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7.3 Picosecond Optics

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

Hermann A. Haus

All Optical Logic Gates

Waveguide optics, or the more ambitiously named Integrated Optics, will not compete seriously with integrated electronics in all those functions that can be performed electronically. Optical devices have a more demanding topology (e.g., optical waveguides have transverse dimensions of several optical wavelengths and do not permit sharp bends) and higher power requirements. However, waveguide optics can perform certain signal processing functions at greater speeds than electronic circuits. High speed signal processing is one application in which waveguide optics can seriously compete with electronics. Another function of integrated optics may become the direct processing of optical signals, obviating the need for conversion to an electrical signal, if the signal processing function can be performed conveniently and at low optical power levels.

In the last progress report we described a universal optical logic gate which was fabricated in $LiNbO_3$ to demonstrate its operation as an all-optical logic gate. The optical nonlinearity in $LiNbO_3$, the n_2 coefficient, was measured in our experiment[1] and was found to be about two orders of magnitude smaller than the values quoted for GaAs. The optical power available in the experiment was too small to demonstrate logic operation of the device; instead we demonstrated the operation of the device as an all-optical waveguide modulator operating on a picosecond time scale.

This experience shifted our interest to the fabrication of GaAs, GaAlAs waveguides. In cooperation with Dr. F.J. Leonberger of Lincoln Laboratory we succeeded in fabricating high quality waveguides with a ridge on top of a guiding layer providing transverse optical confinement.

The waveguides are presently used in an experiment which will determine $\chi^{(3)}$ in a waveguide structure. The value of $\chi^{(3)}$ in GaAs has been quoted differently by three different researchers.[2-4] It is possible that the discrepancy between these reports is due to different background doping and thus different free-carrier contributions to the nonlinearity. Our waveguides are constructed in material with well determined doping characteristics.

Another intriguing possibility for the design of fast logic gates with low-power drives has emerged recently. The quantum well, room temperature exciton absorption line has been modulated with fields of the order of $6 \times 10^4 V/cm$.[5] The excitons were not destroyed with fields of this magnitude. This raises the possibility of removing by fast drift the carriers generated in nonlinear optical interactions and thus speeding up device operation into the 100 Gbit range. The exciton nonlinearity is enormous, so that the logic gate could be operated at power levels available from laser diodes. We are currently investigating the feasibility of such a device.

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Theory of the Soliton Laser

Recently, Dr. Mollenauer and Dr. Stolen at Bell Laboratories succeeded in operating a soliton laser.[1] This laser contains a synchronously pumped laser as its gain section and a nonlinear fiber as the pulse-forming section. The novel feature of this structure is that the pulse width is governed by the width of the characteristic soliton formed in the fiber and less by the shaping of the pulse in the laser section as is the case in conventional modelocked lasers. In this way pulse-widths can be achieved (0.29 ps) that are much shorter than the pulsewidths achievable with the synchronously modelocked laser by itself.

We have been encouraged by Dr. Mollenauer and Dr. Stolen to develop the theory of the soliton laser because our previous work on modelocking bears on the problem. Indeed, the system can be described as a modelocked laser locked in turn to an injection signal consisting of a stream of pulses. We have succeeded in developing the steady state theory of the laser. One puzzling feature of the laser, namely its tendency of operating in the higher order, N = 2, soliton is well explained by the theory.

The temporal shape of the output pulse is predicted and the relation between fiber length and pulsewidth is established. The predictions of the theory will be tested at Bell Laboratories.

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7.4 Ultrashort Pulse Formation

National Science Foundation (Grant ECS80-20639)
Joint Services Electronics Program (Contract DAAG 29-83-K-0003)
Erich P. Ippen

Considerable progress is still being made in the generation of ultrashort pulses. This year we report the production and measurement of pulses as short as 16 femtoseconds. These pulses, with a center wavelength of about 620 nm, are comprised of only 8 optical periods and are the shortest pulses ever generated.[1]

Initially, in our experiments, pulses of 55 fsec duration are generated by a colliding-pulse-modelocked (CPM) ring dye oscillator. Single pulses from this oscillator are selected and amplified at a 10 Hz rate by the first two stages of a high-power femtosecond dye amplifier chain. After spatial filtering and compensation of dispersion with a grating-pair, the amplified pulses of about 65 fsec are coupled into an 8 mm length of optical fiber. Following spectral broadening in the fiber, the pulses are compressed by the final factor of four with a second grating pair. Measurement is performed by noncollinear autocorrelation in a 0.1 mm crystal of KDP.

