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13. ABSTRACT (Maximum 200 words)
This report describes research on eight different projects ranging from fundamental quantum optics to optical engineering. Topics discussed include the following: Collisional dark states and matter-wave transparency, high power diffraction limited surface emitting flared lasers, qubits and quantum gates with laser trapped atoms, radiatively perfect quantumdot, 3D semiconductor nanocavities, excitonic and biexcitonic nonlinear optical processes in semiconductor quantum wells, blue lasers and near-field techniques for ultra-high capacity optical data storage, and an agile complete imaging polarimeter. The JSOP program supported more than 25 graduate students and resulted in more than 160 publications. Some of the projects involved interactions with colleagues and DOD laboratories. University/industry interactions on these projects occurred through direct collaboration with colleagues at several companies and through participation in the Center for Optoelectronic Devices, Interconnects and Packaging.

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AGILE COMPLETE IMAGING POLARIMETER

Michael Descour

Statement of the Problem Studied

The goal of this project was to explore techniques for creating an agile polarimetric imaging instrument. Just as a standard photographic camera is focused on an object and the degree of focus can be estimated by means of contrast associated with that object, we proposed to research imaging instruments that also resolve polarization and spectral data about an object. The hypothesis was that by altering such an instrument's configuration, the contrast of an object with certain properties could be maximized with respect to the scene background, in effect "focusing" a spectropolarimeter on the object.

Summary of the Most Important Results

We have completed an analysis of a technique for snapshot imaging spectropolarimetry. The technique involves the combination of channeled spectropolarimetry with computed tomography imaging spectrometry (CTIS) [Sabatke 2002; Locke 2002]. Channeled spectropolarimetry uses sideband modulation to encode the spectral dependence of all four Stokes parameters in a single spectrum. CTIS is a snapshot imaging spectrometry method in which a computer-generated hologram is employed to acquire dispersed images of the target scene and both spatial and spectral information is reconstructed using the mathematics of computed tomography. The combination of these techniques provides the basis for a snapshot imaging complete Stokes spectropolarimeter that can be implemented with no moving parts.

The snapshot imaging spectropolarimetry technique has the potential for agile imaging that involves maximizing scene contrast based on a combination of a target's polarization and spectral properties. In the case of the CTIS instrument, the computed-tomography-based reconstruction of the scene can be carried out using voxels as a basis set. However, given knowledge of targets' spectral properties, the voxel basis set can be replaced with a basis set consisting of principal-component spectra. The principal components are calculated *a priori* from a training data set that contains multiple linear combinations of spectra representing targets and backgrounds. This technique has been demonstrated in the case of fluorescence-emission spectra measured by the CTIS. Instead of reconstructing an entire spectrum at each pixel, three values were reconstructed. Each value corresponded to the fraction of a principal-component spectrum in the spectrum of that pixel.

The snapshot imaging spectropolarimeter also relies on a nominal voxel-based reconstruction. However, prior knowledge of a target's spectral *and* Stokes-parameter properties, derived from a training set of image data, can be utilized to form a basis set designed to more directly reconstruct images that represent the abundance of a target's spectropolarimetric signature. Focusing on a target with the intent of maximizing contrast with respect to background can therefore be accomplished by adjusting the basis vectors used in reconstruction of the raw image data collected by the snapshot imaging spectropolarimeter.

In addition, the CTIS spectrometer can be outfitted with an electronically variable disperser [Tebow 2002]. This type of disperser is an electronically controlled phase object. By adjusting the phase delay at each pixel within the disperser's aperture, the CTIS spectrometer can be tuned. The tuning can take two forms: (1) modification of the disperser's period and thus dispersion and (2) modification of the diffraction efficiency associated with each diffraction order. The combination of a tunable CTIS with the channeled spectropolarimetry concept developed during the course of this project indicates another avenue for creating an agile spectropolarimeter imaging instrument.

Finally, in exploring how an imaging polarimeter's configuration could be altered to continuously maintain a maximum contrast between an object and scene background, we developed a previously unknown optimal configuration for the conventional polarimeter configuration consisting of a retarder and an analyzer [Sabatke 2000].

List of Publications and Technical Reports

1. D.S. Sabatke, A.M. Locke, E.L. Dereniak, M.R. Descour, J.P. Garcia, T. Hamilton, and R.W. McMillan, "A snapshot imaging spectropolarimeter," *Optical Engineering*, **41**(5), pp. 1048-1054 (May 2002).

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Scientific Personnel

Derek Sabatke, Ph.D. received 2002
Ann Locke, Ph.D. received 2003
Chris Tebow, Graduate student
Michael Descour, Associate Professor

Report of Inventions

None

COMBINING BLUE LASERS AND NEAR-FIELD TECHNIQUES FOR ULTRA-HIGH OPTICAL DATA STORAGE

Alan Kost

Statement of the Problem Studied

A VSAL is semiconductor laser with a very small aperture machined in a metal film applied to the output facet. There has been much excitement lately concerning the use of VSALs for ultra-high density optical data storage. During the late 1990s, a group at Bell Laboratories demonstrated that VSALs could be used to generate sub-wavelength optical spots with optical power approaching one mW [1]. Previous sub-wavelength sources (mostly implemented using tapered fibers) had outputs that were orders of magnitude smaller – much too weak to be used for optical data storage applications. Recently, research groups around the world have begun intensive studies of VSALs.

Optical power is an important issue for near-field optical sources. Optical power of milliwatts or greater is required for writing data. While VSALs offer higher optical power than conventional near-field sources, their power has been observed to drop rapidly to well below one milliwatt when aperture width is reduced to 200 nm or less [1]. Optical data density would appear to be limited by the requirement that VSAL spot size must be significantly greater than 200 nm.

We investigated blue VSALs because we believe they hold the most promise for higher power in smaller optical spots. The concept is straightforward. Aperture transmission scales like roughly like $(d/\lambda)^4$, where d is the aperture width and λ is the optical wavelength (if the aperture is much smaller than the wavelength). The optical throughput for a VSAL with blue emission should be much higher than for a laser with comparable aperture size and longer wavelength emission (e.g. red).

Summary of the Most Important Results

We simulated the transmission of light through very small apertures using Finite Difference Time Domain (FDTD) software. The objective was to determine optimum aperture width, metal thickness, and laser wavelength, in order to verify the usefulness of blue VSALs and to guide their design

Our simulations established three important points:

1. Theoretical results are consistent with experimental data, to the extent with which comparisons can be made.

2. The optimum thickness of metal for apertures is 50 to 100 nm. If the metal film is thin, aperture transmission is high. On the other hand, if the metal film is too thin, light leaks through the portions of the metal that surround the aperture. The optimum metal thickness was found to be between 50 and 100 angstroms.

3. Blue light more easily passes through small apertures. This key result supports our supposition that that blue VSALs will have greater output than their red or infrared counterparts. The simulations show that transmission can be up to three times higher for 400 nm light, as compared with 650 nm light, for apertures wider than about 100 nm. For apertures less 100 nm in width, transmission is small for all wavelengths. We expect even more dramatic performance enhancement for optimized apertures on blue VSALs.

These results were subject to extensive verification using the commercial FDTD software package *XFDT*D from Remcon Incorporated.

List of Publications and Technical Reports

(a) Papers Presented at Meetings, But Not Published in Conference Proceedings

1. "Simulation of Blue VSALs for Optical Data Storage", Alan R. Kost, Melissa Bailey, Glenda Erik, Nick Ericson, Aaron Williams, and Yong Xie, presented at the 2003 Annual Meeting of the Optical Society of America, paper ThZ7.

(d) Manuscripts Submitted But Not Published

1. "The Wavelength Dependence for the Transmission of Light through Very Small Apertures", submitted for publication in Optics Letters (2003).

Scientific Personnel

Yong Xie, Ph.D. student
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Alan Kost, Associate Professor

Report of Inventions

None

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COLLISIONAL DARK STATES AND MATTER-WAVE TRANSPARENCY

Pierre Meystre

Statement of Problem Studied

The original goal of the proposed research was to theoretically investigate novel applications of nonlinear atom optics based on the coherent nature of two-body collisions in ultracold samples. It is known from quantum optics that such coherent dephasing processes can in principle be reversed using, e.g., techniques such as phase conjugation, photon echoes, and the like. The manipulation of optical coherence has also recently lead to exciting new developments including, for instance, EIT and the realization of ultra-slow group velocities of light in nonlinear media. While the matter-wave situation presents important differences, similar techniques should be of use in that case, too. One potential application would be the possibility to tailor, or possibly completely eliminate the effects of collisions between two ultracold atomic beams, leading to them being essentially "transparent" to each other. A potential application of these techniques would be to dispose of the collisional phase shifts that are expected to plague the high-precision performance of atom interferometers. As discussed in the following, we have been able to make significant progress well past this original goal, and in particular to extend nonlinear atom optics to the very promising case of fermionic atoms. This gives us great confidence in future applications of atom optics.

It is important to emphasize that this work would not have been without very substantial cross-fertilization and leverage from several sources of funding, we typically use the JSOP program to investigate high-risk ideas that may eventually lead to more conventional sources of support.

Summary of the Most Important Results

During these last three years, we have made substantial progress on several fronts of nonlinear and quantum atom optics. An early highlight was the theoretical demonstration that atomic four-wave mixing is not limited to bosonic atoms, but should also work for fermions. This opened up a wide new direction of investigations, using fermionic atomic beams in atom optics. Amongst numerous possibilities, we mention fermionic atom lasers, antibunched atomic beams, "atoms on demand", etc. In another early development, we investigated theoretically several ways to generate entangled atomic beams --- a result that was the object of Physical Review Focus story, as well as ways to entangle optical and atomic matter-waves. This is of considerable potential interest in quantum information technology, since atoms are easily stored, while photons are ideal for the transmission of information.

