5. Optics and Quantum Electronics

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5.1 Devices for High-Rate Optical Communications

(A) The Waveguide Lens

Diode laser arrays have been studied by several workers.[1-3] The elements of such structures tend to oscillate in antiphase, resulting in a far field emission pattern which is not single lobed. One method for concentrating all the power in one direction is to use a passive coupled waveguide array to combine the outputs of the elements of the laser array into a single spot. This can be done provided that the individual elements of the laser array oscillate with equal amplitudes, either in phase or in antiphase.[4,5]

The three waveguide lens is currently being fabricated in n-type InP in order to permit future integration of lasers and waveguides on a single wafer. Straight waveguides have been tested with a single diode laser at 1.3 μ. The waveguides are formed by etching shallow (.5 μ) ribs in a 3 μ epitaxial layer of n$^-$ InP grown by LPE on a substrate of n$^+$ InP. Waveguiding can be achieved only by using n-type InP because the change in refractive index in the epitaxial layer due to carrier concentration is much less for holes than electrons.

It is necessary to detune the propagation constants of the coupled waveguides in order to perform the "lens" operation.[5] In order to do this, one may utilize the electrooptic effect in InP. Because the n-type material has a relatively low barrier height, Schottky barriers cannot be used. However, if a p$^+$ layer is grown on the ribs, and electrodes are placed both on this layer and on the back of the substrate, the p-n junction formed can be reverse biased to apply a field to the waveguides. In this way, the propagation constants of the guides can be electrooptically detuned.

References

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(B) Monolithic Mode Locked Lasers

In the program to develop monolithic mode locked diode lasers, we have modelled the development of narrow pulses in a very long diode laser which is active along its entire length, and is driven by suitably phased sinusoidal microwave drives.[1] The modeled behavior has, additionally, been related to device parameters. The effects of frequency pulling to further reduce the pulse width have also been examined and limits have been set on the expected pulse widths and modulation depths.

The requirement of the microwave drive, and the input drive signal conditioning and coupling required to achieve efficient excitation have also been studied both theoretically and experimentally. Microwave strip–line structures providing two drive signals 180° out of phase at approximately 20 GHz have been prepared and characterized using a spectrum analyzer.

Progress on the fabrication and testing of long (2–3 mm), multi–contact laser diodes has been impeded by the difficulty of obtaining suitable device heterostructure layers. Oxide stripe confined lasers and channelled–substrate–planar (CSP) lasers have both proven inadequate. Quantum well laser material seems very promising but we have not had enough available to successfully fabricate lasers. Most recently our efforts have focused on developing an in–house source of laser diode heterostructures. Specifically, we have been operating a Riber MBE 2300 R&D molecular beam expitaxy (MBE) system since January 1984 and are developing the capacity to, among other things, grow quantum well (QW) and multiple quantum well (MQW) laser heterostructures. MBE grown layers offer the uniformity and control over large areas which we feel are essential to our successful fabrication of very long laser diodes. Furthermore, only the QW and MQW geometries have sufficiently low unpumped losses that they fall in the range that is required for success.

The availability of MBE, opens also the possibility of integrating active device regions and passive guide sections, a structure that more closely approximates the situation found when a diode laser is mode locked in an external cavity. We intend to explore this approach, as well, as it offers several advantages over the use of very long active devices.

References

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(C) Analysis and Characterization of Rib Waveguides and Multiple-Guide Couplers

Our work on III-V waveguide structures has concentrated on fabricating, characterizing, and especially, modelling shallow rib waveguides and multiple-guide couplers. Using a methodology proposed by Peng and Oliver[1] as a starting point, we have developed a mode matching analysis technique for rib dielectric waveguides which has proven to be particularly effective in analyzing actual structures and in fitting experimental data.[2] Using this technique it is possible to develop a microwave equivalent circuit for the transverse field problem. Simple transmission line circuits with ideal transformers at step discontinuities result.

The transformer ratio is the overlap integral of the inner and outer slab modes. Interestingly, if the transformer ratio is assumed to be unity, then the resulting equation for the propagation constant is exactly the same as the result of the commonly used effective dielectric constant (EDC) method. In practice, the ratio is less than one, however, and thus the propagation constant is different than what is predicted by the EDC method, a result which is particularly important for couplers.

Recently, we have extended this model to rib guides with realistically sloped side walls.[3] The equivalent circuit for such a situation is shown in Fig. 5-1 to illustrate the nature of the model. Presently, we are working on the use of the model to calculate coupling parameters and propagation constants in couplers and multiple guide arrays.

