ments. This phenomenon is of interest as it is a classic example of spontaneous symmetry breaking in a nonlinear system. We have identified this instability as being due to a *modulational instability* that develops around the peak of each spatial ring.[5]

Highly nonlinear phenomena in optical waveguides present some novel opportunities for device applications, including optical limiting and switching.[1,2] In particular, we have shown that a soliton emitted from one waveguide can be trapped in a second adjacent waveguide.[2] This *soliton coupler* gives nonlinear directional-coupler action with the need for evanescent field overlap, and is not far removed from current spatial soliton experiments in glass[6] if two adjacent waveguides were imbedded into the structure.

REFERENCES

1. C.T. Seaton *et al.*, "Calculations of nonlinear TE waves guided by thin dielectric films bounded by nonlinear media," IEEE J. Quant. Electron. **QE-21**, 1985, 774-783.
2. E.M. Wright *et al.*, "Emisson of spatial solitons from nonlinear waveguides," Phys. Rep. **194**, 1990, 309-323.
3. D.R. Heatley *et al.*, "Solitary wave emission from a nonlinear slab waveguide in three dimensions," Appl. Phys. Lett. **56**, 1990, 215-217.
4. Y. Silberberg, "Collapse of optical pulses," Opt. Lett. **15**, 1990, 1282-1284.
5. D.R. Heatley *et al.*, "Spatial ring emission and filament formation in an optical fiber with a saturable noninear cladding," Opt. Lett. **16**, 1991, 291-293.
6. J.S. Aitchison et al., "Spatial optical solitons in planar glass waveguides," J. Opt. Soc. Am. B 8, 1991, 1290-1297.

QUANTUM OPTICS

COHERENT TRANSIENT OPTICAL PHENOMENA IN SEMICONDUCTORS

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Coherent transient spectroscopy of resonances in gas phase atoms and molecules has provided considerable information on irreversible decay processes in these systems due, for example, to collisions. However, despite the presence of strong resonances in semiconductors such as excitons, the rapid dephasing times even at liquid helium temperatures made the study of coherent optical phenomena difficult.

The dephasing time is the scale for which an ensemble of coherently prepared excited states lose phase coherence. Excitation decay as well as inelastic *and* elastic scattering contribute to this process. However, the development of short pulse laser systems has made it possible to see these effects and other related phenomena in semiconductors. These experiments are providing new insight into the basic physics of electronic excitation and relaxation in these systems that are important for electronic and optical applications. This past year has seen several interesting reports of experimental progress.

In a series of experiments, measurements have revealed the presence of quantum beats in the decay of the optical polarization of the heavy hole and light hole resonances in GaAs/AlGaAs quantum well structures[1,2] as well as beats between free and bound excitons[3] following coherent excitation with a short pulse. In general, quantum beats arise due to the coherent superposition of two-excited states oscillating at slightly different eigen frequencies. In GaAs, the light-hole and heavy-hole states are degenerate and no quantum beats would be expected. However, in quantum well structures, the degeneracy is lifted in the presence of one-dimensional quantum confinement. The quantum beats occur at the frequency corresponding to the heavy-hole and light-hole splitting. Quantum beats have also been reported in type II GaAs/AlAs quantum wells.[4]

In closely related experiments, coherent excitation of an electrically biased asymmetric double quantum well produced the first study of the dynamics of an extended wave packet in a solid.[5] A short optical pulse was used to create the packet and follow the coherent oscillations between the two wells. The period of the oscillation was determined by the potential-energy barrier height and width. The oscillation was observed in both transient four-wave mixing and transient absorption. These measurements provided complementary information since the oscillations observed in four-wave mixing decayed due to the polarization decay of the excited states, while the oscillations in transient absorption decayed due to dephasing of the coherent superposition that formed the wave packet.

In other experiments, researchers reported the first observation of time resolved picosecond stimulated photon echoes in semiconductors. A stimulated photon echo or three pulse echo is closely related to the classical two pulse echo, except that by using three time separate pulses, it is possible to simultaneously measure both the dephasing rate and the excitation decay rate. In the first experiments, a streak camera was used to time resolve the emission of the stimulated photon echo created by coherent excitation of the mixed crystal CdSSe.[6] Using a backward stimulated photon echo, measurements were reported on dephasing and excitation decay of excitons in GaAs/AlGaAs quantum well structures.[7] Long dephasing times were reported in both measurements and were attributed to the fact that disorder induced localization results in reduced scattering rates. In the GaAs quantum well measurements, the time resolved measurements showed that the signal emission included a delayed pulse corresponding to the echo, and a prompt pulse (coincident with the third pulse) due to a free polarization decay signal, showing the presence of two classes of excitons in these systems that is attributed to disorder.

