

7. Optics and Quantum Electronics

A. Nonlinear Phenomena

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7.1 Picosecond Optical Signal–Sampling Device

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Hermann A. Haus

The goal of the research is to develop prototype optical waveguide devices that operate at rates of many tens of Gigahertz. Such devices can be driven either electrically, by microwave oscillators, or optically. Examples of the former devices are samplers, multiplexers and demultiplexers. Examples of the latter are optical logic gates described in Section 7.3. In contrast to work done elsewhere with broadband microwave drive circuits,¹⁻³ we have concentrated on narrowband microwave circuits, because they permit operation with lower drive powers. We have constructed a waveguide Mach Zehnder interferometer in LiNbO₃ with Ti indiffused waveguides that functions as a sampler producing samples of 16 ps FWHM of an optical waveform at 20 GHz when driven with a 10 GHz sinewave. Preliminary results pointed toward microwave enhanced photo-refractive effects which led to gradual deterioration of device performance. A new structure with electrodes deposited on top of a SiO₂ layer on top of the LiNbO₃ greatly reduced these photorefractive effects. The device performance was verified by measurement of the optical spectrum⁴ because direct detection of the samples by second harmonic generation is not possible due to the low optical powers used to avoid photorefractive damage. The next steps to be pursued are:

(a) Construction of symmetric microwave drive structure, to be driven push–pull. Such a structure reduces further the effect of the microwave enhanced photo–refractive effect because it tends to symmetrize the index changes in the Mach Zehnder interferometer. Symmetric index changes do not affect device performance.

(b) Construction of two interferometers in cascade. Two interferometers driven in cascade

produce as their output the product response. A phase shift φ of the microwave drive at frequency ω_m , $\varphi = \omega_m \tau$, in the second interferometer with respect to the first one, traces out the autocorrelation function $T(\tau) T^*(\tau)$ of the optical intensity response function $T(t)$.

(c) Construction of a (multiplexer) demultiplexer by replacing the (input) (output) Y of the interferometer by a 3 db waveguide coupler.

The fabrication of the interferometers is carried out at the M.I.T. Lincoln Laboratory in collaboration with Dr. F.J. Leonberger.

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7.2 Devices for High-Rate Optical Communications

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Clifton G. Fonstad, Hermann A. Haus

(a) Monolithic Mode-Locked Lasers

By active mode-locking a diode laser it is possible to produce optical pulses of under 5 picoseconds duration at repetition rates exceeding 10^{10} per second. Such pulse trains used with high frequency guided wave optics components like those discussed in the following section could form the basis of fiber optical communications systems with data rates in excess of 100 G/s. Existing lasers, however, are mode-locked in an external cavity and the associated mirrors, lenses, positioners, and optical bench are far too cumbersome to be useful outside the laboratory. We are consequently studying very long, non-uniformly excited diode lasers which we expect to be able to mode-lock without the use of an external cavity.

Lasers with multiple segment contacts each 600 μm long are being fabricated. A four-segment laser is 2.4 μm long and is expected to mode-lock at approximately 12.5 GHz; a three-segment laser at 17 GHz.

The initial long lasers fabricated were oxide-defined stripe contact (Ga, Al) As/GaAs double heterojunction laser diodes. Measurements on these devices, however, showed that even 600 μm

long diodes were actually only operating as super-radiant diodes and showed no evidence for cavity resonances. Consequently, it was determined that a laser structure having built-in guiding and lower spontaneous emission background would be required.

Such lasers were obtained through A. Ceruzzi of Laser Diode Laboratories in the form of Gaussian channelled-substrate planar (GCSP) wafers. These were fabricated into one, two, three, and four segment devices which have subsequently shown laser operation at all lengths. To our knowledge, the three and four segment lasers are the longest ever produced.

While capable of lasing in lengths up to 2.4 mm, the GCSP lasers still have a significant amount of background amplified spontaneous emission and have not yet been mode-locked. Work is presently concentrating on fully characterizing shorter devices and on mode-locking the three-segment lasers. We are at the same time investigating the possibility of obtaining multi-quantum well (MQW) laser material which has recently been demonstrated (1983 Device Research Conference) to have very low absorption, an important feature for these devices.