We have been able to verify experimentally several important results of our theoretical analysis. First we have shown that the model can accurately predict the cut-off dimension of rib waveguides, even in the situation where the inner rib section is thick enough to support two modes while the outer section will support only one. That within certain well defined ranges the entire structure in such a situation is a single mode waveguide has also been verified experimentally. Also, it has been verified that the effective width of a rib guide with sloped side walls is the width at the base of the rib, rather than the average width, as is usually assumed in the literature. Again, this result is predicted by the theory. We are presently working on fabricating multiple guide couplers with the objective of correlating results on these structures with the model, as well.

The ultimate goal of this program is to make efficient multiple guide switches capable of operating at very high data rates. The MBE capability discussed in the previous section, clearly plays a major role in our planning in this area, as well.
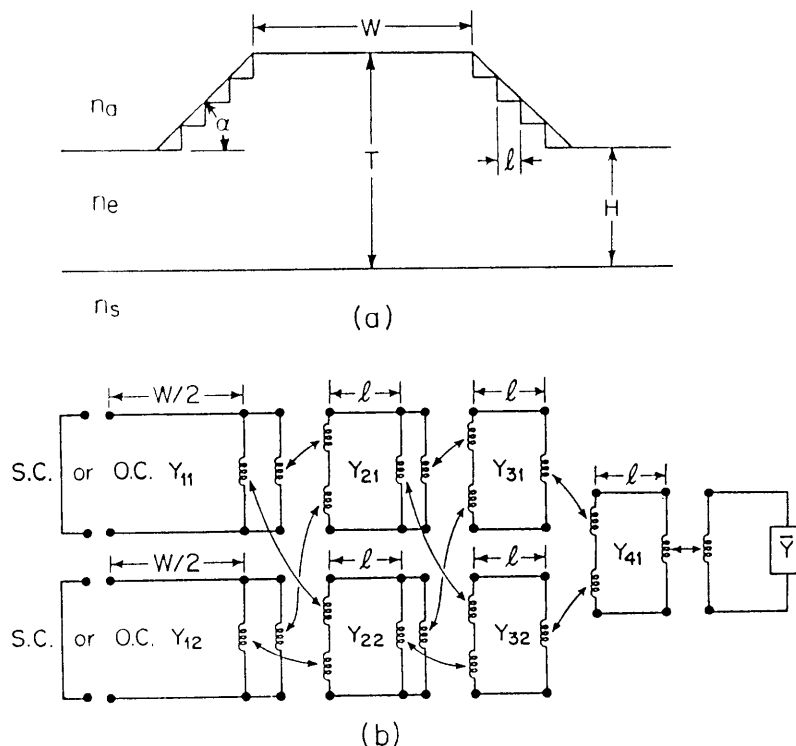
Figure 5-1: Approximate representation of the rib guide with sloped sides (a), and the resulting equivalent circuit (b). A three-step approximation is shown, and for purposes of illustration it is assumed that the slab guides are single mode in the last step and in the outer region.

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5.2 Picosecond Optics

Hermann A. Haus

(A) All-Optical Switch

The rapid progress of fiber optic technology within recent years has been due in part to the extremely high data rates fibers are capable of carrying. An optical communication system which makes use of the full fiber bandwidth will transmit data at a rate faster than any electronic system can receive it. This data must be processed optically. For this reason we are developing all-optical signal processing devices which use optical signals to control signals. Such devices hold promise for great speed with much lower integration levels than electronic devices.

We have designed and fabricated a GaAs all-optical XOR logic gate. This device has been tested as an electro-optic device with full modulation at a voltage of approximately thirty volts. We have constructed the interferometer out of low-loss waveguide Y's constructed with single-moded rib guides on a doped GaAs substrate. We have fabricated low-loss Y's of this type with a full branch angle of approximately 2 degrees with less than 3dB residual radiation loss. This has allowed fabrication of the XOR gate with 5mm optical interaction in a 1.2 cm device. The device will be tested at Lincoln Laboratory using a Nd:YAG laser with λ = 1.06 μm and polarization preserving fibers.

(B) Theory of Solitons

We have developed an analytic theory which explains how sub-picosecond pulses are generated in the F-center soliton laser.[1] The soliton laser is a recent invention in which a fiber forms a feedback loop around the color center laser, forcing a shortening of the pulse width down to 130 fsec.[2] A simplified model of the laser is used to study the interplay between the various pulse forming mechanisms. The pulse shape and width are controlled by a fiber, while the F-center laser acts primarily as an amplifier. Gain dispersion and temporal shaping by the time-dependent gain discriminates among multiple possible solutions. Computer simulations verify the analytic predictions. Several experimental observations are explained, and experimental confirmation of the theory includes the observation of double-humped pulses under appropriate conditions.