These early results led to a systematic study of the nonlinear atom optics of fermionic fields. There are several fundamental and practical reasons to investigate the use of fermionic atomic fields in nonlinear atom optics. First, and in contrast with bosonic systems, there is no immediate analogy between the behavior of fermionic fields and photons. As such, fermions open up a completely new and unexplored range of possibilities, which might lead to exciting novel effects and applications. In particular, by exploiting the Pauli Exclusion Principle it might become possible to generate highly non-classical atomic sources that would find applications in high-precision measurements below the shot-noise limit; sources of atoms on demand, etc. In addition, ultracold and polarized sources of fermionic atoms do not suffer *s*-wave collisions, thereby eliminating the uncontrolled and hence detrimental collisional broadening that may limit the accuracy of future atomic clocks. We are also exploring ways to generate and manipulate fermionic matter waves, exploiting in particular the mixing between light and fermions, but also the nonlinear mixing between bosonic and fermionic atomic samples. (We recall that such systems have now been realized in the laboratory by several groups, e.g. in 6Li-7Li and 6Li-23Na mixtures.)

To make a long story short, the main outcome of these last three years is it is now clear that nonlinear atom optics with fermions is possible, and our results indicate that there are indeed situations where fermionic atom optics is potentially more favorable than its bosonic counterpart. For example, preliminary work has shown that fermionic atom interferometers can be superior to their bosonic counterparts in some applications, especially in those situations when mean-field effects become important. We have also recently demonstrated the possible generation of fermionic "phase-conjugate", or "time-reversed." We are now actively pursuing investigations along these lines, under funding from NSF and ONR.

List of Publications and Technical Reports

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19. P. Meystre, “Cavity de Broglie optics --- a molecular micromaser,” invited talk, QUEST 2003 Symposium, Santa Fe, New Mexico (2003).

20. P. Meystre, “Four-wave mixing of fermionic matter waves,” invited talk, 12th International Laser Physics Workshop LPHYS'03, Hamburg, Germany (2003).

21. P. Meystre, “Nonlinear mixing of pulsed optical and matter waves,” invited talk, 12th International Laser Physics Workshop LPHYS'03, Hamburg, Germany (2003).

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(d) Manuscripts Submitted, But Not Published

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2. Han Pu, Weiping Zhang, and Pierre Meystre, "Wave mixing of optical pulses and Bose-Einstein condensates," submitted to Phys. Rev. Lett.

3. Chris P. Search, Weiping Zhang, and P. Meystre, "A molecular micromaser," to be published in Phys. Rev. Lett.

4. B. P. Anderson and P. Meystre, "Nonlinear atom optics," to be published in Contemporary Physics.

Scientific Personnel

Twaje Byakunda, Research Specialist
Marcus Cramer, Research Specialist
Christian Schwalb, Research Specialist
Henning Christ, MS May 2003
Chris Search, Research Associate
Cesar Brito, Graduate Student
Pierre Meystre, Professor

Report of Inventions

None

DEVELOPMENT OF HIGH POWER DIFFRACTION LIMITED SURFACE EMITTING FLARED LASERS

Mahmoud Fallahi

Statement of Problem Studied

The development of high power, high brightness semiconductor lasers is important for applications such as efficient pumping of fiber amplifiers and free space communication. For example, the ability to couple directly into the core of a single-mode fiber can vastly increase the absorption of pump light. This is compared to the traditional "cladding pumping" scheme, where many fiber cladding modes are excited but overlap integrals with the signal (guided in the core) show very low coupling.

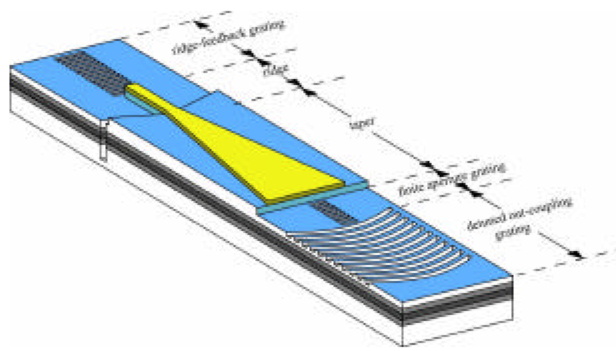

Figure 1 FATURL schematic

Unstable resonators are high mode-dependent loss laser cavities, designed to facilitate large mode-volume combined with single-mode operation. Large gains typical of semiconductor material are well suited to such laser cavities [1]. Improvements to common semiconductor-based unstable resonators are desired, as lasing efficiencies are still quite low. We choose to address the loss by attempting to shift internal mode-dependent loss to mode-dependent mirror loss in tapered unstable resonator lasers (TURLs). This is done by incorporating a finite aperture mirror as the output laser reflector, selectively reflecting the light such that the majority of the light is coupled back into the spoiling grooves. Such a cavity is schematically shown in Figure 1, and has been termed a "finite aperture tapered unstable resonator laser" (FATURL).

Additionally, reduction of cost is paramount to successful transfer to industry. Because an overwhelming portion of the cost is attributed to packaging, methods to ease tolerances can make significant impact on total cost of production. Typical edge-emitting semiconductor lasers have elliptic, astigmatic modes, which are difficult to couple into a single-mode fiber. However with the advent of curved-grating surface-emitting lasers, the output beam is quasi-circular with low divergence. Ellipticity and astigmatism are virtually negligible [2].

Summary of the Most Important Results

In order to analyze such a cavity, it is useful to introduce a set of cavity descriptors in order to evaluate different cavity components. We do this by tracing the power around the cavity, minding the necessary cavity descriptors. Power is chosen rather than electric field amplitude because this allows for simple description of laterally dependent elements [3].

$$g_{\mathrm{mod}}^{+/-}(z) = \Gamma_y \frac{\int_{-\infty}^{\infty} dx\, \psi^{+/-*}(x;z)\, g(x;z)\, \psi^{+/-}(x;z)}{\int_{-\infty}^{\infty} dx\, \psi^{+/-*}(x;z)\, \psi^{+/-}(x;z)}$$

$$\alpha_{\mathrm{mod}}^{+/-}(z) = \frac{\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, \psi^{+/-*}(x,y;z)\, \alpha(x,y;z)\, \psi^{+/-}(x,y;z)}{\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, \psi^{+/-*}(x,y;z)\, \psi^{+/-}(x,y;z)}$$

$$R_{eff} = \frac{\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, \psi^{*}_{ref}(x,y)\, \psi_{ref}(x,y)}{\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, \psi^{*}_{inc}(x,y)\, \psi_{inc}(x,y)}$$

$$C_{sg}^{+/-} = \frac{\int_{-\infty}^{\infty} dx\, \rho(x)\, \psi^{+/-*}(x;z_{sg})\, \psi^{+/-}(x;z_{sg})}{\int_{-\infty}^{\infty} dx\, \psi^{+/-*}(x;z_{sg})\, \psi^{+/-}(x;z_{sg})}$$

In the above equations, $g^{+/-}_{\mathrm{mod}}$ and $\alpha^{+/-}_{\mathrm{mod}}$ are the modal gain and modal internal loss, respectively, in a small slice of width *dz*, centered about *z*, the propagation direction. The +/- indicates propagation in either the +*z* or –*z* direction, whose values can differ significantly, especially in the case of modal gain dominated by lateral confinement within the gain region. R_{eff} is the effective reflectivity off of a mirror, and is essentially the mode-dependent total power reflectivity. Finally, a very important metric within TURLs and FATURs is $C^{+/-}_{sg}$, the forward, and backward spoiling groove coupling of the mode.

Most of the internal loss in a TURL is due to C^{-}_{sg}, the backward spoiling groove coupling. This may be seen in Figure 2 which shows the forward (top) and backward (bottom) propagating field amplitudes within the cavity. On the left (Figure 2a), an "infinite aperture" TURL is shown. The backward-propagating field is broad at the plane of the spoiling grooves, and is significantly truncated due to the aperture function of the grooves. Alternatively, there is a significant reduction in field truncation indicated in the backward propagating field in Figure 2b, which shows a FATURL with a 25 µm wide output aperture (right). This loss is shifted from internal loss (dominated by C^{-}_{sg}) to output mirror loss. Mirror loss contributes directly to lasing output power and is therefore useful to maximize this loss.

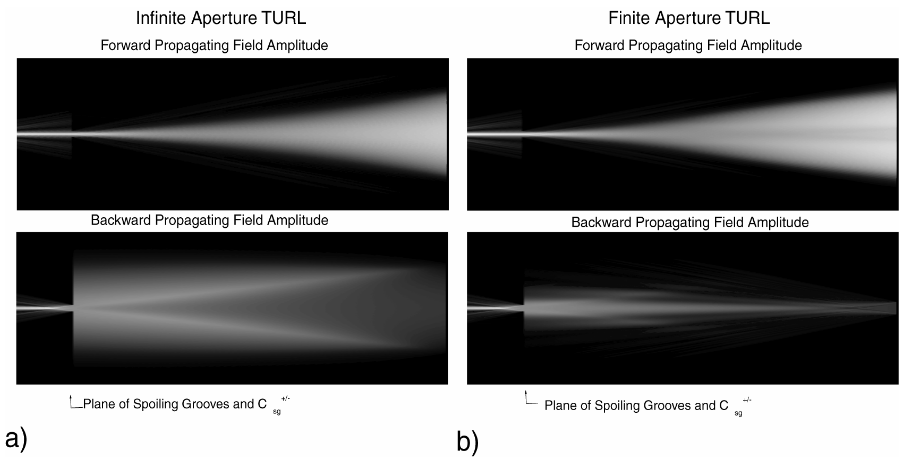

Figure 2 Simulated a) forward and backward propagating field for an infinite aperture TURL and b) for a FATURL