(b) Guided Wave Optics in InP

To complement the work on monolithic mode-locked diode lasers described above, we are studying the development of III-V based guided wave optics structures suitable for modulating, multiplexing, and demultiplexing trains of pulses from such lasers. As such, these structures must be efficient, low-loss, and compact, and must be capable of being driven at 100 GHz or more, with modest power requirements. To this end we have, in addition to our own earlier efforts on material preparation and InP guide characterization, continued our research on development of multiguide couplers and switches, and collaboration with Dr. F. Leonberger of Lincoln Laboratories on III-V waveguide design and characterization.

The three-guide coupler, developed earlier in this effort, remains a very exciting development and one we are pursuing aggressively. The concept is simply that bends, which of necessity are long and gradual, i.e., very space-consuming, can be eliminated in optical waveguide circuitry if couplers are made, not by bending two guides so that they come close to each other, but rather by inserting a third guide in between the two guides to be coupled. The coupling length of a three-guide structure is only 1.4 times that of a two-guide coupler, and the overall length including the bend transition regions is much less. We are presently fabricating and studying shallow-rib and metal-gap three-guide couplers in GaAs based planar guide structures. Our next goals are to demonstrate efficient switching in three-guide switch-couplers, and to define the minimum limits on guide spacing and coupling length.

Our measurement system has been extensively restructured to incorporate a scanner mirror to facilitate the display of output guide mode profiles. The sample is now also mounted horizontally, and a base for mounting the probes necessary for the switch studies, has been installed.

Our model for heterostructure rib waveguide analysis developed earlier has also been extended and has recently been successfully applied to fit coupling length data obtained on two- and three-guide passive waveguide couplers. This is an important step because the design of complex switching systems will require the ability to predict, i.e., design, the coupling length prior to fabrication.

(c) Multiple-Waveguide Couplers

The interconnection of optical waveguide devices requires the control of the path(s) of the optical signal. Waveguide Y's and bends with small optical loss are possible only with small deflection angles. It is possible to construct Y's, and produce transfer of optical radiation parallel to itself, by coupling of parallel optical waveguides. In the last report we outlined the applications of three waveguide couplers. In the meantime, we have developed the theory for N parallel waveguides of varied coupling between the guides, so as to fully transfer power from one outermost waveguide to the one on the opposite side.¹

In a system with an odd number of waveguides it is possible to adjust the coupling between the guides so that all of the power entering the central waveguide is transferred symmetrically to the outermost waveguide, or vice versa.¹ In this way one may construct waveguide Y's without bends. This may have advantages in fabrication of waveguide Mach Zehnder interferometers.

In this connection it is of interest to compare the radiation loss of conventional waveguide Y's with the radiation loss of effective Y's produced by waveguide coupling. We have begun a theoretical study of radiation loss² and came to the conclusion that, with proper parameter adjustment, the coupled waveguide version can perform at least as well as the conventional Y for the same effective divergence angle. Further, studies concerning the optimization with regard to radiation loss are in progress.

At Lincoln Laboratory, fabrication and testing of coupled three-waveguide structures has been initiated. The performance of the guides was as predicted, for weak coupling- large guide-separations. With increased coupling, shorter transfer lengths, the transfer from one outermost guide to the other wave not perfect. We are currently engaged in developing a theory for the "proximity effects" so that fabrication can correct for it.

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(d) Quantum Theory of Laser Oscillator Locking

Semiconductor lasers, by virtue of their small size and short resonator-relaxation-time, exhibit large quantum noise often dominating the classical noise contributions. Phase modulation of semiconductor lasers is being tested in the laboratories^{1,2} for possible use in optical communications. No quantum theory of oscillator locking has been published in the literature to our knowledge. We have initiated a theoretical study of quantum noise in a locked oscillator. This study was motivated, apart from its relevance to phase-modulation of semiconductor lasers, by the question whether a locked oscillator output provides an ideal quantum measurement of the phase of the locking signal. Linear laser amplifiers are known to provide an ideal simultaneous quantum measurement of amplitude and phase.³⁻⁶ A locked oscillator sacrifices amplitude information by gain-limiting, but reproduces the phase of the injection signal (except for the phase-noise introduced by the oscillator). We found that a locked oscillator approaches an ideal measurement to not better than 3 db (doubling the fundamental noise imposed by the Heisenberg uncertainty principle).⁷

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7.3 Picosecond Optics

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

Hermann A. Haus

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.