More recently, we have collaborated with Dr. L.F. Mollenauer at AT&T Bell Laboratories on numerical and experimental demonstration of the feasibility of a fiber-optic communication system based on solitons. The distortionless propagation of 10 psec FWHM soliton pulses over 10 km of single-mode fiber with loss compensated by Raman gain has been demonstrated experimentally.[3] With computer simulation. we are studying soliton propagation in an all-optical,

long distance communication system where fiber loss is compensated periodically by Raman gain.

References

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(C) The Nonlinear Refractive Index in III–V Compound Semiconductor Waveguides

Operation of waveguide devices based on the Mach–Zehnder interferometer requires that the refractive index in the two interferometer arms be externally modulated. For all–optical logic, index changes must be accomplished with an intense beam in the guide. Since a major attraction of optical logic is its potential for high speed, it is essential for the intensity–induced material index change to have a short relaxation time.

Near–infrared operation and compatibility with semiconductor laser technology make III–V compounds interesting candidates for waveguide devices. Many different physical mechanisms can cause a nonlinear index change; for device applications, a large effect with fast material relaxation must be used. We are measuring intensity–dependent refractive index changes and response times inside integrated waveguides of several III–V compounds. Excitation is with picosecond laser pulses in the near infrared, where all the materials are transparent. This selects against mechanisms involving carrier generation or absorption saturation, which have undesirably slow relaxation rates. The waveguides are fabricated at Lincoln Laboratory where the materials can be carefully characterized.

Preliminary results suggest that there is a thermal contribution to the nonlinear index, which is at least as large in these waveguides as the fast electronic nonlinearity. This seems to be due to free–carrier absorption, either in the doped substrate or in the waveguide itself. It may be possible to design waveguides with a smaller thermal nonlinearity. The alternatives are either to pursue schemes for enhancement of the recombination rate in resonantly excited material, or to find other transparent materials with a larger bulk electronic nonlinearity.

5.3 Ultrafast Pulse Generation

Recent theoretical investigations indicated that dispersion arising from multiple layer dielectric mirror coatings may produce significant pulse shaping effects in the femtosecond domain. An understanding of these processes is particularly relevant to the design and operation of femtosecond lasers. Using pulses as short as 16 fs, generated in our laboratory by optical fiber compression, we have performed the first, femtosecond time–resolved reflectometry measurements of multi–layer dielectric mirrors. Dramatic pulse distortion effects are observed for certain broadband mirrors even though their reflectivity spectra indicate no bandwidth limitation.

A simplified theoretical model of a passively modelocked dye laser with self phase modulation and group velocity dispersion has been developed. It treats pulsewidth and chirp as dynamical variables and follows their evolution in a pulsewidth–chirp phase plane as they approach steady–state. The model allows the separate dynamical effects of pulse shortening, pulse broadening, chirp build–up and chirp decay to be examined in detail.

The use of ultrashort optical pulses to generate ultrashort electrical pulses in submicron dimension silicon devices has also been investigated. Transmission lines with photo–conductive gaps as narrow as 0.2 μm were fabricated on 1 μm thick silicon on sapphire. By operating these switches in the sweep–out mode we were able, with 5 ps optical pulses and energies of 0.3 nJ, to generate electrical pulses of a greater than 1 volt with FWHM durations of less than 27 ps.

Publications

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5.4 Femtosecond Spectroscopy

Erich P. Ippen

Multiphoton photo–electron emission from metal has been the subject of experimental and theoretical investigations for several years. For intense pulses of short enough duration, it has been postulated that a transient thermal nonequilibrium between electrons and phonons may be generated. Because of the much smaller heat capacity of the electron gas, it should be possible to heat the electrons to temperatures in excess of the lattice melting temperature. Previous

experimental investigations performed with picosecond pulses have not had the temporal resolution necessary to observe this anomalous heating. This year, using high intensity, 75-fs pulses at λ = 620 nm on a tungsten metal surface, we have studied multiphoton and thermally assisted photoemission and have observed the thermal nonequilibrium. Pump-probe measurements indicate an electron-phonon energy relaxation time of several hundred femtoseconds.