This shift in loss is important to lasing efficiency. The typical form of differential quantum efficiency (DQE) is:

$$\eta_D = \eta_i \frac{\alpha_m}{\alpha_m + \langle \alpha_i \rangle}$$

The fraction in the above equation is the mirror loss over the total cavity loss. For FATURLs, as the mirror loss increases, the internal loss decreases resulting in the fraction in the above equation approaches unity, thus maximizing η_D. C^-_{sg} is shown in Figure 3a as a function of finite

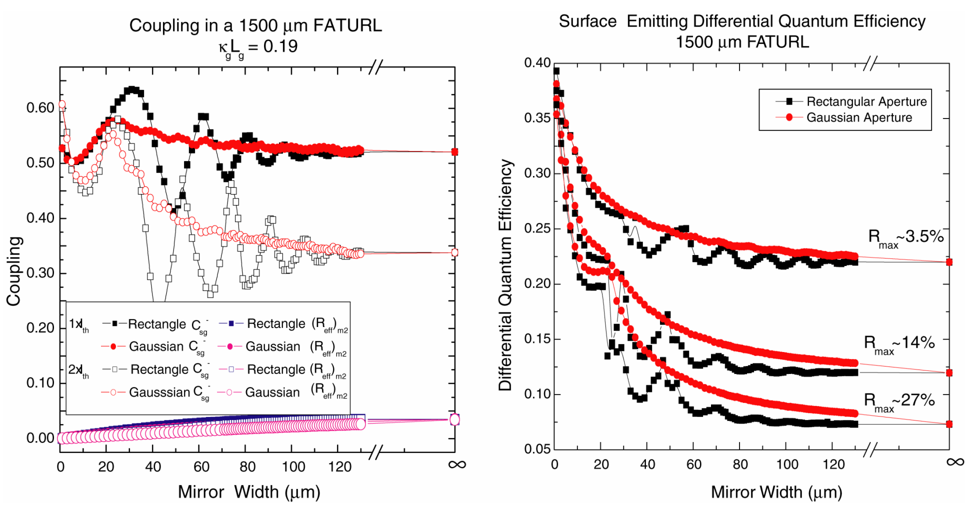

Figure 3 a) Cavity components (C^-_{sg} and R_{eff}) as a function of mirror width at $1{*}I_{th}$ and $2{*}I_{th}$. b) DQE as a function of mirror width.

aperture mirror width. It is important to note that this is oscillation is common in systems with an aperture [4]. The frequency of this oscillation should increase as the square of the aperture width, but is slightly modified due to the non-linearity of the semiconductor material. In Figure

3b, we see how this oscillation affects DQE for different maximum mirror maximum reflectivities. Considering this effect, we choose to fabricate a mirror in the 20 μm - 40 μm range.

A typical grating-coupled surface emitting laser fabrication process is developed for InAlGaAs/InGaAsP/InP material emitting in the 14xx nm range (our material has a nominal wavelength of 1410 nm) [5]. The wafer includes a separate-confinement heterostructure (SCH) to act as a guiding region for the mode. There is an InGaAsP etch-stop located 0.25 μm above the SCH which allows for positioning the grating as well as controlling the index-confinement in the ridge.

The ridge is defined in the InGaAs p^+ cap layer using H_2SO_4:H_2O_2:H_2O. The InGaAs is used as a mask to etch InP to the etch-stop using HCl:$C_2H_4O_2$. The taper is fabricated by removing the InGaAs cap adjacent to the taper using the previous technique. The spoiling grooves are defined using the non-selective etch HBr:H_2O_2:H_2O. Gratings are fabricated in the surface at the etch-stop and are defined using electron-beam lithography with a first-order grating period of 220 nm and a detuned out-coupling grating period of 424 nm. The pattern is transferred into the material using electron-cyclotron resonance reactive-ion etching (ECR-RIE) with a CH_4:H_2 chemistry, resulting in a tooth-height of roughly 100 nm.

A 240 nm SiO_2 layer is deposited using electron-beam evaporation. Vias are opened up in the SiO_2 and a p-metal is deposited using lift-off. The sample is then lapped to 125 μm and an n-metal is deposited on the opposite side. Contacts are annealed using a rapid thermal annealer at 360 ^oC for 20 seconds. Figure 4a shows this process, while Figure 4b and 4c show micrographs of finished FATURLs and a cross section of grating.

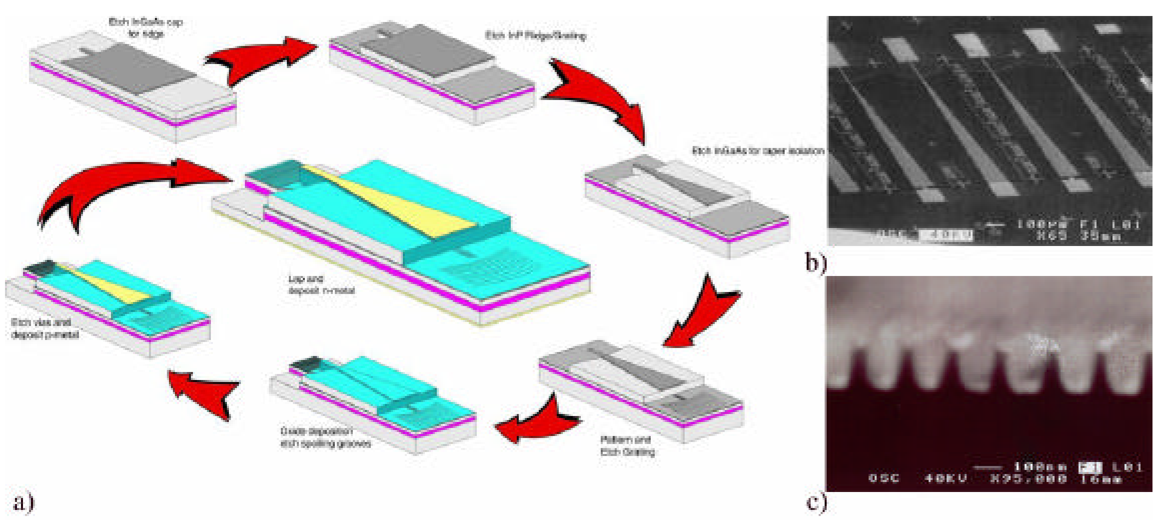

Figure 4 a) Schematic of the seven-step process used to create the FATURL. b) SEM micrograph of infinite aperture TURLs along with FATURLs. c) Cross-section of a first order grating, 200 nm period.

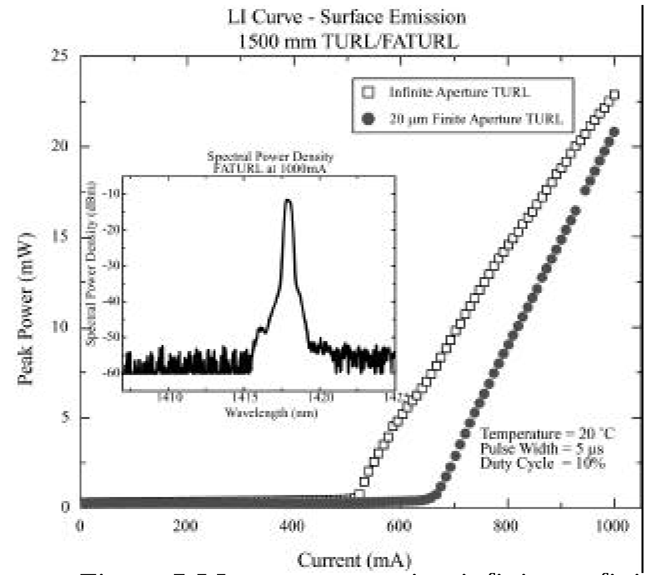

Figure 5 LI curve comparing infinite vs finite aperture TURL. Inset shows spectrum at $1.5*I_{th}$

FATURLs are fabricated next to otherwise identical infinite-aperture TURLs. Sets of two adjacent lasers (distanced at 500 µm centers) can then be tested to compare as directly as possible performance of the FATURL with that of the more classical infinite-aperture TURL. This close spacing reduces both material and processing variations. Lasers are probe-tested unmounted on a copper heat-sink, under 5 µs pulse operation with a 10% duty cycle. The current source is limited to 1 A peak pulses. Power is taken from the surface of the lasers, while power that is diffracted into the substrate as well as light transmitted through the grating is unaccounted for.

Surface-emitting power vs. current characteristics for the longer cavity are shown in Figure 5. The threshold current density (J_{th}) is 582 A/cm^2 for the infinite aperture laser, and 739 A/cm^2 for the finite aperture laser. This increase threshold is a direct result of the reduced effective reflectivity due to the finite aperture. However, in addition to the increased threshold current,

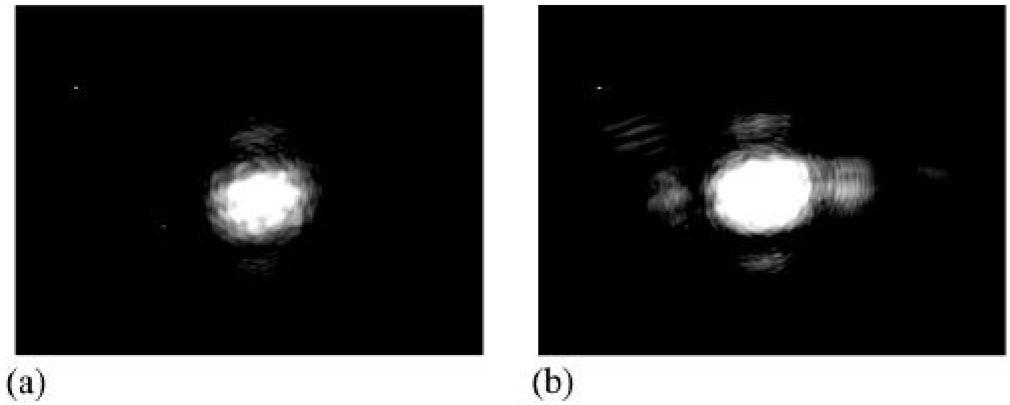

Figure 6 Far field of a) infinite aperture TURL and b) FATURL.

there is also an increase slope efficiency from 0.05 W/A to 0.07 W/A, not accounting for substrate and transmitted radiation. In comparison, the 1000 μm FATURLs have a 0.09 W/A slope efficiency and a threshold of 450 mA. This 40% increase in efficiency compares well with the simulated results of a 49% increase in slope. The difference between theoretical and experimental slope improvement is likely due to approximations made about material loss, as the simulation does not account for carrier effects in the grating region. An inspection of the near-field reveals that the coupling efficiency of the out-coupling grating is lower than expected, allowing an appreciable amount of in-plane transmission. A deeper grating should therefore improve grating coupling and increase the out-coupled slope efficiency. Additionally, there are several techniques to recover the radiation that is diffracted into the substrate which accounts for roughly half of the total power, including an epitaxially grown DBR stack, and grating metallization. The maximum surface-emitting DQE achieved is about 0.17 for the FATURL.

