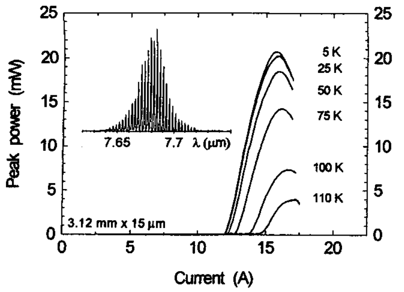
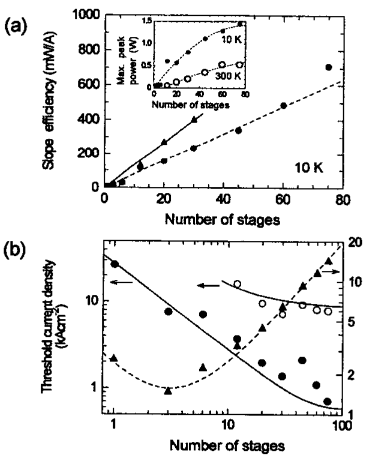


JMA5 Fig. 2. Light output-current characteristics at various heat sink temperatures of a deep etched ridge waveguide laser (3.12 mm long, 15 μm wide) driven in pulsed mode with 50 ns pulse width and 5.0 kHz repetition rate. The light is collected with approximately 60% efficiency from one facet using f/0.8 optics and is focused onto a gated, fast room temperature HgCdTe detector. *Inset*: Emission spectrum of the device at 10 K.

7-mW/A has been obtained. The inset in Figure 2 shows the characteristic mode spectrum (center wavelength ≈ 7.7-μm) of a pulsed laser with Fabry-Perot resonator.

Furthermore, as partly presented in Figure 3, we studied the QC-laser behavior as a function of the number N of stacked active regions (for the design see Figure 1 and reference 2), both experimentally (for $N = 1, 3, 6, 12, 20, 30, 45, 60,$ and 75) and theoretically. We determine the optimum value of N in various aspects: the highest optical power and lowest threshold current density are obtained for laser devices with N as high as possible. QC-lasers with 75 stages showed pulsed peak powers of 1.4-W, 1.1-W and 0.54-W at 50-K, 200-K, and room temperature, respectively. The lowest threshold voltage (1.5-V) and the lowest dissipated power at laser threshold (6.3-kW cm^{-2}) are achieved at values of $N = 3$ and 22, respectively.



JMA5 Fig. 3. (a) *Main graph*: measured slope efficiency per facet as a function of the number of stages N; the triangles correspond to data obtained in continuous mode (cw), the circles to pulsed data. The lines are the best fit to the data. The discrepancy between the two lines is due to the different collection efficiencies of the two measurements: ~100% for cw, and ~60% for pulsed. The data have been obtained at cryogenic temperatures. *Inset*: Maximum peak power as a function of N measured for all lasers in pulsed mode at 10 K and 300 K heat sink temperature (symbols). The dashed lines are drawn as a guide to the eyes. (b) Threshold current density as a function of N measured in pulsed mode at cryogenic temperatures (solid circles) and at room temperature (open circles). The solid lines are the calculated functions for $J_{th}(N)$ at the two temperatures. The solid triangles indicate the measured voltage at laser threshold as a function of N. The dashed line indicates our model calculations based on the cascading scheme.

This material is based upon work supported in part by DARPA/US Army Research Office under Contract No. DAAH04-96-C-0026 and DAAG55-98-C-0050.

1. F. Capasso, J. Faist, C. Sirtori, and A.Y. Cho, Solid State Commun. **102,** 231 (1997).
2. C. Gmachl, A. Tredicucci, F. Capasso, A.L. Hutchinson, D.L. Sivco, J.N. Baillargeon, and A.Y. Cho, Appl. Phys. Lett. **72,** 3130 (1998).
3. J. Faist, A. Tredicucci, F. Capasso, C. Sirtori, D.L. Sivco, J.N. Baillargeon, A.L. Hutchinson, and A.Y. Cho, "High-Power Continuous-Wave Quantum Cascade Laser," IEEE J. Quantum Electron. **34,** pp. 336–343, 1998.