During this period we have also achieved cw and modelocked operation of a syncronously-pumped ZnCdSe platelet laser. Pulses of 10 psec duration are generated at a wavelength of 482 nm, the shortest wavelength operation achieved to data with a semiconductor laser.[2]

Work has also continued on improving our theoretical understanding of pulse generation[3] and propagation, especially in the presence of dielectric mirror and material group velocity dispersion. Investigations of fiber pulse compression for the wavelength range 800-900 nm and of semiconductor diode laser modelocking at 1.3 μm have been initiated.

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7.5 Femtosecond Laser System

Joint Services Electronics Program (Contract DAAG29-83-K-0003)
Erich P. Ippen

Work continues on the development of femtosecond optical techniques for broadband time-resolved spectroscopy and on their application to specific problems.

Our femtosecond oscillator-amplifier system, the construction of which was described in last year's report, has been further improved by optimizing the pumping configuration and dye concentration in each stage and by improving the temporal stability of the Q-switched Nd:YAG pump laser. Present characteristics are: 2nd stage — 5 μJ, 65 fsec; 3rd stage — 50 μJ, 65 fsec; 4th stage — 250 μJ, 70 fsec. New, in-house developed software routines for data recording and analysis have increased sensitivity and accuracy in spectroscopic applications.

An especially interesting area of application is the study of relaxation processes in optically excited semiconductors. This year we investigated the phenomenon of exciton screening by free carriers in the direct-gap II-VI semiconductor CdSe.[1,2] Our experiments show that, following above band-gap excitation of free carriers, the free-exciton resonance, which occurs about 15 meV below the bandgap at 77 K, broadens and loses amplitude without shifting wavelength. This screening, which was observed by dynamic spectral changes of sample reflectivity, occurred on a time-scale of 100 fsec and was effectively complete for excitation densities greater than $2 \times 10^{17}/cm^3$. Recovery of the exciton peak was also studied on the longer time-scale of several hundred picoseconds.

Preliminary results have also been obtained (in collaboration with N. Bloembergen of Harvard and J.-M. Liu of GTE) from experiments designed to study electron-photon coupling in metals. Electron heating by intense femtosecond optical pulses is being observed by multi-photon photoelectron emission.

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7.6 Parametric Scattering with Femtosecond Pulses

Joint Services Electronics Program (Contract DAAG29-83-K-0003)
Erich P. Ippen

Transient four-wave mixing is being investigated as a means for generating shorter pulses and as a means for studying polarization dephasing in liquids and solids. Several important advances have been made within the past year.

By focusing two intense pulses into a solution of the dye malachite green we have obtained relatively high-power, parametrically scattered pulses with durations as short as 37 fsec.[1] The durations of the scattered pulses are observed to depend strongly on the time delay between the two incident pulses; and we have shown theoretically that this dependence can be used to obtain information about the actual pulse shapes as well as the medium response time.

For studies of femtosecond dephasing, we have introduced a novel, multiple-pulse scattering technique[2] that offers several important advantages over previous two-pulse methods. These include i) separation of transverse relaxation (T_2) effects from those due to longitudinal (T_1) relaxation; ii) ready availability of an experimentally determinable (T_2 = 0) reference curve for accurate deconvolution of data; and iii) a clear distinction between scattering from homogeneously and inhomogeneously broadened transitions. With the first experiments using this technique we have observed dephasing of the electronic polarization in the dye nile blue to occur in less than 20 fsec.

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7.7 Near-IR Diagnostics

National Science Foundation (Grant ECS80-20639)
Joint Services Electronics Program (Contract DAAG29-83-K-0003)
Erich P. Ippen

A cavity-dumped, synchronously-pumped dye laser has been developed for tunable operation in the range 760–900 nm. Picosecond pulses from this system are being used for pump-probe studies of active, semiconductor diode laser devices. Effort is also presently directed at achieving sub-picosecond pulse durations in this wavelength regime by compression techniques using polarization preserving optical fibers. For pump-probe studies in optical waveguides, we have demonstrated an experimental technique for separating, and temporally resolving, the collinear pump and probe beams following transmission through a guide. The method utilizes a synchronized, third pulse to gate the desired probe pulse by sum-frequency up-conversion. In preliminary experiments we have resolved and monitored multiple reflections occuring in an uncoated diode. Gain saturation by successive pulses and group velocity delays are easily observed.