We are currently working on the realization of all-optical logic gates. The basic structure is shown in Fig. 7-1. The central guide is pulse excited in one polarization (TM-mode) the outer "control" guides are excited by synchronous pulses in an orthogonal polarization (TE-mode). The cotraveling pulses in orthogonal polarizations change the index as "felt" by their "partner" via the third order nonlinearity $\chi^{(3)}$. Depending upon the applied dc voltage in one arm of the interferometer, and the use of input ports, the device can perform as an XOR gate, AND gate and inverter.

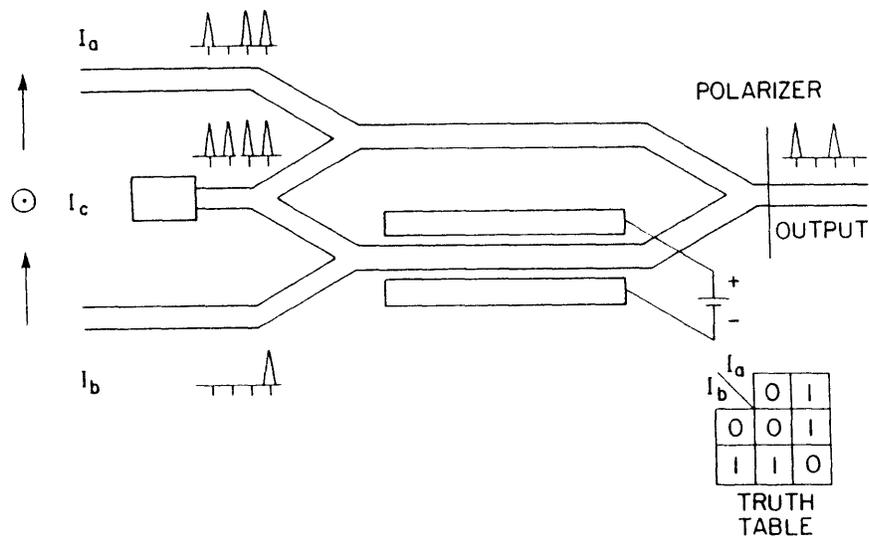


Figure 7-1

We have demonstrated operation of the device fabricated in LiNbO_3 as a picosecond waveguide modulator.¹ The testing of the device produced the first measurement of $\chi^{(3)}$, or n_2 , in LiNbO_3 . The value found was: $3 \times 10^{-9}(\text{Mw}/\text{cm}^2)^{-1}$.

With the available optical powers this value was too small to produce XOR operation, an optically induced phase shift of π in one of the arms. Therefore, picosecond optical-optical modulation was demonstrated on the first device of this kind.¹ The nonlinear coefficient $\chi^{(3)}$ in GaAs is two orders of magnitude higher than the one found for LiNbO_3 . Waveguide fabrication in GaAs has made progress in the last years so that fabrication in GaAs can be attempted.

Our future work will be aimed at producing a waveguide logic gate in GaAs. We are also investigating nonlinear processes with higher nonlinearities than those attributed to insulating bulk GaAs, e.g., optical hole-electron generation. Such processes have relaxation times of nanoseconds and as such are not usable for picosecond devices. However, there are several possibilities for

increasing the relaxation rates which would then make them applicable to picosecond signal processing at power levels available from semiconductor lasers.

