because of their high nonlinear susceptibilities $\chi^{(3)} > 10^{-9}$ esu and rapid response speeds.[3] We are currently collaborating with Dr. G.M. Carter of GTE Laboratories to examine the dynamics of the excited state of these materials. These studies will help to elucidate the rapid response times observed in these materials as well as yielding important information on the physics of quasi-one-dimensional electronic systems.

References

1. J.G. Fujimoto, J.M. Liu, E.P. Ippen, and N. Bloembergen, "Femtosecond Laser Interaction with Metallic Tungsten and Nonequilibrium Electron and Lattice Temperatures," Phys. Rev. Lett. 53, 1837–1840 (1984).
2. S. DeSilvestri, J.G. Fujimoto, E.P. Ippen, E.B. Gamble, L.R. Williams, and K.A. Nelson, "Femtosecond Time-Resolved Measurements of Optic Phonon Dephasing by Impulsive

Stimulated Raman Scattering in α-Perylene Crystal from 20 to 300 K," Chem. Phys. Lett. 116, 146-152 (1985).
3. G.M. Carter, M.K. Thakur, Y.J. Chen, and J.V. Hryniewicz, "Time and Wavelength Resolved Nonlinear Optical Spectroscopy of a Polydiacetylene in the Solid State using Picosecond Dye Laser Pulses," Appl. Phys. Lett. 47, 457-459 (1985).

5.9 Diode Laser Dynamics and Diagnostics

National Science Foundation (Grant ECS84-06290)
Joint Services Electronics Program (Contract DAAG29-83-K-0003)
Erich P. Ippen

We have recently performed experiments which reveal, for the first time, subpicosecond dynamics in GaAlAs laser diode devices. Using compressed pulses from our near-infrared (780-850 nm) synchronously-pumped dye laser, we are able to probe GaAlAs laser amplifiers near their operating wavelengths. In our experiments, both pump and probe pulses travel collinearly through the active region of the diode in guided modes. The laser diodes, Hitachi HLP-1400's (CSP structure), are biased with a DC current so that they exhibit gain. A subpicosecond pump pulse traveling through the diode induces a dynamic change in transmission that is then monitored as a function of delay by the probe pulse, traveling in a guided mode of orthogonal polarization. In all cases a fast transient, with a time constant of about 400 fs, is observed in addition to longer-lived saturation signals. We interpret this fast response as being due to nonequilibrium energy dynamics of carriers in the active layer. Future experiments will be carried out as a function of wavelength, current density, diode structure, and temperature.

Work with semiconductor lasers with intracavity saturable absorbers has also continued, with particular attention on regimes of chaotic pulsation. Using InGaAsP diode lasers with proton-bombardment-induced absorber sections, we have mapped out stable and chaotic regimes as a function of bias current and length of external resonator.[1] Several interesting results have been obtained: stable pulsation requires a minimum bias level and only occurs when the natural pulsation frequency of the diode is greater than that of the external resonator, i.e., the stability regime is asymmetric. Also, the transition between stable and chaotic regimes is often characterized by a period-two or period-three pulsation suggestive of deterministic chaos.[2] This possibility is presently being tested by additional experiments and analytic modelling.

References

1. M. Kuznetsov, "Pulsation of Semiconductor Lasers with a Proton Bombarded Segment: Well Developed Pulsations," IEEE J. Quant. Electron. QE-21, 587-592 (1985).
2. M. Kuznetsov, "Theory of Bistability in Two Segment Diode Lasers," Opt. Lett. 10, 399-401 (1985).

5.10 Quaternary (InGaAsP) Diagnostics

National Science Foundation (Grant ECS84-06290)
Joint Services Electronics Program (Contract DAAG29-83-K-0003)
Erich P. Ippen

The nonlinear optical properties of semiconductors are being studied for potential application to optical switching and signal processing devices. Those of the InGaAsP compounds are particularly important for the 1.3 – 1.6 μm wavelength band, since their composition-dependent bandgaps can be tuned for resonance in this regime. During the past year, we reported the first picosecond, near-bandgap measurements of nonlinear absorption and refraction of these materials.

Our experiments were performed with a modelocked color center laser, based on Tl° (1) centers in KCl kindly provided to us by L. Mollenauer of AT&T Bell Laboratories. The laser, synchronously-pumped by a cw modelocked Nd:YAG laser, produces pulses of 10-15 ps in duration at a repetion rate of 100 Mhz and an average power of 300 mW. The output wavelength is controlled digitally by stepper-motor rotation of two birefringent plates and can be tuned over the range 1.48 – 1.58 μm.

