CV – Philip Hemmer – October 2010

Title/Address:

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Technical Areas of Expertise:

Solid materials for quantum optics, Sub-wavelength imaging, Single molecule imaging, Ultra-sensitive room temperature solid-state magnetometers, Nano-fabrication of surface plasmon structures. Quantum computing and storage in solid materials, Quantum communication and teleportation in with solid materials, Sensitive chemical/biological agent and IED detection using quantum coherence, Ultraslow and stopped light in solids, Materials and techniques for resonant nonlinear optics, Phase-conjugate-based turbulence aberration compensation, Spectral holeburning materials and techniques for ultra-dense memories and high temperature operation, Holographic optical memory materials, Smart pixels devices, Optical correlators, Photorefractive applications, Atomic clocks, Laser trapping and cooling.

Education:

Ph.D. in Physics, 1984, MIT; B.S. in Physics, 1976, University of Dayton

Previous Experience:

2004-present	Professor, Texas A&M University
2002-2004:	Associate Professor, Texas A&M University
1983-2001:	Physicist/Senior Physicist, Air Force Research Laboratory
1980-1983:	Research Assistant, MIT
1977-1980:	National Science Foundation Fellowship
1976-1977:	Teaching Assistant, University of Dayton

Brief Statement of Work History:

I have primarily concentrated on adapting the latest concepts in the forefront of optics to solving difficult problems of commercial and military importance. Past and current work includes:

1) Sub-wavelength electron spin resonance (ESR) imaging of single molecules,
2) Ultra-sensitive room temperature solid state magnetometers,
3) Ultrasound optical tomography with persistent spectral hole burning materials
4) The use of optically excited spins in room temperature solids to demonstrate quantum processor nodes,
5) Plasmon nano-optics for few molecule chemical sensors and quantum information,
6) Quantum storage using stopped light in solids,
7) Room-temperature slow-light in solid-state materials for optical buffers and delay lines,
8) Holographic beam combiners for high power lasers,
9) Low-threshold nonlinear optics applied to optical processing and turbulence aberration correction,
10) Materials and techniques for high-temperature spectral holeburning memories,
11) Polymer-based holographic optical memory materials for automatic target recognition,
12) Design of quantum well structures for novel infrared photon detectors,
13) Uses of smart-pixel devices for optoelectronic image processing and aberration correction,
14) Investigation of laser cooled and trapped atoms,
15) Development of more compact atomic clocks using optical Raman excitation.

Awards:

National Science Foundation Fellowship
Summa Cum Laude, University of Dayton
Air Force Research Laboratory Chief Scientist's Award
AFOSR Star Team Award (3 times)
Ruth and William Neely '52 Dow Chemical Fellowship
TEES Fellow 2007

Highlights from Research Career:

- Demonstrated sub-wavelength imaging of single molecules with optically detected electron spin resonance (ODESR).
- Demonstrated along with Univ of Stuttgart collaborators the use of diamond magnetometer to map out fields of nano-magnets.
- Demonstrated deep tissue imaging in a phantom using ultrasound optical tomography with persistent spectral hole burning materials.
- Proposed and theoretically analyzed, along with Texas A&M collaborators, a technique to perform quantum lithography and sub-Rayleigh imaging with classical laser light.
- Demonstrated, along with Harvard collaborators, all the elements for a quantum repeater node including local few-qubit processing. Significantly, this was done at room temperature in a solid.
- Demonstrated along with Univ of Stuttgart collaborators, multi qubit quantum operations at room temperature in diamond.
- Initiated novel plasmon nano-wire research and demonstrated, along with Harvard collaborators, enhanced emission of quantum dots into metallic optical nanowires at room temperature.
- Demonstrated ultra-slow and stopped light in a solid. This work has been referenced in a number of news articles including New Scientist, Science News, Business week, Science magazine, Wired magazine, Nature science update, Physics news update, Optics.org news update.
- Developed novel, experimentally realizable techniques for performing quantum logic using optical dark resonances to manipulate spins in solids. This led to a successful multi-million dollar research effort to experimentally demonstrate these techniques. Ultimately the research done on this contract contributed in a large part to the current popularity of diamond-based quantum computing.
- Co-developed a novel model for quantum computing in solid materials wherein spin-based qubits can be optically coupled using spectrally selective dark resonance techniques.
- Demonstrated that it is possible to excite dark resonances in solid materials with enough efficiency to useful for many applications.
- Discovered an improved dark resonance technique, based on the double-Lambda system that is applicable to a much larger class of materials than standard electromagnetically induced transparency. Also performed preliminary studies to investigate potential applications such as sub-shot-noise imaging. Later this experiment was repeated by Harvard researchers using better equipment and the quantum noise correlation potential was demonstrated and published in Science.
- Developed the idea and experimentally demonstrated the potential for using Raman excited spin coherences to increase the operating temperature of ultra high capacity optical memories based on spectral hole burning materials.
- Identified and experimentally demonstrated a novel class of materials, based on dark resonances, that enable nonlinear optical applications such as phase conjugation at unusually low laser intensities, without sacrificing speed or efficiency.
- Developed and performed proof-of-principle studies of novel dark resonance techniques that have applications to infrared detection and switching in semiconductor materials. Based on the experimental portion of this work, a former post-doc received a multi-million dollar grant from the Korean government to develop novel devices using dark resonances in semiconductor materials.
- Co-developed a novel theory of sub-recoil laser cooling that was later demonstrated in three dimensions by the group of Claude Cohen-Tannoudji. Our paper is referenced in this work, which in turn was cited by the Nobel Prize committee in awarding the prize to Prof. Cohen-Tannoudji.
- Experimentally demonstrated novel techniques for image multiplexing/demultiplexing at up to GHz modulation frequencies using nonlinear optics. This technique has also recently found application to ultrasound modulated optical tomography.
- Identified and experimentally demonstrated a novel opto-electronic feedback technique for suppressing the nonlinear response of imaging arrays and constructing array-scale optical logic elements.
- Experimentally observed self-organized grating formation and backward-directed gain in atomic vapors and beams. This has potential application to X-ray generation by relativistic particle beams, and to remote detection of airborne chemical contaminants present in low concentrations.
- Experimentally observed (and co-predicted) optical force rectification in a Λ-system.