The inset of Figure 5 shows the spectrum at $1.5*I_{th}$. We see a very narrow spectrum with approximately 30 dB side-mode suppression. Furthermore, we test the wavelength as a function of operation temperature. The peak wavelength changes at less than 1 Å/K, indicating good DBR wavelength stabilization and filtering. This compares to about a 6 Å/K change in a Fabry Perot laser fabricated with the same material.

Finally, for high brightness, it is essential to verify we have only a single transverse mode lasing. This is done by placing a vidicon camera about 9 cm from the surface of the semiconductor. Figure 6a shows the quasi-circular far-field of an infinite aperture laser compared to that of a FATURL (Figure 6b) at approximately $1.1*I_{th}$. The lateral dimension of the laser is along the horizontal axis of Figure 6. Divergence angles are more typically characterized by their full-width at half of maximum (FWHM) or their 1/e full-width. At $2.3*I_{th}$, the FWHM of the FATURL is just under 1 degree, still near diffraction limited. There is however a growth of the side-lobes, and is most-likely caused by a field phase deviation from the grating out-coupler phase.

We have presented experimental results indicating finite-aperture tapered unstable resonator lasers previously proposed show superior efficiencies compared to conventional infinite mirror

TURLs. Experiments show a 40% increase in slope efficiency, while increasing the threshold 27%. According to simulation, this increase in threshold should be able to be reduced by optimizing the mirror width. We also show a diffraction-limited beam that is quasi-circular with a significant amount of power in the central lobe.

List of Publications and Technical Reports

(a) Papers Published in Peer-Reviewed Journals

1. R. Bedford, M. Schillgalies, M. Fallahi, "Demonstration of Finite Aperture Tapered Unstable Resonators," Applied Physics Letters, Vol. 83, pp 822-824, August 2003.

2. R. Bedford, M. Fallahi, "Semiconductor Unstable Resonators With Laterally Finite Mirrors," IEEE Journal of Quantum Electronics, Vol 38, pp 716-723, July 2002.

(b) Papers Published in Conference Proceedings

1. R. Bedford, L. Fan, M. Fallahi, "Semiconductor Unstable Resonators with Laterally Finite Mirrors," Proc. of SPIE, Vol. 4993, Jan. 2003

2. R. Bedford, M. Fallahi, "Metal/Dielectric High-Reflectivity Facet Coating for Semiconductor Lasers," LEOS Annual Meeting, October 28, 2003

(c) Papers Presented at Conferences

1. R. Bedford, M. Schillgalies, L. Fan, M. Fallahi, "Finite Aperture Tapered Unstable Resonators," OSA Annual Meeting 2003, October 6, 2003.

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Mahmoud Fallahi, Associate Professor

Report of Inventions

"High Efficiency Tapered Cavity Unstable Resonator Semiconductor Laser Using Laterally Finite Mirrors"

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[5] R. Bedford, M. Schillgalies, M. Fallahi, "Demonstration of Finite Aperture Tapered Unstable Resonators," App. Phys. Lett., Vol 83, pp 822-824, August 2003.

List of Appendixes, Illustrations and Tables

Figure 1 FATURL schematic

Figure 2 Simulated a) forward and backward propagating field for an infinite aperture TURL and b) for a FATURL

Figure 3 a) Cavity components (C^{-}_{sg} and R_{eff}) as a function of mirror width at $1*I_{th}$ and $2*I_{th}$. b) DQE as a function of mirror width.

Figure 4 a) Schematic of the seven-step process used to create the FATURL. b) SEM micrograph of infinite aperture TURLs along with FATURLs. c) Cross-section of a first order grating, 200 nm period.

Figure 5 LI curve comparing infinite vs finite aperture TURL. Inset shows spectrum at $1.5*I_{th}$

Figure 6 Far field of a) infinite aperture TURL and b) FATURL.

QUBITS AND QUANTUM GATES WITH LASER TRAPPED ATOMS

Poul Jessen

Statement of the Problem Studied

The main focus of our research during the grant period has been to develop new methods to prepare, manipulate and measure the quantum state of ultracold neutral atoms, which in our experiments are typically confined in the potential wells of far detuned optical lattices. We have

1. Developed a general approach to resolved-sideband Raman cooling in optical lattices, which allows us to prepare a sample of atoms in a nearly pure center-of-mass and internal quantum state.
2. Developed a general method for quantum state tomography, which allows to experimentally determine the entire density matrix for an angular momenta of arbitrary magnitude.
3. Developed a method for continuous, non-destructive measurement of the collective spin of a sample of laser cooled atoms, based on the Faraday rotation of a far-off-resonance probe beam.

These accomplishments are important milestones in our long term effort to study quantum chaos and real-time quantum feedback control, as well as quantum information processing with trapped neutral atoms.

Summary of the Most Important Results

We have continued our work on resolved-sideband Raman cooling in optical lattices, following our general technique to design Raman coupling into the lattice potential. Our eventual goal is to use neutral Cs atoms trapped in 3D optical lattices as carriers of quantum information – i. e. qubits - and to use resolved-sideband Raman cooling to initialize these atomic qubits in a single pure internal and center-of-mass state. We have taken delivery of an MBR-110/VerdiV10 Ti-Saph laser system (funded by a grant from DARPA), and set up an ultra-deep blue-detuned far-off-resonance optical lattice of a type suitable for the encoding of qubits and implementation of quantum logic gates. In a series of experiments, we have implemented first 1D and then 3D Raman sideband cooling, and achieved populations of at least 85% in the target 3D vibrational ground state. This result, while encouraging, is still well below ~100% ground state population that the technique should be capable of producing, most likely due to imperfect control of magnetic fields in the experiment. We are currently upgrading our vacuum system to address this problem. In the near future we hope to begin work on single- and two-qubit quantum gates.

We have demonstrated and evaluated in detail a general method to measure the quantum state of an angular momentum of arbitrary magnitude. The (2F+1) x (2F+1) density matrix is completely determined from a set of Stern-Gerlach measurements with (4F+1) different orientations of the quantization axis. We have implemented the protocol for laser cooled atoms in the F=4 hyperfine ground state, and applied it to a series of test states prepared through optical pumping and Larmor precession. Comparison of input and measured states show typical reconstruction fidelities larger than 95%. We have developed, but not yet tested, an extension of the method which allows us to measure the density matrix for the entire ground hyperfine manifold. This capability is expected to be very valuable for our ongoing work on neutral atom quantum logic and quantum information processing.

We have developed and implemented a new method for continuous, non-destructive measurement of the collective spin of a sample of laser cooled atoms, based on Faraday rotation of a far-detuned probe beam. In an optical lattice the measurement can be done by making one of the lattice beams serve also as the probe beam. We have developed a solid theoretical understanding of the sensitivity, the tradeoff between sensitivity and decoherence caused by the scattering of probe photons, and the conditions under which measurement backaction becomes significant. We have performed a careful evaluation of the measurement scheme in the context of Larmor precession, looking in particular at the signal-to-noise ratio and decoherence times in measurements of a component of the spin, and shown that the measurement performs at the theoretical limit. Ultimately, we hope to increase sensitivity to the point of significant backaction, and to use the Faraday measurement scheme in experiments on quantum chaos and real-time quantum feedback control.

List of Publications and Technical Reports

(a) Papers Published in Peer-Reviewed Journals

1. *"Faraday Spectroscopy in an optical lattice: a continuous probe of atom dynamics,"* G. A. Smith, S. Chaudhury and P. S. Jessen, J. Opt. B: Quantum Semiclass. Opt. **5**, 323 (2003).

2. *"Quantum control and information processing in optical lattices*," P. S. Jessen, D. L. Haycock, G. Klose, G. A. Smith, I. H. Deutsch and G. K. Brennen, Quant. Inf. Comp. **1**, 20 (2001)

3. *"Measuring the Density Matrix for a Large Angular Momentum*," G. Klose, G. A. Smith and P. S. Jessen, Phys. Rev. Lett. **86**, 4721 (2001).

4. *"Mesoscopic quantum coherence in an optical lattice"*, D. L. Haycock, P. Alsing, I. H. Deutsch, J. Grondalski and P. S. Jessen, Phys. Rev. Lett. **85**, 3365 (2000).

5. *"Quantum Transport in Magneto-Optical Double-Potential Wells"*, I. H. Deutsch, P. M. Alsing, J. Grondalski, S. Ghose, P. S. Jessen and D. L. Haycock, J. Opt. B: Quantum Semiclass. Opt. **2**, 633 (2000).

6. *"Quantum Computing with Neutral Atoms in an Optical Lattice",* I. H. Deutsch, G. K. Brennen and P. S. Jessen, Fortschritte der Physik **48**, 925 (2000).