7.8 Quaternary (InGaAsP) Diagnostics

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Erich P. Ippen

Under high excitation densities, carrier lifetimes in semiconductors can be shortened dramatically by Auger recombination processes. Loss of carriers by such processes is now thought to be a contributing factor to the high threshold current densities (relative to GaAlAs) and strong temperature dependence of long wavelength (InGaAsP/InP) laser diodes. Improved understanding of Auger recombination is therefore important to future device development.

Most of the existing experimental data on the Auger coefficients of interest have been derived from characteristics of existing laser devices. In our experiments this year we have used a direct, picosecond pump-probe technique to both excite carriers and monitor their recovery dynamics. Thin film samples of three different compositions (bandgaps: 1.3, 1.55, and 1.65 μm) were studied with 80 psec pulses from a cw modelocked Nd:YAG laser. Accurate evaluation of the data was achieved by developing a computer model which relates the observed absorption bleaching to carrier density and takes into account spatial averaging effects as well as temporal convolution of the nonlinear response with the laser pulses. The effective Auger coefficients, determined as curve fitting parameters, were found to be A(1.3 μm) = 1.5 x 10^{-29}cm^6/s, A (1.55 μm) = 7.5 x 10^{-29}cm^6/s and A(1.65 μm) = 9.8 x 10^{-29} cm^6/s. These experimental values are lower than those calculated theoretically by previous authors and exhibit a wavelength dependence that is stronger than that observed by device threshold measurements.

Our present efforts are directed at trying to separate nonlinear radiative effects from the nonradiative effects by time-resolved fluorescence and photo-acoustic spectroscopy. Development of a Tl-defect color center laser for extending our probing capability to shorter pulses and longer wavelengths is also underway.

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B. Grating Structures

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7.9 Surface Acoustic Wave Grating Structures

National Science Foundation (Grant ECS82-11650)

Hermann A. Haus, John Melngailis

The goal of this research is to develop a better understanding of SAW grating structures for mode control, suppression of spurious and improved transducer design.

In the design of a unidirectional SAW transducer, C. Hartmann and P. V. Wright discovered[1] that the wave excited by the transducer traveled in a direction opposite to the one predicted by theory.[2,3] This prompted us to look into the theory of SAW excitation by metal strips. It became clear in the course of the investigation that a reliable theory could be used to design reflection-free metal strips. This in turn would obviate the necessity of splitting the metal fingers, a current practice to reduce reflection with an attendant doubling of the demand on fabrication tolerances and an increase in finger loss.

We have developed a comprehensive theory of metal strip gratings and transducers based solely on a previously utilized variational principle. The theory shows the possibility of constructing metal strips with zero reflectivity by proper balancing of the mass-loading, stress- and piezoelectric effects of the metal strip. The theory derives all pertinent grating- and transducer-parameters in terms of the material constants and geometry. The mistake in the previous theory was corrected so that the behavior of unidirectional transducers is now predicted correctly.

The design of SAW filters with low sidelobes in their transfer characteristics is difficult to implement with apodization and uniform spacing. The constraint of uniform spacing leads to small tap weights which in turn produces undesirable effects. We have developed a filter design that maintains uniform overlap. The spectral weighting is accomplished with variation of the finger spacing. The parameters are selected by a quasi-Newton optimization technique.[4]

Many years ago we published a theory of transverse modes in grating structures.[5] The predicted mode structure was rather peculiar in that the mode pattern of a particular mode could acquire, with increasing frequency, additional maxima and minima. The experimental evidence on higher order transverse modes is very limited[6,7] and none of the published experiments followed the mode pattern over a sufficient frequency range to confirm the theoretical predictions. We have made measurements with a laser probe on the mode patterns of a SAW resonator with a large spacing between the grating reflectors so that many resonant modes occurred within the stopband (reflection-band) of the grating. The experiments confirmed the predicted mode pattern behavior.

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