Thin InGaAsP films (grown on InP for us by E.G. Burkhardt and T.J. Bridges of AT&T Bell Laboratories) were used at room temperature. Nonlinear absorption was observed directly by pump-probe measurement, and nonlinear refraction was then deduced from degenerate four-wave mixing experiments. Time-resolved nonlinear signals were obtained as a function of laser wavelength and excitation density for materials of several different bandgap energies. Nonlinear absorption cross-sections σ_{eh} as large as -5.7×10^{-15} cm^2 were obtained from the pump-probe results, while effective nonlinear cross-sections σ_{eff} as large as 7.8×10^{-16} cm^2 (corresponding to a steady state $|\chi^{(3)}| \sim 3.8 \times 10^{-3}$ esu for a 20 nsec relaxation time) were observed in the DFWM experiments. The spectral behavior of the data showed, very interestingly, that above the bandgap the nonlinearity is due to a combination of band-filling and excitonic screening effects.[1] The effectiveness of the screening enhancement diminishes, however, within one or two plasma frequencies of the band edge.

References

1. M.N. Islam, E.P. Ippen, E.G. Burkhardt, and T.J. Bridges, "Picosecond Nonlinear Absorption and Four-Wave Mixing in GaInAsP," Appl. Phys. Lett. 47, 1042-1044 (1985).

5.11 Short and Ultrashort Pulse Laser Medicine

National Institutes of Health (Grant 1 RO1 GM35459)

James G. Fujimoto, Erich P. Ippen

During the past year we initiated a new program to investigate the applications of short and ultrashort pulse lasers to laser medicine. This program is being conducted in collaboration with Dr. C.A. Puliafito of the Massachusetts Eye and Ear Infirmary and with investigators at the Wellman Laboratory of the Massachusetts General Hospital.

One of the major components of our program is the application of time resolved spectroscopic techniques to the investigation of problems in laser medicine. In this context we have investigated the physical processes associated with laser induced optical breakdown. This type of laser tissue interaction has emerged as an important therapeutic technique in ophthalmic laser surgery. The use of high intensity nanosecond or picosecond pulses generated by an Nd:YAG laser allows the surgical incision of intraocular structures which are nominally transparent to the laser wavelength. Using time resolved pump and probe techniques we have investigated the processes of plasma formation, acoustic shock wave propagation, and cavitation associated with laser induced breakdown.[1] These measurements can provide a better understanding and an approach to optimizing the theraputic process.

The use of femtosecond lasers in medicine has also been under investigation. We have demonstrated the first application of femtosecond optical ranging in biological systems.[2] This technique is similar to radar or ultrasound except that short pulses of light are used instead of radio or acoustic waves. The use of transient optical gating techniques allows the discrimination of signals generated by the external and internal features of biological specimens. Using pulse durations of 70 fs in conjunction with nonlinear optical gating, we have performed measurements of corneal thickness in rabbit eyes in vivo as well as epidermal structure in human skin in vitro.

Finally, as a step toward understanding the biological aspects of femtosecond laser tissue interaction, we have begun preliminary studies of retinal damage produced by exposure to 70 fs pulses. The retina is one of the most highly investigated systems in the context of laser tissue interaction and thus constitutes an important model system for developing an understanding of laser tissue effect. The study of laser effects in this time regime can provide information on the relative roles of thermal, acoustic, and photochemical damage as well as determining damage thresholds from the viewpoint of eye safety. These studies constitute the first investigations performed on biological systems in this regime. This research is being conducted in collaboration with Dr. R. Birngruber of the University of Munich.

References

1. J.G. Fujimoto, W.Z. Lin, E.P. Ippen, C.A. Puliafito, and R.F. Steinert, "Time-Resolved Studies of Nd:YAG Laser Induced Breakdown. Plasma Formation, Acoustic Wave Generation, and Cavitation," Invest. Ophthalmol. Vis. Sci. 26, 1771-1777 (1985).
2. J.G. Fujimoto, S. DeSilvestri, E.P. Ippen, C.A. Puliafito, R. Margolis, and A. Oseroff, "Femtosecond Optical Ranging in Biological Systems," Opt. Lett. 11, 150-152 (1986).