(b) Papers Published in Non-Peer-Reviewed Journals or in Conference Proceedings

1. *"Quantum And Classical Dynamics Of Atoms In A Magneto-optical Lattice,"* S. Ghose, P. M. Alsing, I. H. Deutsch, P. S. Jessen, D. L. Haycock, T. Bhattacharya, S. Habib and K. Jacobs, in *Experimental Chaos: 7th Experimental Chaos Conference,* Eds. V. In, L. Kocarev, T. L. Carroll, B. J. Gluckman, S. Boccaletti and J. Kurths, AIP Conference Proceedings **676** (2003).

2. *"Probing the motion of cold atoms by Faraday spectroscopy,"* G. A. Smith, S. Chaudhury and P. S. Jessen, Proc SPIEE **5111**, 396 (2003).

3. *"Coherent Tunneling and Quantum Control in an Optical Double-Well Potential,"* P. S. Jessen, D. L. Haycock, G. Klose, G. Smith, P. M. Alsing, I. H. Deutsch, J. Grondalski and S. Ghose, in "Laser Spectroscopy, XV International Conference",, eds. S. Chu, V. Vuletic, A. J. Kerman and C. Chin (World Scientific 2002).

4. *"Quantum Information Processing in Optical Lattices: Cold Atomic Qubits in a Virtual Crystal of Light"*, I. H. Deutsch and P. S. Jessen, IEEE LEOS Newsletter 16, No 2, 3 (2002).

5. *"Quantum Control and Entanglement Engineering with Cold Trapped Atoms,"* P. S. Jessen, D. L. Haycock, G. Klose, I. H. Deutsch and G. K. Brennen, Proceedings of ICQ 01 (Rinton Press 2001).

6. *"Quantum Information Processing in Optical Lattices,"* G. K. Brennen, I. H. Deutsch and P. S. Jessen, Proceedings of ICQ 01 (Rinton Press 2001).

(c) Papers Presented at Meetings, but not Published in Conference Proceedings

1. *"Sideband Cooling and Qubit initialization in a 3D Optical Lattice"*, W. Rakreungdet, L. Harrison and P. S. Jessen, 2003 meeting of the Division of Atomic and Molecular Physics, Boulder, Colorado, May 20-24, 2003.

2. *"Qubits and Quantum Gates in Optical Lattices"*, Joint IPAM/MSRI Workshop on Quantum Computing, Los Angeles, California, 21-23 October 2002.

3. *"Elements of a Neutral Atom Quantum Processor"*, DARPA QUIST Meeting, Cambridge, Massachusetts, 9-13 September 2002.

4. *"Continuous Measurement of the Mean Magnetic Moment of a Cold Atomic Vapor"*, G. Smith, 2002 Meeting of the Division of Atomic and Molecular Physics, Williamsburg, Virginia, 29 May - 1 June 2002.
5. *"Mesoscopic Quantum Coherence in an Optical Lattice,* Annnual APS March Meeting 2002, Indianapolis, Indiana, 18-22 March, 2002.

6. *“Continuous measurement and feedback on atomic motion in optical traps”*, Fourth Annual Workshop of the SQuInT Network, Boulder, Colorado, 8-10 March 2002.

7. *“Elements of a Neutral-Atom Based Quantum Processor”*, DARPA QUIST Kickoff Meeting, Dallas, Texas, 26-29 November 2001.

8. *“Spinor Wavepacket Dynamics in a Magneto-Optical Double-Well lattice”*, OSA/ILS Annual Meeting 2001, Long Beach, California, 14-18 October 2001.

9. *“Methods to Measure angular Momentum States, and Their Possible Application to Quantum Chaos and Control”*, QUEST 2001 Summer Retreat, Santa Fe, New Mexico, 6-10 August 2001.

10. *“Quantum Control and Quantum Logic in Optical Lattices”*, P. S. Jessen, Gordon Research Conference on Atomic Physics, Williamstown, Massachusetts, June 17-21 2001.

11. *“Spinor Wavepacket Control in Optical Double-well Potentials*, P. S. Jessen, 2001 meeting of the APS Division of Atomic and Molecular Physics, London, Ontario, 16-19 May 2001.

12. *“Quantum Control in nanoscale atom traps”*, Arizona Research Forum on Nanotechnology, Tucson, Arizona, 21 March 2001.

13. *“Measuring the quantum state of a large angular momentum”*, G. Klose, Third Annual Workshop of the SQuInT Network, Pasadena, California, 2-4 March 2001. (Invited)

14. *“Quantum Control and Entanglement Engineering with Cold Trapped Atoms”*, International Conference on Experimental Implementation of Quantum Computation (IQC 01), Sydney, Australia, 16-19 January 2001.

15. *“Quantum and Classical Dynamics in an Optical Double-Well Potential”*, QUEST Workshop, Santa Fe, New Mexico, 24-28 July 2000.

16. *“Reconstructing the density matrix of an angular momentum"*, G. Klose, 2000 meeting of the Division of Atomic and Molecular Physics, Storrs, Connecticut, 14-17 June 2000.

Scientific Personnel

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Souma Chaudhury, Ph.D. student
Poul S. Jessen, Professor

Report of Inventions

None

RADIATIVELY PERFECT QUANTUM DOT

Hyatt M. Gibbs

Statement of the Problem Studied

The basic goal of this project was to locate perfect regions of a quantum well and then use various techniques such as monolayer fluctuations or interdiffusion to provide transverse confinement to construct a large quantum dot (QD). Such a large QD was desired because it should have a very large dipole moment as needed for cavity QED and entanglement experiments using strong coupling between a single QD (SQD) and a 3D nanocavity.

Summary of the Most Important Results

It is nontrivial to study the properties of a single quantum dot or a nanocavity containing a single quantum dot. Both the spatial and spectral resolutions must be high. The technique we are employing is optical microscopy, providing moderate spatial resolution with very high light throughput. By using a reflective microscope objective corrected for the aberration introduced by the dewar window, we obtain a spatial resolution of one wavelength in air. At first we placed a microscope cryostat on external nanopositioning stages, but this arrangement has the disadvantage that the helium transfer line attached to the cryostat cannot be secured solidly to the table. Now we have a Cryovac cryostat with internal nanopositioners and have much less problem with vibrations and drift.

[Wu et al. 99] reported a photoluminescence excitation line that was very narrow and hardly shifted over mm regions of the sample as they monitored the photoluminescence (PL) from many different dots. They interpreted this as an extended state belonging to a “perfect” quantum well occupying a large area of the sample. Further evidence for delocalized states extending up to 600 nm in a GaAs/AlGaAs single quantum wire appeared in [Crottini et al. 01]. Based on these rather convincing results, we believed such perfect regions exist and set out to observe them directly in reflection. Our computed reflectivity from a single QW, assuming that it has a FWHM linewidth of 50 μeV and a nonradiative width of 20 μeV FWHM and is at least as large as our 800 nm spatial resolution, is more than 75%. I.e., it should be easy to see even if it is only 200 nm in diameter.

We have observed isolated narrow-linewidth lines in PL from our thin GaAs/AlGaAs SQW’s that we attribute to interface fluctuation QD’s. In a search for perfect regions exhibiting delocalized states, we have scanned several of our own samples and one sample from Dan Gammon and Scott Katzer that they think is another piece of the same sample used in [Wu et al. 99]. Since there is no hint of any strong reflectivity anywhere we looked, *we conclude that there are no perfect QW regions larger than 200 nm in diameter*. This is consistent with other measurements on our samples indicating that the island size distribution peaks around 50 nm, dropping to zero well before 200 nm [von Freymann et al. 02; Neuberth et al. 02a&b].

We pointed out to Duncan Steel that the absorption of a SQD should be measurable based on the following estimate. We observe a peak absorption of 20% in a SQW with 0.5 meV linewidth; a perfect region of diameter 40 nm, the size determined in [Gammon et al. 96a, 96b], observed through a 400 nm aperture should have a lower absorption in the ratio of the areas, i.e. 0.2%. But the linewidth should be only 0.05 meV, increasing the peak absorption to 2%. Indeed his group, in collaboration with ours, has seen SQD absorptions as large as 4% [Guest et al. 02]. Note, however, that they have never seen larger absorptions as they should if any of the interface fluctuation QD's had diameters much larger than 40 nm. They saw many narrow lines in many different apertures that were as large as a few percent, but they did not see any with larger absorptions. They also made searches using near-field scanning optical microscopy with similar spatial resolution, again with no large absorptions. This agrees very well with our own negative search; there seem to be no perfect regions of the QW with diameters larger than about 100 nm. If really large perfect regions exist in any abundance, we should have seen them by the reflectivity measurements and Steel's group should have seen them as well. Closer examination of the PL excitation data of Wu, et al., reveals that the energetic position of the extended state resonance does vary by a few tenths of an meV, approaching the observed absorption linewidth and perhaps explaining the absence of a narrow strong reflectivity peak.

Even though no really large QD's were found in the work with Steel, we did find QD's with dipole moments in the range 50 to 100 Debye, very promising for strong coupling to a 3D nanocavity. Also from our calculations of the dipole moments of QD's, we have concluded that not only interface fluctuation QD's but also large self-organized QD's may be able to undergo strong coupling in a photonic crystal nanocavity. Consequently, during the last half of this grant most of our research focused on the study of InAs self-organized QD's grown by MBE by the group of Prof. Dennis Deppe, U. Texas-Austin. The measurements were made on samples containing many photonic crystal nanocavities fabricated by Prof. Axel Scherer and Tomo Yoshie, Caltech. The early samples containing three layers of high density QD's were excellent for their primary purpose, demonstrating photonic-crystal-nanocavity lasing, but did not yield any isolated sharp lines indicative of single QD's.