- Experimentally demonstrated novel approaches for developing improved atomic clocks and magnetometers using coherent population trapping in atomic beams and vapors.

Descriptions of Current and Selected Past Research Areas

Novel imaging schemes for sub-Rayleigh and sub-wavelength imaging
In recent years there has been much interest in imaging below the limit impose by the Rayleigh criteria in conventional optics. Much of this work has been in the context of biological systems where the goal is to image sub-optical wavelength structures in living cells. A number of nonlinear techniques have been developed including saturated absorption or gain near optical nodes (STED) or selective photo activation of dye molecules (PALM). In addition some coherent optical techniques like Raman Stark shift imaging have been proposed and demonstrated in non-bio-compatible systems. Although these systems appear very different on the surface, it is possible to view them all in a generalized framework and similar mathematical expressions can be found to describe the ultimate resolution enhancement capabilities or each. Even techniques that are considered independent of the wavelength, like magnetic resonance imaging, can also be view in the same generalized model and again similar equations describe the ultimate resolution. In this area I am investigating several alternatives to existing sub-wavelength imaging techniques that have the potential to reach better resolution. These include techniques that involve microwave spin transitions in atoms or molecules, as well as optical Raman transitions that induce spin flips. The advantage of spin systems is that the coherence time can be long at room temperature and this improves the ultimate resolution enhancement that is possible in vivo.

Ultra-sensitive magnetometry using nitrogen-vacancy (NV) diamond
With collaborators at Harvard and Univ of Stuttgart I have been studying the prospects of developing ultra-sensitive magnetometers based on NV diamond. With NV diamond, the potential exists to make magnetometers that are even more sensitive than the best existing magnetometers (namely atomic vapors) yet operate at room temperature in ambient environment. In addition, by using single NV centers as a magnetometer, nano-scale magnetic measurements can be made with unprecedented resolution, even at room temperature. This opens the door to a new class of sub-wavelength cellular imaging techniques. By using ensembles of NV centers it may also be possible to image ultra-small magnetic gradients such as those needed for military magnetic imaging sensors, non-perturbing current measurements on micro-electronics chips, or imaging the action potential of single neurons.

Indestructible fluorescent markers for sub-wavelength cellular probing
I have a new project to investigate whether or not diamond nanocrystals can be made as small as 1 – 2 nm is size while still having stable nitrogen-vacancy (NV) optical emitters. This will address two key problems in the field of fluorescent markers for biological imaging applications. The first problem is that the dyes commonly used for this purpose bleach out after a minute or less and so cannot be used for any long term tracking of biological processes on the single molecule level. Quantum dots solve the bleaching problem, but are inherently too large, >5nm, to enter the cell without being detected and isolated by the cellular immune system. The key point is that the nitrogen vacancy center is inherently sub-nanometer in size so that it may be possible to reduce the diamond nanocrystal host to a size near 1 nm which is below the threshold needed to enter the cell unnoticed.