QMA 8:00 am–10:00 am
Rooms 337/338

Quantum Logic and Decoherence

Christopher Monroe, *NIST, USA, Presider*

QMA1 (Invited) 8:00 am

Quantum computing with trapped ions

C. Monroe, W.M. Itano, D. Kielpinski, B.E. King, C.J. Myatt, C.A. Sackett, Q.A. Turchette, D.J. Wineland, *National Institute of Standards and Technology, Boulder, Colorado 80303 USA; E-mail: monroe@nist.gov*

Currently, the most promising physical system for the realization of a quantum computer is a collection of trapped atomic ions. Here, internal electronic states of the ions act as quantum bits, and with the use of quantum logic operations they are coupled through their collective motion in the trap.[1] At NIST, following the demonstration of rudimentary quantum logic gates[2] and related experiments[3] with a single trapped ion, we have begun experiments with up to three ions. We have laser-cooled all modes of two ions[4] and select modes of three ions to the ground state, thereby paving the way for subsequent quantum logic operations. We have also used quantum logic on two ions to engineer the Bell entangled states,[5] representing the first source of entanglement not relying on a selection process. This type of deterministic entanglement is a crucial requirement for large-scale quantum computation. We continue to investigate the several technical problems with the ion trap quantum computer such as the decoherence of collective motion as well as issues dealing with the scale-up to larger numbers of ions. Supported by the U.S. National Security Agency, Office of Naval Research, and Army Research Office.

1. J.I. Cirac and P. Zoller, Phys. Rev. Lett. **74,** 4091 (1995).
2. C. Monroe, D.M. Meekhof, B.E. King, W.M. Itano, and D.J. Wineland, Phys. Rev. Lett. **75,** 4714 (1995).
3. C. Monroe, D.M. Meekhof, B.E. King, and D.J. Wineland, Science **272,** 1131 (1996).
4. B.E. King, C.S. Wood, C.J. Myatt, Q.A. Turchette, D. Leibfried, W.M. Itano, C. Monroe, and D.J. Wineland, Phys. Rev. Lett. **81,** 1525 (1998).
5. Q.A. Turchette, C.S. Wood, B.E. King, C. J. Myatt, D. Leibfried, W. M. Itano, C. Monroe, and D. J. Wineland, Phys. Rev. Lett. **81,** 3631 (1998).

QMA2 (Invited) 8:30 am

Experimental study of noise and dissipation effects on dynamical localization

M.G. Raizen, B.G. Klappauf, W.H. Oskay, D.A. Steck, V. Milner, *Department of Physics, The University of Texas at Austin, Austin, Texas 78712-1081 USA; E-mail: raizen@physics.utexas.edu*

The interface between nonlinear dynamics and quantum mechanics leads to qualitatively new physical phenomena, and has been the subject of much work in recent years. One of the key predictions in this area is the phenomenon of dynamical localization, a quantum suppression of diffusion in a classically chaotic regime. Previous work in our group centered on the study of dynamical localization, using cold atoms in a time-dependent standing wave of light, and established atom optics as a new testing ground for this field.[1,2]

To go beyond the first generation of experiments, we have begun a new set of experiments designed to address the important issue of quantum decoherence in the context of quantum chaos.[3] Dynamical localization, as a quantum interference effect, should be susceptible to noise or dissipation. Noise and dissipation are thought to play an important role in recovering the classical limit.

Cesium atoms are first trapped and cooled in a magnetic-optical trap (MOT). After this stage, the trapping fields are turned off and the atoms are exposed to a standing wave from a Ti:sapphire laser that is tuned far from the cesium resonance. The standing wave is applied in a series of pulses with a period of 20 μs and pulse widths of ~300 ns. We observe dynamical localization, reproducing the earlier results found in sodium. We introduce amplitude noise in this system by adding a random component to the intensity of the individual kicks. Dissipation is introduced by increasing the probability of a spontaneous scattering event between the pulses. The signature in both cases is a growth in energy with qualitatively similar but not exponential momentum distributions. We plan to extend this work to study the effects of phase noise and dimensionality on dynamical localization.