Recently we obtained a sample containing a single layer of lower density InAs dots. In this case, we are able to identify single QD's and high-Q photonic-crystal nanocavity modes. And we have been able to temperature scan the SQD resonance through the cavity mode, mapping out the crossing curve characteristic of weak coupling. At powers high enough to begin to saturate SQD's not coupled to the nanocavity, we see enhanced spontaneous emission when a coupled SQD is scanned into resonance with the nanocavity mode [Rupper et al. 03]. *These measurements demonstrate that we have assembled and optimized an apparatus capable of studying the interaction between a SQD and a nanocavity.* We are continuing to collaborate with Professors Deppe and Scherer hoping to obtain photonic crystal nanocavities with high enough Q and small enough volume in order to see strong coupling. The present sample Q is by our calculation about a factor of two, too small.

List of Publications and Technical Reports

(a) Papers Published in Peer-Reviewed Journals

1. Grote, B., C. Ell, H. M. Gibbs, G. Khitrova, S. W. Koch, J. P. Prineas, and J. Shah, "Resonance Rayleigh scattering from semiconductor heterostructures: the role of radiative coupling", Phys. Rev. B **64**, 045330 (2001).

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(b) Papers Published in Non-Peer-Reviewed Journals or Conference Proceedings

1. Hoyer, H., S. W. Koch, M. Kira, P. Brick, S. Chatterjee, C. Ell, G. Khitrova, and H. M. Gibbs, "Nonequilibrium characteristics of excitonic luminescence", in OSA *Trends in Optics and Photonics (TOPS)* ***74*** *Quantum Electronics and Laser Science Conference,* OSA Technical Digest, Postconference Edition (Optical Society of America, Washington, DC, 2002), p. 106.

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(c) Papers Presented at Meetings, But Not Published in Conference Proceedings

1. Neuberth, U., G. von Freymann, H. Kalt, M. Wegener, G. Khitrova, and H. M. Gibbs, “Zeitabhängige Untersuchung einzelner Photolumineszenzlinien ungeordneter GaAs-Quantenfilme”, Frühjahrstagung der Deutschen Physikalischen Gesellschaft, Regensburg, Germany, March 11-15, 2002.

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(d) Manuscripts Submitted, But Not Published

None

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Report of Inventions

None

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3D SEMICONDUCTOR NANOCAVITIES

Galina Khitrova and Claudia Ell

Statement of the Problem Studied

The main goal of this project is to obtain a 3D nanocavity adequate for seeing strong coupling with a single quantum dot. This means it must have a single mode with sufficiently high Q and small volume.

Summary of the Most Important Results

(a) Progress Toward Quantum Limit in a 3D Normal-Mode-Coupling Microcavity

Recent progress in microfabrication involving etching processes makes it possible to engineer three-dimensional nanostructures from MBE-grown planar Fabry-Pérot microcavities. The optical mode is confined laterally by implementing a thin dielectric (native oxide) aperture layer on top of the cavity spacer. The sample under investigation consists of a 16 period GaAs/AlAs bottom mirror, a λ GaAs spacer, and a 4 period ZnSe/MgF_2 dielectric mirror on top of the oxide aperture. The aperture diameters range from 1 to 7 μm. A high-quality 85 Å InGaAs single quantum well [4] is located in the anti-node of the spacer.

The effect of three-dimensional confinement on the bare cavity mode is revealed in transmission spectra [Lee et al. 01b]. Several transverse modes can be observed for each aperture size. As expected for a three-dimensional mode quantization, the mode spacing increases with decreasing aperture diameter. To confirm the quantized nature of the photon mode, we performed additional measurements with various angles of incidence with respect to the normal. While the spectral position λ_c of each transverse mode is preserved, the amplitudes of the high-order modes increase with increasing angle. The cavity quality factors Q ($\lambda_c/\Delta\lambda_c$) for all aperture diameters are high enough to provide a clear normal-mode coupling even though Q degrades as the aperture size decreases. By adding one more period of top mirror layers, we could increase the Q-value by 15%. The high quality of the cavity together with the narrow exciton absorption line of ≈0.6 meV FWHM results in a well resolved normal mode coupling and a splitting-to-linewidth ratio of 4.9 at minimum splitting much larger than previously seen for a 3D photonic structure. A typical normal mode coupling anticrossing behavior is seen using different temperatures to tune the exciton resonance through the cavity mode.

The observation of such a well-defined normal mode coupling in a small optical mode volume allows controlled nonlinear measurements. Present-day planar microcavities are still far from the strong coupling regime. All previous experiments can be described using a classical light field or be understood in analogy to a many-atom picture. As a first step towards the strong coupling regime, microcavities are investigated in which the optical mode is confined by oxide apertures with diameters between 2 and 5 μm. Pump-probe experiments on these microcavities revealed that the number of absorbed photons required to saturate the NMC peaks scales with the transverse area of the cavity mode and drops to 300 photons for an aperture diameter of 2 μm [Lee et al. 01a]. This is three orders of magnitude smaller than the 200,000 photons needed in a planar microcavity [Khitrova et al. 99]. Clearly, we have made an important step toward the quantum limit.

(b) Third-Transmission-Peak Mystery Solved

Nonlinear measurements for an excitation resonant with the normal-mode peaks in a semiconductor microcavity show a very intriguing effect: A third peak in transmission (or a 3rd dip in reflection) shows up between the two normal-mode peaks. It appears both in nonlinear fs single beam experiments and in ps-pump-probe experiments [Brick et al. 00]. Microscopic calculations (done by M. Kira) based on a quantized light description show that quantum fluctuations give rise to intraband coherences if simultaneously an interband polarization and a pump-induced occupation of electron and hole states is present. These quantum correlations couple back to the interband polarization via guided modes. They contribute to the phase space filling and consequently to the macroscopic polarization. Measurements on an oxide-aperture microcavity showed no third peak confirming the important role of the guided modes in this effect. Additional measurements and calculations were performed to clarify the dependence of the 3rd peak on the energetic position of the pump pulse and its spectral shape. The results were published in a Phys. Rev. Letter [Ell et al. 00].

(c) Theory of SQD Dipole Moment and Radiative Lifetime

In order to achieve strong SQD-nanocavity coupling, one wants to maximize the strength of the dipole moment. In the past, most values of the dipole moment used in strong-coupling estimates have been extracted from lifetime or ensemble dipole moment measurements. We have collaborated with the groups of Duncan Steel at Michigan and Dan Gammon at NRL to determine the dipole of interface fluctuation SQD's by direct absorption through an aperture or a scanning near-field optical microscope probe [Guest et al. 02]. Very importantly for strong coupling, we find that the dipole moments are very large, in the range 50 to 100 Debye. We have addressed several questions related to those measurements. How does one extract the size and shape of the SQD, information needed to compare the measured dipole moments with theoretical expectations [Thränhardt et al. 02b]? How do the measured and computed dipole moments compare [Guest et al. 02]? What is the relationship between dipole moment and radiative lifetime [Thränhardt et al. 02a]?

(d) Oxide-Aperture and Photonic-Crystal Nanocavities

Whereas the results above were important advances in the development of 3D microcavities and in the understanding of the quantum properties of excited semiconductors, much remains to be done if one is to reach the regime of quantum entanglement. Strong coupling requires that the SQW be replaced by a single quantum dot (SQD) and that the 3D microcavity be improved by reducing its mode volume and increasing its Q. For the growth and fabrication of SQD nanocavities, we are collaborating with Professor Dennis Deppe, University of Texas – Austin. He has had excellent success with the growth of self-organized InAs and InGaAs QD's. And he is developing smaller volume, higher Q nanocavities based on etching and oxidation techniques. We have measured the Q's of some of his nanocavities, exciting the QD's with a diode laser at 670 nm and monitoring the photoluminescence (PL) with a photomultiplier tube. Since the emission spectrum of the QD's without a cavity is very broad, the PL linewidth is determined by the cavity linewidth. Therefore, the Q is just the transition energy of the PL emission peak divided by its FWHM linewidth. We have measured Q's as high as 2900. However, the mode volumes are much too large for strong coupling.

Consequently, during the last year of this grant we have turned our attention to photonic-crystal nanocavities that have much smaller mode volume, close to the limit of the cube of the wavelength in the material. Samples grown by Professor Deppe's group containing InAs quantum dots are fabricated into photonic-crystal nanocavities by Professor Axel Scherer and Tomo Yoshie, Caltech.

One challenge was to develop a method enabling us to easily refind a specific photonic crystal cavity. The periodic air/material pattern of a photonic crystal nanocavity causes an effective refractive index different from that of the surrounding material. Thus, reflectivity images of the sample allow us to refind the position of a specific nanocavity.

We have measured the PL of hundreds of individual photonic crystal nanocavities at room and low temperatures. A cavity mode could only be detected for several of the nanocavities, with Q's between 300 and 2000. Unfortunately, these Qs are not high enough for strong coupling. But in the weak coupling regime, we have seen evidence of enhanced spontaneous emission and mapped out a crossing of a single-quantum-dot transition through a nanocavity resonance by temperature scanning.

However, the Caltech group has fabricated photonic crystal nanocavities with Q's close to 3000. According to our estimates of the dipole moment based on the lifetimes of our InAs SQD's, that should be adequate for strong coupling. We are optimistic that we can see strong coupling if we can find a SQD close to the anti-node of the field in such a nanocavity.

List of Publications and Technical Reports

(a) Papers Published in Peer-Reviewed Journals

1. Blansett, E. L., M. G. Raymer, G. Khitrova, H. M. Gibbs, D. K. Serkland, A. A. Allerman, and K. M. Geib, "Ultrafast polarization dynamics and noise in pulsed vertical-cavity surface-emitting lasers", Opt. Exp. **9**, 312 (2001).

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(c) Papers Presented at Meetings, But Not Published in Conference Proceedings

1. Donovan, M. E., A. Schülzgen, J. Lee, P.-A. Blanche, N. Peyghambarian, G. Khitrova, H. M. Gibbs, I. Rumyantsev, N. H. Kwong, R. Takayama, Z. S. Yang, and R. Binder, "Coupled optical Stark shifting in a quantum well through Raman coherences", March Meeting of the American Physical Society, 2002.