Nanotechnology and nanoscale optics
A new age in optics is dawning. Up until now, optical materials and devices have mostly concentrated on modifying the wave properties of light, such as the propagation direction and speed via modifications of refractive index or absorption. Even photon band-gap materials rely heavily of the wave properties of light. But recently, novel plasmon-based materials with feature sizes in the range of 1-50 nm have begun to emerge. In these materials, for the first time, the electric field of light can directly interact with the material in ways reminiscent of microwave electronics. For example, the action of light on certain plasmon-based nanomaterials can be characterized in terms of capacitance and inductance, rather than the refractive index or absorption coefficient. In this area I am investigating the use of state-of-the-art electron beam lithography to reproducibly fabricate plasmon nano optics. I have also recently begun investigating the use

of atomic force microscope probes as an even higher resolution fabrication tool for nano-optics. So far, we have shown that optical wires can efficiently collect the fluorescence of a single quantum dot. In the future nano-scale plasmon structures with stronger field enhancement will be explored. For example, fractal-enhanced optical resonant cavities have shown unprecedented Q-values. These cavities combine a high Q conventional optical cavity with a high Q plasmon mode of a fractal-like metallic structure. Similar fractal-enhanced cavities have already demonstrated the potential to be ultra-sensitive chemical/biological detectors, but have so far only been fabricated using inherently non-reproducible techniques

Quantum imaging and lithography with classical light

There have been recent proposals to extend the resolution limit of optical lithography by up to an order of magnitude by using multi-photon quantum interference involving entangled Fock states of photons. With collaborators, I have shown that this same limit can be achieved with classical light if one has a coherent, number resolving photon detector. The particular detector we have been studying is the Doppleron since it is present in every two level atom, and can be easily generalize to Raman systems for improved performance for optical transitions at room temperature. Since this approach is very general, it also works on microwave transitions, where it opens new possibilities for quantum optical detection and sub-Rayleigh imaging in this frequency range. Recently I have shown that it is possible to use a Doppleron transition to resolve two point sources separated by much less than the optical wavelength. Significantly, the point sources are classical objects and are illuminated by classical light. Only the final detector has quantum optical properties. This opens the door to sub-wavelength imaging in living cells without any fluorescent tags. This is the “holy grail” of biological sub-wavelength imaging because it can be applied to any bio-system without the perturbing effects of fluorescent tags.

Ultrasound modulated optical tomography (UOT) with spectral hole burning (SHB) materials

With a collaborator at Washington Univ in St Louis I have been exploring the use of SHB materials to provide high contrast ultrasound images of living tissue, even for deep tissue imaging. The problem with direct imaging in tissue samples thicker than a few millimeters is that light is multiply scattered to such an extent that all spatial resolution is lost. On the other hand, ultrasound can maintain a high resolution for deep tissue imaging but has poor imaging contrast due to low tissue discrimination capability. By combining ultrasound imaging with optical detection, it is possible to keep the best advantages of both techniques, namely the resolution of ultrasound and the tissue discrimination of optics. However, due to the extreme scattering properties of living tissue, the frequency shift of the incident light caused by the focused ultrasound is only a small amount of the total scattered light. This necessitates powerful filtering techniques to remove the non-frequency shifted background light. While many optical techniques exist to selectively filter out particular optical frequencies, essentially none of them work well with the broad-area, wide angle scattered light found in UOT imaging. One exception to this is real time holography using for example, photorefractive crystals. However, even these do not perform well enough for clinical applications where a signal to background ratio in excess of 69 dB is expected. Therefore we have been exploring SHB crystals for this application. In these materials up to 70 dB of frequency selection has been seen, but more importantly there is no solid-angle or area (up to centimeters) limitation. Preliminary results with persistent a spectral hole burning (PSHB) material Pr doped YSO has shown that images can be made deep inside tissue phantoms up to 9 cm so far. More importantly projections based on straigntforward improvements to the setup, including using a PSHB material with an active wavelength in the near infrared (like Tm:YAG), show that single shot video rate UOT should be possible in real tissue thicker than 15 cm. This is deep enough for clinical applications.

Room temperature few-qubit solid state quantum computers in diamond

The nitrogen-vacancy (NV) color center in diamond can be optically spin polarized and the spin state can be detected at room temperature. Coherence times of the spin are also long, fractional milliseconds for the NV electron spin and fractional seconds for 13C nuclei near NV centers. By using the interaction of the NV spin with proximal 13C atoms, it is possible to entangle the electron and nuclear spins or to use the nuclear spins as a storage register for a quantum state that has been loaded into the electron spin. The nuclear spin storage is robust to multiple read/write cycles of the electron spin. Multiple 13C in the NV frozen core can be entangled so that a few-qubit quantum computer can be constructed.