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7.4 Ultrashort Pulse Formation

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Erich P. Ippen

We have extended and refined our analytical model for pulse shaping and shortening in passively mode-locked dye lasers and semiconductor lasers. Last year this model was developed to include, in mode-locking theory, the effects of coherent pulse coupling in colliding-pulse ring lasers. As a result of numerical studies based on the model, we were able this year to introduce the concept of 'pulse shortening velocity' (PSV) as an accurate and practical measure of mode-locked laser performance. With PSV we have, for the first time, a straightforward prescription for shorter pulses that includes coherent coupling and illuminates the effects of different types of resonator dispersion. A paper on the subject has been accepted for publication in the IEEE Journal of Quantum Electronics.

7.5 Femtosecond Laser System

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

Erich P. Ippen

For optical studies in the femtosecond time domain, we have constructed during the past year a passively-mode-locked cw ring dye laser that operates in the colliding-pulse (two counterpropagating beams) configuration. This laser oscillator is now a stable, reliable source of pulses as short as 60 fsec at a repetition rate of 88 MHz. The pulses have individual energies of about 10^{-10} J and peak powers on the order 10^3 W, sufficient for a variety of pump-probe studies as well as for observation of transient parametric scattering by degenerate 4-wave mixing.

High power amplification of femtosecond pulses from the oscillator has also been accomplished. The pulses are passed through four dye amplifier stages, each transversely pumped with energy from a frequency-doubled Q-switched Nd:YAG laser. Each amplifier stage is isolated optically from the succeeding stages by a free-flowing absorber stream that can be saturated only by the amplified pulse. Proper adjustment of gain and saturable absorption in each of the sections is found to be important to maintaining ultrashort pulse durations. After four stages we have achieved pulse

energies of 400 μJ with pulse durations of 70 fs. More energy can be achieved with longer pulses. This system is now available for application to a wide variety of time-resolved measurements.

7.6 Parametric Scattering with Femtosecond Pulses

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

Erich P. Ippen

We have begun to investigate, theoretically and experimentally, transient parametric scattering (TPS) by degenerate 4-wave mixing with femtosecond pulses. Our initial attention has focused on two potentially important applications: the first is the generation of shorter pulses by the nonlinear scattering process; the second is the direct measurement of femtosecond coherence (dephasing) properties of molecules and solids. Our theoretical work has already clarified the existing analysis of scattered intensity as a function of material response times and has led us to propose a new, three-pulse technique for resolving ambiguities. Experimentally, we have made preliminary observations of femtosecond pulse shortening by TPS in molecular dye solutions. Measurements are in progress to determine the dependence of this shortening on the specific dye molecule, pulse power, and relative delay between two pulses. With optimization, we expect to be able to generate pulses shorter than 40 fsec.

7.7 Near-IR Diagnostics

National Science Foundation (Grant ECS80-20639)

Erich P. Ippen

Work progressed significantly this year in the development of a picosecond dye laser source for the GaAs bandedge regime. Our dye laser is synchronously-pumped by about 1 watt of 6471 \AA power from a mode-locked Kr^+ laser. With specially designed mirrors, birefringent tuning plates, and a new nontoxic solvent, we have extended the tuning range of a single dye (Oxazine 750) to cover completely the wavelength region of interest: 7600 \AA – 9000 \AA . Over this range we have obtained approximately transform-limited pulses of 4 psec in duration and average powers ranging from several hundred milliwatts at peak to about 25 mW at the long wavelength end. Pulses from this laser have been used, in conjunction with another research program, to demonstrate picosecond optical switching with optical nonlinearities in LiNbO_3 waveguides. Our laser is especially suited for these studies because of reduced damage in LiNbO_3 at longer wavelengths. By the end of this year application to studies of picosecond saturation in GaAs waveguides will also have begun.