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3. Hoyer, W., M. Kira, S. W. Koch, H. Stolz, S. Mosor, G. Khitrova, and H. M. Gibbs, "Photon correlation effects in semiconductors", Workshop on Semiconductor Quantum Optics", June 23-25, 2003, Bremen, Germany.

(d) Manuscripts Submitted, But Not Published

1. Kira, M., W. Hoyer, S. W. Koch, P. Brick, C. Ell, M. Hübner, G. Khitrova, and H. M. Gibbs, "Quantum correlations in semiconductor microcavities", Semiconductor Science and Technology, invited paper.

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Report of Inventions

None

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EXCITONIC AND BIEXCITONIC NONLINEAR OPTICAL PROCESSES IN SEMICONDUCTOR QUANTUM WELLS

R. Binder

Statement of the Problem Studied

We have developed, evaluated and applied a microscopic theory for optical nonlinearities of semiconductors involving excitons (bound electron-hole pairs) and two-exciton states (including bound two-exciton states, so-called biexcitons, and unbound two-exciton continuum states). The theory has been applied to a variety of semiconductor systems (semiconductors microcavities, single and multiple quantum wells, compound systems of quantum wells and polarizers used for optical switching). The theory is based on the so-called dynamics-controlled truncation formalism (DCT), evaluated in the lowest-order nonlinear optical regime, the $c^{(3)}$ regime. There were two major goals of this study. First, we wanted to be able to analyze low-order optical nonlinearities in the spectral vicinity of exciton resonances and to understand the microscopic processes that give rise to the observed nonlinearities. Secondly, we wanted to use that understanding and the fact that our theory has predictive capabilities in order to propose ways to enhance or optimize specific nonlinearities.

Summary of the Most Important Results

The third-order nonlinear response theory for excitons in semiconductors was applied to the investigation of four-wave mixing (FWM) signals from semiconductor microcavities. In collaboration with the experimental group of Prof. M. Kuwata-Gonokami, University of Tokyo, we found that our theory gives indeed excellent agreement with experimental FWM spectra, and hence can be regarded as accurate description of the microscopic processes underlying excitonic nonlinearities in the $c^{(3)}$ regime. Furthermore, we found that important features two-exciton continuum scattering (which is, in part, responsible for the nonlinear response) depend crucially on the dimensionality of the system. In the case of quasi-two dimensional semiconductor quantum wells, the two-exciton scattering processes cannot be described perturbatively. This finding is based on our theoretical results for two-exciton scattering in conjunction with evidence based on the experimental data, and confirms similar statement known from the theory of scattering of Bosonic particles with short-range interaction.

Another sub-project during the 3-year period was an investigation of excitonic and biexcitonic optical nonlinearities in semiconductor single and multiple quantum wells. Specifically, we analyzed generalized Raman coherences (i.e. non-radiative quantum coherences) in quantum wells, which are realized by the heavy-hole (hh) and light-hole (lh) valence bands. In collaboration with the experimental group of Prof. A. Smirl, University of Iowa, we performed theoretical investigations of time-integrated and time-gated differential absorption signals. We found that the signatures (generalized quantum beats) of Raman coherences can be masked by similar signatures due to two-exciton correlations, especially in the case of long optical pulses (100 fs and longer) and samples containing many quantum wells. We also identified a parameter regime where the contribution of the two-exciton correlations to the quantum beats can practically be eliminated in the time-integrated differential absorption signal.

Also in collaboration with the group of Prof. A. Smirl, we studied an all-optical polarization switch that is based on optical nonlinearities in a semiconductor quantum well. The switch is based on a polarization rotation of a signal pulse brought about by a control pulse, and is based on the possibility of selectively exciting various spin states of the excitons. We found that, at large detuning of the control light with respect to the exciton resonance, the dominant many-particle effects are related to the Hartree-Fock mean field terms. This, in turn, allowed us to deduce the dependence of the switching action on the effective exciton mass, the latter being a function of the material used in the quantum well. We found that the polarization rotation is proportional to the sixth power of the reduced mass, m_r^6. This finding is based on the differential nonlinear absorption spectra which we calculated for various detunings of the control pulse and various exciton binding energies (Fig. 1).

In collaboration with another experimental group, the group of Prof. H. Wang, University of Oregon, we concentrated on the realization of electromagnetically-induced transparency (EIT) via the biexciton coherence. We found that two-exciton correlations leading to coherent biexcitons (bound two-exciton states) can help to create a very strong and robust EIT effect in a semiconductor quantum well. Specifically, we found that counter-circularly polarized picosecond light pulses can produce EIT if the pump beam is spectrally centered at the exciton-to-biexciton transition frequency. In this case, the probe absorption at the exciton resonance can be strongly reduced. Our theoretical investigations are in good agreement with the experimental data obtained by the Oregon group, and they allow for a detailed understanding of the microscopic origin of the EIT effect which is quite different from the simpler atomic EIT effect. The main results with a clear EIT effect seen both experimentally and theoretically can be seen in Fig. 2.

In addition to the spatially homogeneous optical nonlinearities, we have also completed the first part of our investigation of light-forces in semiconductors. We found that there are forces on electron-hole pairs in semiconductors that are similar to gradient-forces known from atomic systems, if the atom (or, in our case, electron-hole pair) is in the vicinity of a spatially inhomogeneous light field. However, we found that there are certain differences between the electron-hole pairs and atoms. One important difference is that the light field that creates the force on an existing electron-hole pair also creates new electron-hole pairs, in contrast to the atomic case. This has a variety of implications for the visibility of the light-force effect in semiconductors.

Also, typical momentum distributions of electrons and holes in semiconductors span a wide range of momenta, so that the momentum gained from the light-force is usually small compared to existing momenta. This limits the induced spatial flow of electron-hole pairs. We believe, however, that this problem can be solved if one studies light-forces on excitons (rather than unbound electron-hole pairs), because we found the light-force in principle to be present in exciton systems. Detailed studies of light-induced exciton transport are planned for the future.

List of Publications and Technical Reports

(a) Papers in preparation for submission in the near future

1. R. Takayama, N.H. Kwong, I. Rumyantsev, M. Kuwata-Gonokami, and R. Binder, "On the material and light-pulse parameter dependence of the nonlinear optical susceptibilities in the quasi-coherent $c^{(3)}$ regime in semiconductor quantum wells"

2. I. Rumyantsev, N.H. Kwong, R. Binder, E.J. Gansen and A.L. Smirl, "Many-particle theory of all-optical polarization switching in semiconductor quantum wells"

(b) Papers published in peer-reviewed journals or as book chapters

1. M. Phillips, H. Wang, I. Rumyantsev, N.H. Kwong, R. Takayama, and R. Binder, "Electromagnetically-induced transparency in semiconductors via biexciton coherence", Phys. Rev. Lett. (in press)

2. S. A. Hawkins, E. J. Gansen, M. J. Stevens, A. L. Smirl, I. Rumyantsev, R. Takayama, N. H. Kwong, R. Binder, and D. G. Steel, "Differential measurement of Raman coherence and two-exciton correlations in quantum wells", Phys. Rev B, **68**, 035313 (2003)

3. S. A. Hawkins, E. J. Gansen, M. J. Stevens, I. Rumyantsev, R. Takayama, N. H. Kwong, R. Binder, G. Khitrova, H. M. Gibbs, D. G. Steel, and A. L. Smirl, "Polarization dependence of quantum beats in quantum wells: Raman coherence and two-exciton correlations", phys.stat.sol. (c) **0**, 1453-1458 (2003)

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6. N. H. Kwong, R. Takayama, I. Rumyantsev, Z. S. Yang, and R. Binder, "Excitonic Correlations in the Nonlinear Optical Response of Two-dimensional Semiconductor Microstructures: a Nonequilibrium Green's Function Approach," in *Formation of correlations: Nonequilibrium at Short Time Scales*, K. Morawetz (ed.) (Springer, New York, 2003).

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(c) Papers Published in Non-Peer-Reviewed Journals or in Conference Proceedings

1. Z.S. Yang, N.H. Kwong, R. Takayama, and R. Binder, "Coherent dynamics of optically-inactive excitons in semiconductor quantum wells", paper QThM4, Quantum Electronics and Laser Science Conference (QELS '03), Baltimore, Maryland, June 1-6, 2003

2. I. Rumyantsev, N.H. Kwong, R. Takayama, R. Binder, M. Phillips, and H. Wang, "Optically-induced biexciton energy shift in semiconductor quantum wells", post deadline paper QThPDA7, Quantum Electronics and Laser Science Conference (QELS '03), Baltimore, Maryland, June 1-6, 2003

3. I. Rumyantsev, N.H. Kwong, E.J. Gansen, A.L. Smirl, and R. Binder, "Many-particle theory of all-optical polarization switching in semiconductor quantum wells", poster presentation QThJ13, Quantum Electronics and Laser Science Conference (QELS '03), Baltimore, Maryland, June 1-6, 2003

4. M. Phillips, H. Wang, I. Rumyantsev, N.H. Kwong, R. Takayama, and R. Binder, "Electromagnetically-induced transparency at the exciton resonance", paper QFD1, Quantum Electronics and Laser Science Conference (QELS '03), Baltimore, Maryland, June 1-6, 2003

5. S.A. Hawkins, E.J. Gansen, M.J. Stevens, I. Rumyantsev, R. Takayama, N.H. Kwong, R. Binder, G. Khitrova, H.M Gibbs, D.G. Steel, and A.L. Smirl, "Polarization dependent signatures of Raman coherence and two-exciton correlations in quantum beats in semiconductor quantum wells", Seventh International Workshop on Nonlinear Optics and Excitation Kinetics in Semiconductors (NOEKS 2003), Karlsruhe, Germany, February 24-28, 2003