1. F.L. Moore, J.C. Robinson, C.F. Bharucha, P.E. Williams, and M.G. Raizen, Phys. Rev. Lett. **73,** 2974 (1994).
2. F.L. Moore, J.C. Robinson, C.F. Bharucha, Bala Sundaram, and M.G. Raizen, Phys. Rev. Lett. **75,** 4598 (1995).
3. B.G. Klappauf, D.A. Steck, W.H. Oskay, and M.G. Raizen, Phys. Rev. Lett. **81,** 1203 (1998).

QMA3 9:00 am

Non-perturbative electromagnetically induced transparency and conditional quantum logic

M.J. Werner, A. Imamoğlu, *Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106 USA*

We investigate EIT in the non-perturbative regime as a way to achieve maximal photon-photon interactions. In this new regime we discuss single versus multi-atom systems and conditional quantum logic operations.

Recently a proposal for two-photon absorption limited π phase-shifts at the few photon level was presented.[1] Its novelty lies in its ability to realize some of the fundamental models used in quantum optics over the last decade. At the heart of the idea is a suppression of one-photon absorption via quantum interference using a technique known as Electromagnetically-Induced Transparency. The first experimental implementation showed a dramatic increase in the nonlinear refractive index of more than 6 orders of magnitude using recent developments in Bose-Einstein condensation of Sodium to achieve high densities and long coherence times.[3]

The original work was done in the context of a atomic gas containing a large number of atoms.[2] At the one or two photon level discussed for photon-blockade we can better appreciate the limitations of not having a single atom by looking at the exact energy eignenstates of the coupled multi-atom+cavity system. Then we can see that there is a qualitative change in the energy spectrum when comparing one and two (or more) atom cases. This can be expected from the simple idea that if you excite the dark state of the lambda system in both atoms then no nonlinear phase-shift or photon-blockade can result from two photons. This manifests itself as two energy eigenstates degenerate in the absence of a 4th upper level at twice the cavity frequency whose splitting decreases with the number of atoms. On the other hand, for one atom, injection of two photons necessarily leads the system into a nonlinear regime.

Conditional quantum logic using single photons at two frequencies under various conditions will be discussed using two cascaded lambda systems (double-EIT) or non-perturbative 4 level system with transparency conditions satisfied at one frequency. Finally, conditional phase shifts using EIT are compared with those discussed earlier using Jaynes-Cummings interactions.[4]

1. A. Imamoğlu, H. Schmidt, G. Woods, and M. Deutsch, "Strongly Interacting Photons in a Nonlinear cavity," Phys. Rev. Lett. **79,** 1467–1470 (1997).
2. H. Schmidt and A. Imamoğlu, "Giant Kerr nonlinearities obtained by electromagnetically induced transparency," Opt. Lett. **21,** 1936 (1996).
3. L. Hau, S.E. Harris, Z. Dutton and C. H. Behroozi, "Light Speed reduction to 17 meters per second in an ultracold atomic gas," (unpublished).
4. Q.A. Turchette, C.J. Hood, W. Lange, H. Mabuchi and H.J. Kimble, "Measurement of Conditional Phase Shifts for Quantum Logic," Phys. Rev. Lett. **75,** 4710 (1995).

QMA4 9:15 am

Quantum logic gates using photon exchange interactions

T.B. Pittman, J.D. Franson, *Applied Physics Laboratory, The Johns Hopkins University, Laurel, Maryland 20723 USA*

Nonlinear interactions between two photons are normally very weak because of the weak electric field associated with a single photon. We recently suggested[1,2] that this difficulty could be avoided by relying on exchange interactions, which can have large effects even when there is no physical interaction at all between two particles.