Publications

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(B) Femtosecond Dephasing Studies

We have recently developed a transient three-pulse diagnostic technique that is sensitive to the initial dephasing of coherent electronic polarization as well as to energy relaxation processes. The method provides clear means to distinguish between homogeneous and inhomogeneous broadening and to monitor excitation transport on a submicron scale. During the past year we have verified our theoretical predictions with experiments on dye molecules (cresyl violet) in a polymer host (PMMA). At room temperature, the polymer result is the same as that for liquid solution; homogeneous broadening is observed and dephasing occurs in 10-20 fsec. But, as the temperature is lowered, the asymmetric scattering signature predicted for inhomogeneous broadening clearly appears. Additional time-resolved measurements also indicate that, once inhomogeneous broadening is dominant, spectral cross-relaxation does not play a role even on a picosecond timescale.

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5.5 Diode Laser Dynamics and Diagnostics

Investigations of semiconductor diode laser modelocking continues with the aim of achieving reliable, controlled, saturable absorber modelocking. A collaboration was established with Drs. James Walpole and Dean Tsang of M.I.T. Lincoln Laboratory to study custom–fabricated InGaAsP lasers with multiple electrodes for simultaneous loss modulation and gain control. The characteristics of devices with a proton bombarded section isolating the two control electrodes were studied experimentally and theoretically. Regimes of bistable laser operation were observed as well as regimes of well–developed pulsations; and a new phenomenon, the evolution of stable pulse behavior through period–three pulsation to chaos, was observed for the first time in a semiconductor laser. Significant pulse shortening due to saturation of a D.C. biased absorber section was not observed, and it now seems clear that the ratio of absorber to gain cross section necessary for pulse shortening into the sub–picosecond domain will not be achieved by variations of bias voltage or injection current alone.

For laboratory diagnostics of saturable absorber and gain dynamics in diode lasers, we have also continued to develop a tunable, short–pulse dye laser for use in the 760 nm – 900 nm range. This year we have succeeded in generating sub–picosecond pulses for the first time in this range. We have focused on obtaining these shorter pulses because studies of pulse distortion and gain cross–relaxation dynamics in diodes will require such resolution. Our laser is a synchronously–pumped, cavity–dumped oxazine 750 laser, pumped by a modelocked Kr^+ ion laser. Pulses from this laser, about 5-10 psec in duration depending upon wavelength, have been compressed to less than 350 fs with the use of 50 m of polarization preserving fiber and a grating pair. Pump–probe studies of GaAlAs diode laser amplifiers with these shorter pulses have just begun.

Publications

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5.6 Quaternary (InGaAsP) Diagnostics

Erich P. Ippen

A modelocked color center laser, based on Tl° (1) centers in KC , has been developed for wavelength–tunable picosecond studies in the 1.5 μm region. The laser, pumped by a cw modelocked Nd:YAG laser, produces pulses of 10-15 ps in duration at a repetition rate of 100 MHz and an average power of 300 mW. The output wavelength is digitally controlled by stepper–motor rotation of two (0.4 mm and 0.8 mm) birefringent plates and can be tuned from 1.48 to 1.58 m. Our present application for this system is to picosecond nonlinear optical studies

of InGaAsP compounds with band-gaps in this important wavelength range, which spans the points of minimum loss and zero dispersion in optical fibers. Thin film layers of InGaAsP, grown by vapor phase epitaxy and lattice matched to InP, have been used for preliminary measurements of nonlinear absorption. Nonlinear bleaching cross-sections as large as $1.8 \times 10^{-14}\text{cm}^2$ have been observed.

Studies of the nonlinear recovery dynamics of optically excited carriers in InGaAsP have been performed with 80 ps pulses from our cw modelocked Nd:YAG laser. Careful evaluation of pump-probe data, with a computer model that takes into account spatial and temporal averaging of the nonlinear response, has resulted in accurate measurements of the nonlinear, "Auger" recombination rate in materials with several different bandgaps.

To develop a method for distinguishing between the radiative and nonradiative components of the nonlinear recombination rates measured in our optical pump-probe experiments we have been investigating the feasibility of nonlinear photo-acoustic spectroscopy. The idea is that, if nonradiative recovery depends upon excitation, nonlinear correlation of carrier excitation can be monitored acoustically. Experimentally, we have recently demonstrated optical generation and phase-sensitive detection of surface acoustic waves (SAW) on semi-insulating InP. SAW transducers placed directly on InGaAsP epilayers had greatly reduced sensitivity due to the unintentional conductivity levels in the layer. In future experiments with InGaAsP layers, the SAW transducers will be placed in regions where the quaternary layer has been etched away.

Publications

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