6. I. Rumyantsev, R. Binder, R. Takayama, N.H. Kwong, M.J. Stevens, and A.L. Smirl, "Signatures of exciton correlations in the time-resolved vectorial polarization state of four-wave mixing signals from semiconductor quantum wells", QThF4, *Quantum Electronics and Laser Science Conference* (QELS '02), Long Beach, California, May 19-24, 2002

7. R. Takayama, N.H. Kwong, R. Binder, T. Aoki, and M. Kuwata-Gonokami, "Influence of exciton lineshape asymmetries on four wave mixing spectra of semiconductor microcavities", QThG28, *Quantum Electronics and Laser Science Conference* (QELS '02), Long Beach, California, May 19-24, 2002

8. Z.S. Yang, R. Binder, N.H. Kwong, and R. Takayama, "Adiabatic following of incoherent exciton density in semiconductor quantum wells", QThG32, *Quantum Electronics and Laser Science Conference* (QELS '02), Long Beach, California, May 19-24, 2002

9. I. Rumyantsev, R. Binder, R. Takayama, N.H. Kwong, "On the interplay between excitonic and biexcitonic quantum coherences", QFE5, *Quantum Electronics and Laser Science Conference* (QELS '02), Long Beach, California, May 19-24, 2002

10. H.M. Gibbs, G. Khitrova, C. Ell, R. Binder, W. Hoyer, M. Kira, S.W. Koch. T. Meier, and C. Sieh, "Higher-order correlations and semiconductor optical nonlinearities", in *OSA Trends in Optics and Photonics* (TOPS), Vol. 79 (Nonlinear Optics), p. 140, 2002 (INVITED)

11. R. Takayama, N.H. Kwong, I. Rumyantsev, M. Kuwata-Gonokami, and R. Binder, "Excitonic correlations in nonlinear phase shift in semiconductor quantum wells", Quantum Electronics and Laser Science Conference (QELS '01), Baltimore, Maryland, May 6-11, 2001

12. N.H. Kwong, R. Takayama, I. Rumyantsev, M. Kuwata-Gonokami, and R. Binder, "Evidence of nonperturbative exciton-exciton scattering in four-wave mixing signals in quantum well microcavities", Quantum Electronics and Laser Science Conference (QELS '01), Baltimore, Maryland, May 6-11, 2001

13. M. Donovan, A. Schuelzgen, J. Lee, R. Binder, I. Rumyantsev, N.H. Kwong, R. Takayama, Z.S. Yang, and N. Peyghambarian, "Evidence for intervalence band coherences in semiconductors via coherently coupled optical Stark shifts", Quantum Electronics and Laser Science Conference (QELS '01), Baltimore, Maryland, May 6-11, 2001

(d) Papers Presented at Meetings, But Not Published in Conference Proceedings

1. R. Binder "Theory of biexcitonic electromagnetically-induced transparency in semiconductors", 33th Winter Colloquium on the Physics of Quantum Electronics (PQE), Snowbird, Utah, January 6-9, 2003 (INVITED)

2. R. Binder, "Theory of intervalence band coherences in semiconductor quantum wells", 32th Winter Colloquium on the Physics of Quantum Electronics (PQE), Snowbird, Utah, January 7-10, 2002 (INVITED)

3. R. Binder, "Theory of excitonic and biexcitonic optical nonlinearities in semiconductor quantum wells", ERATO Workshop *Cooperative Effects on Photo-Controlled Systems II*, Tokyo, Japan, July 11, 2002 (INVITED)

4. N.H. Kwong, and R. Takayama, and R. Binder, "Excitonic correlation effects in the nonlinear optical response of semiconductor quantum wells", ERATO *Workshop Cooperative Effects on Photo-Controlled Systems II*, Tokyo, Japan, July 11, 2002

Scientific Personnel

Ilya Rumyantsev, Ph.D. May 2003
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Report of Inventions

None

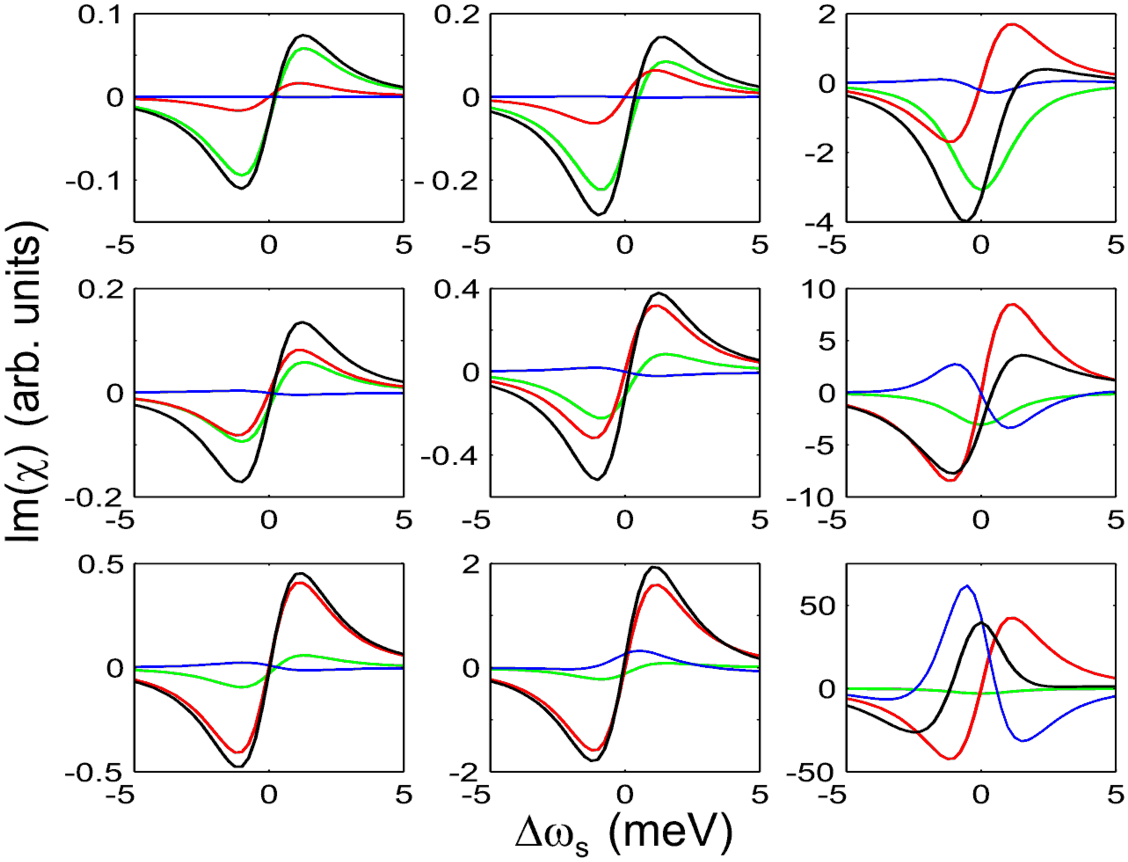

FIG.*1 Calculated imaginary part of the 3rd-order susceptibility as a function of the detuning of the signal pulse from the exciton resonance. The three rows of the plots from the top to bottom correspond to an exiton binding energy of 2.6, 13, and 65 meV, and the three columns from left to right correspond to a control detuning of -20, -10 , and 0 meV. The results shown are for phase-space filling (green), Hartree-Fock (red), two-exciton correlations (blue) only, and the black curves show the total results (i.e. all terms included in the calculation). The calculation was performed at the University of Arizona as part of an investigation of an all-optical polarization switch in collaboration with the University of Iowa.*

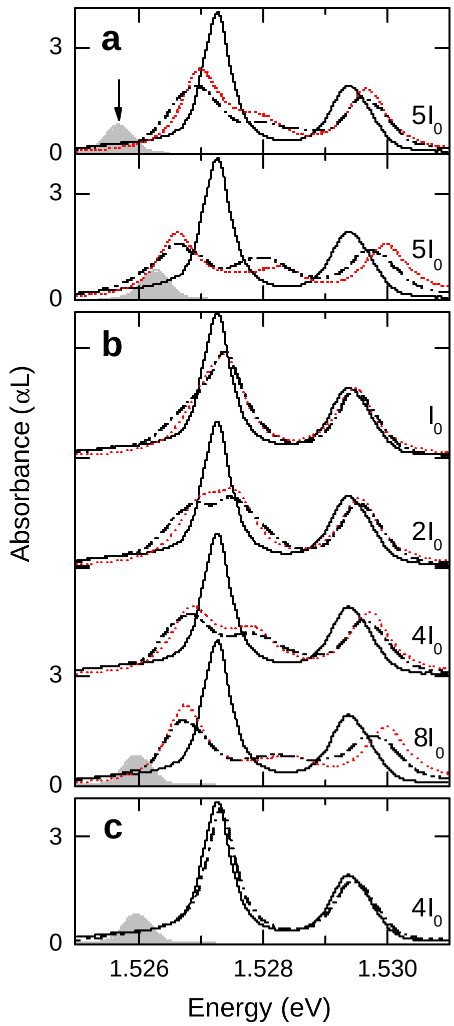

FIG. 2: *Absorption spectra measured with the probe pulse in the absence (solid lines) and presence (dot-dashed lines) of the control pulse, with the probe and control having opposite circular polarization. The shaded area shows the spectrum of the control pulse. The arrow indicates the position of the biexciton resonance. The energy flux of the control pulse is indicated in the figure, with I_0 = 400 nJ/cm^2 (corresponding to a peak intensity of order 100 kW/cm^2). For (a) and (b), the probe pulse arrives 1 ps before the peak of the control pulse. For (c), the probe pulse arrives 10 ps after the peak of the control pulse. Results of the full microscopic many-particle theory are shown as dotted lines. All experimental data were obtained at the University of Oregon, and the theoretical results were obtained at the University of Arizona.*