We consider two photons in well-collimated beams that are incident upon an atomic vapor cell. The probability of there being two excited atoms in the medium is shown to be a factor of two larger in that case than if the two photons were incident upon two separate but otherwise identical media. This factor of two is due to quantum interference between two probability amplitudes: (a) photon 1 may have excited atom A while photon 2 excited atom B, or (b) photon 1 may have excited atom B while photon 2 excited atom A, where A and B are any two atoms in the vapor cell. Under the appropriate conditions, constructive interference between these two processes gives a factor of two enhancement that is closely analogous to the factor of two that occurs in photon bunching. A short laser pulse is then used to produce a phase shift in the excited states of the atoms. Since the population of excited states is different when the two photons propagate together through the same medium, this gives a nonlinear phase shift in that case.

Recent theoretical analysis has been concerned with the design of laser pulse sequences that can produce a nonlinear phase shift of π radians with little or no loss or decoherence. An optimal five-pulse sequence of that kind will be described.

In an on-going experiment of this kind, two single photons in the form of short (5 ns) wave packets are incident on a sodium vapor cell. The phase of any excited atoms in the vapor cell is shifted using an 8 ps laser pulse, which is expected to produce nonlinear phase shifts when both photons are in the medium at the same time, as described above. The status of this experiment and future plans will be discussed.

1. J.D. Franson, Phys. Rev. Lett. **78,** 3852 (1997).
2. J.D. Franson and T.B. Pittman, submitted to Nature.

QMA5 9:30 am

Fast quantum search using coherent electronic states of Rydberg atoms

J. Ahn, T.C. Weinacht, P.H. Bucksbaum, *Physics Department, University of Michigan, Ann Arbor, Michigan 48109-1120 USA; E-mail: jwahn@umich.edu*

We demonstrate the use of an N-state Rydberg system to mimic an N-qubit quantum register, and apply this system to solve the database search problem proposed by Grover in a single unitary operation.

When an N-qubit quantum register is prepared with one bit out of phase (i.e. flipped) from all the others, how many operations does it take to find the flipped qubit? This is the problem posed by Grover.[1] Methods employing quantum parallelism permit faster searching of the flipped state than the classically allowed average of $N/2$ steps. Grover's algorithm, for example, takes only order $\sqrt{N}$ steps. Grover's search algorithm performs an "inversion about the average" operation defined by the following unitary operation on the N-element register ket state: D: $D_{ij} = 2/N$ if $i \neq j$; $D_{ii} = -1 + 2/N$. This operation amplifies the flipped qubit and attenuates the others.

Grover's model of a quantum register is a collection of N 2-level qubits. Here we show that one can recast this problem using N levels of a single quantum system. This reformulation destroys the 2^N scaling of the problem, but there is a significant payoff in parallelism: the search algorithm now takes only a single quantum operation.

We employ an optically driven unitary transformation on a coherent electronic state in atomic Cesium. The quantum register is a coherent superposition of Rydberg eigenstates prepared from a pure eigenstate (the "reservoir" state) with a programmable broadband coherent laser pulse.[2] This unitary transformation, which acts on the subspace consisting of the N Rydberg levels coupled to the reservoir, can be represented by a matrix P: $P_{0i} = -P_{i0} = a_i e^{i\varphi_i}$; $P_{ii} = 1$, and other $P_{ij} = 0$. In this experiment the reservoir state is $7s$. The Rydberg levels all have equal amplitudes, and they are prepared in such a way that at some target time they all have the same relative phase, except for the one whose phase is flipped. This represents the flipped qubit in the data base search problem. In this case we have:

$$P\psi = \begin{pmatrix} 1 & \varepsilon & -\varepsilon & \cdot & -\varepsilon \\ -\varepsilon & 1 & 0 & \cdot & 0 \\ \varepsilon & 0 & 1 & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \varepsilon & 0 & 0 & \cdot & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ \cdot \\ 0 \end{pmatrix}$$

$$= \begin{pmatrix} 1 \\ -\varepsilon \\ \varepsilon \\ \cdot \\ \varepsilon \end{pmatrix} \begin{array}{c} 7s \\ (n+1)p \\ (n+2)p \\ \cdot \\ (n+N)p \end{array}$$

Note that at this point the populations of each of the states in the N-state register are equal. At