7.8 Quaternary (InGaAsP) Diagnostics

National Science Foundation (Grant ECS80-20639)

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

Erich P. Ippen

During the past year we have begun studies of carrier dynamics in quaternary semiconductor films of InGaAsP on InP. For fabrication of thin film samples we have established collaboration with colleagues at Bell Telephone Laboratories, Holmdel, New Jersey and RCA Research Laboratories, Princeton, New Jersey. Our first experiments have utilized pulses from a mode-locked cw Nd:YAG laser to excite and probe at $\lambda = 1.06\mu$ changes in interband absorption in thin film samples. Preliminary results very nicely show recombination to be due to a combination of linear and nonlinear (Auger) processes. Further work with different material compositions and different laser wavelengths will now be used to provide a clearer separation of effects. For this purpose, and also for long wavelength waveguide studies, we have spent time this year building a tunable, picosecond F-center ($KC\ell:T\ell$) laser for $1.4\mu < \lambda > 1.6\mu$. Crystals have been obtained from L.F. Mollenauer of Bell Laboratories, and laser performance will be characterized in the near future. We have also begun to pursue a novel, and we think very interesting, approach to studies of carrier dynamics: the use of surface-acoustic-wave electrode structures to detect picosecond nonradiative relaxation. The technique utilizes, high repetition rate, picosecond pulse trains to generate a spatially and temporarily periodic carrier density. Nonradiative recombination is resonantly detected by a similarly periodic electrode structure.

B. Grating Structures

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7.9 Surface Acoustic Wave Gratings

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Hermann A. Haus, John Melngailis

Several types of surface acoustic-wave (SAW) devices operate on the principle of coherent reflection of the waves from gratings. The gratings used are generally shallow with a depth equal to a few percent, at most, of the grating period. Thus, apart from a small reflection from each groove edge, the SAW, to first order, propagates in the grating undisturbed. Small deviations from this lowest order model, which result in a slowing and attenuation of the wave in a grating, are important in some critical devices. Resonators, in which a surface acoustic wave bounces between two gratings as in a Fabry-Perot cavity, are used as high-Q frequency standards. Here, frequency shifts occur due to the propagation in a finite-depth grating. Reflective-array compressors are used to compress chirped radar waveforms which are often up to 80 μ sec in length. The frequency within the waveform varies monotonically over the length of the pulse. The compressor, in effect, adds the signal at the head of the pulse to the signal at the tail with the correct phase and amplitude. Thus, transit time and attenuation within a grating must be accurately controlled.

Our work on surface acoustic-wave grating structures has a dual goal: (a) development of methods of analysis of grating structures that are simpler than those generally employed, and (b) utilization of simple analytical methods in the design of novel structures using surface acoustic waves.

We have applied a variational principle to predict the radiation loss from gratings, a problem of importance in the design of Reflective Array Compressors of small insertion loss. Because of the radiation loss the system is not "self-adjoint". Our work¹ showed how one may adapt the variational principle to treat this case. Experimental results on the insertion loss of ion milled groove-gratings were obtained and compared with theory.²

Currently we are extending the variational treatment to metal-strip gratings with a twofold objective: (a) To obtain relatively simple analytic expressions for the reflection of by metal-strips. (b) To understand the spurious response of transducers whose likely cause are the higher order

transverse modes of the transducer acting as a reflection grating. Preliminary studies have shown that the change of propagation velocity caused by metalization of LiNbO_3 and quartz can be predicted simply, analytically using the variational principle with a very high degree of accuracy when compared with published computer analyses. This finding gives us confidence that the accuracy of the approximate analytic treatment of metal gratings will be satisfactory.

In another investigation, the optimum design of unidirectional transducers is pursued. Unidirectionality is achieved by combining the reflective properties of a grating interspersed with an interdigital transducer. This work is done in cooperation with Dr. C. Hartmann of RF Monolithics.

Because of our concurrent work in optical waveguide structures it was natural for us to investigate the question whether useful structures may be built combining the surface acoustic wave interactions via the acousto-optic effect, with the guiding properties of optical waveguides. Optical guiding layers made with proton exchange permit adjustment of the difference between the ordinary and extraordinary optical indices.³ One may construct Y- propagating optical waveguides in X-cut LiNbO_3 in which the TE and TM modes are coupled by a SAW of given frequency. This permits the construction, in principle, of an acousto-optic spectrum analyzer with no optical lenses. Preliminary theoretical studies suggest better resolution and greater dynamic range than the one achieved with more conventional designs.⁴

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