In the presence of a magnetic field directed perpendicular to the layers in a GaAs quantum well, the quasi two-dimensional excitons become further confined to quasi-zero dimensions, leading to new interesting physics. Using femtosecond laser pulses, transient absorption measurements show that exciton-exciton Coulomb interactions are strongly modified by the increase in confinement.[8] At high magnetic fields (12 T), 1s electron-hole pairs behave like a gas of noninteracting particles. The magnetic field also serves to split the Zeeman substrates of the heavy hole exciton. In the range of 2-4 T, quantum beats were observed between the split rates of magneto-excitons.[9] The magnetic field dependence of the beat frequency enables a measurement of the corresponding Lande'g factor.

REFERENCES

1. Karl Leo *et al.*, "Quantum beats of light hole and heavy hole excitons in quantum wells," Appl. Phys. Lett. **57**, 1990, 19-21.
2. B.F. Feurerbacher *et al.*, "Quantum beats between the light and heavy hole excitons in quantum wells," Sol. St. Comm. **74**, 1990, 1279-1283.
3. Karl Leo *et al.*, "Quantum beats of free and bond excitons in GaAs/AlGaAs quantum wells," Phys Rev. B **42**, 1990, 11359-11361.
4. W.A.J.A. van der Poel *et al.*, "Quantum beats in the exciton emission of type II GaAs/AlAs quantum wells," Opt. Comm. **76**, 1990, 116-120.
5. Karl Leo *et al.*, "Coherent oscillations of a wave packet in a semiconductor double-quantum-well structure," Phys. Rev. Lett. **66**, 1991, 201-204.
6. G. Noll *et al.*, "Picosecond stimulated photon echo due to intrinsic excitations in semiconductor mixed crystals," Phys. Rev. Lett. **64**, 1990, 792-795.
7. M.D. Webb *et al.*, "Observation of time-resolved picosecond stimulated photon echo and free polarization decay in GaAs/AlGaAs multiple quantum wells," Phys. Rev. Lett. **66**, 1991, 934-937 and "Stimulated-picosecond-photon-echo studies of localized exciton relaxation and dephasing in GaAs/AlGaAs multiple quantum wells," Phys. Rev. B **43**, 1991, 12658-12661.
8. J.B. Stark *et al.*, "Femtosecond dynamics of excitons under extreme magnetic confinement" Phys. Rev. Lett. **65**, 1990, 3033-3036.
9. S.Bar-Ad and I. Bar-Joseph, "Absorption quantum beats of magnetoexcitons in GaAs heterostructures," Phys. Rev. Lett. **66**, 1991, 2491-2494.

SQUEEZED LASERS

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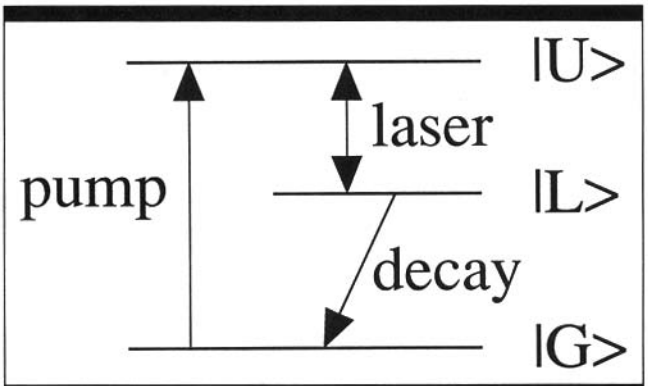
A simple mechanism whereby lasers can "lase" squeezed light has recently been discovered.[1-5] Unlike previous schemes, the pump does not have to be regular; rather, the atoms themselves regularize the pumping process. This is significant because optical measurements are ultimately limited in their sensitivity by the light's quantum mechanical noise.[6]

Until recently, it was believed that laser light must have at least shot-noise. However, in 1987 Machida *et al.*[7] operated diode lasers that produced sub-shot-noise light. This was achieved by controlling the pump noise—that is, the noise in the injection current. The new theoretical result is that certain laser systems can intrinsically reduce the "pump noise" and hence produce sub-shot-noise (intensity squeezed) light.



SCHEMATIC DIAGRAM OF THE ATOMIC LEVEL STRUCTURE FOR THE THREE-LEVEL LASER DISCUSSED IN THE TEXT.

The physics of this squeezing is uncomplicated and applies to a variety of laser systems. The key observation is that by dividing a stochastic process into steps it can be made less noisy. Consider the three-level laser shown in the figure. The relevant stochastic process is the excitation of an electron from the lower laser level |L> to upper laser level |U>, via level |G> The stochastic variable is the "pump-cycle time" for this excitation to occur. Usually the decay rate out of |L> is fast to maximize the population inversion. However this means that the pumping is comparatively slow and hence that its noise dominates the pump-cycle noise. If the decay and pump rates can be made approximately equal, the percentage noise in the pump-cycle time is reduced,[2-4] the excitation process becomes more regular, and the laser becomes quieter. The more the pump cycle is divided into transitions with nearly equal rates, the more regular both the excitation process and the laser light become. The effect had previously gone unnoticed because laser theorists usually made the ap-