Solid state quantum computers based on VLSI techniques in diamond

Now that it has been experimentally proven that quantum weirdness can be used for provably secure communications, and possibly ultra-high performance computing, the goal is to build the first prototype of a scalable quantum computer. To this end, I am organizing a major research effort to develop a quantum computer using VLSI fabrication techniques. The basic design consists of implanting single nitrogen-vacancy (NV) centers into a diamond wafer at well-defined locations with a precision of 10's of nanometers. An electrode above each NV center will be used to tune it into resonance with an optical laser beam that will be used to perform one and two qubit operations. Since the basic design involves qubit coupling that can be switched on and off at will and makes use of already-demonstrated VLSI fabrication techniques, the design is highly scalable. To achieve the necessary precision for quantum error correction to be effective, optical Raman transitions will be used to manipulate the qubits. This allows GHz-rate gate operations since an allowed optical transition is used, yet it does not perturb the long spin coherence time. This spin lifetime has already been observed to approach 1 msec, even at room temperature, with the promise of even longer times as better diamond substrates are becoming available. This translates to more than 10^6 quantum operations per coherence time, where a minimum of 10^4 is needed to apply quantum error correction. Therefore, this is a very promising system, and is unique in that it may even eventually work at room temperature.

Ultra-sensitive chemical and biological detection:

Background: There is an urgent need to be able to detect and identify chemical and/or biological agents that are present in very low concentrations. Currently, one of the best techniques for accomplishing this is surface enhanced Raman spectroscopy, because it has demonstrated the capability for single molecule detection, at least at low temperature. Recently it was shown that fractal-like structures composed of nanometer sized metal balls, deposited on the surface of a high Q optical cavity, can give orders of magnitude higher field concentration, and therefore much greater sensitivity. The data shows that sensitivities close to single molecule levels have been achieved at room temperature. Unfortunately, the fabrication process is not reproducible, as it requires nanometer-sized metal balls to randomly organize into the optimal pattern. My approach to solving this problem is to use nano-lithography to fabricate these metallic patterns. Not only does this give the needed reproducibility, but will also allow feedback between experiment and theory, as required to maximize performance and manufacturability. A second approach is in collaboration with Scully in Physics, and has major DARPA funding. Here, optical Raman dark resonances are used to create maximal coherence on the vibrational state of a molecule. If done properly, the optical Raman signal can be made larger than the spontaneous emission signal. Since the spontaneous emission is routinely used by biologists to track single molecules in living cells, this implies that single molecule optical Raman may be possible. The advantage over ordinary fluorescence is that the Raman spectrum is high resolution and gives valuable chemical and environmental information. Clearly, this would make a superior biological sensor, especially in conjunction with the plasmon structures described above.

Applications: Aside from chemical and biological detection, the ability to couple strongly to a single atom or molecule has applications to single photon sources for quantum cryptography.

Solid state materials for quantum computing:

Background: There has been much recent interest in the possibility of developing a solid state quantum computer using spins on dopant ions in semiconductors. In these systems the problems of efficient excitation, decoherence, and especially readout are much more challenging than trapped atoms or other potentially scalable systems. The excitation and control of spin coherences by Raman dark resonance techniques provides a natural solution to many of these problems. To this end, I have been exploring the use of optical Raman dark resonances to manipulate electron and nuclear spins in nitrogen-vacancy (NV) diamond color centers. Recently, I have been transitioning this work to single NV centers where I have demonstrated coupling between a NV and a nearby substitutional nitrogen.

Applications: The most commonly quoted applications of quantum computing are the factoring of large numbers and sorting of lists. However, in the short term, the major applications are to secure communication, and optimization problems that have no classical solution. By making regular arrays of qubits, such as in NV diamond or quantum dot arrays, it should also be possible to perform implement a variety of algorithms, with both short and long-term interest. For example, one of my projects seeks to implement quantum lattice gas simulations, of the type used to model high Reynolds number fluid flow, on a quantum computer. This is important since a large percentage of the world's current supercomputing power is devoted to fluid flow simulations, so that there is an economic incentive to explore quantum-computing alternatives.

Quantum storage with “stopped” light in solids:
Background: Most proposed quantum computers will require high-fidelity quantum storage to operate. However, very little effort has been expended to identify adequate storage techniques. The few that have been proposed are difficult to implement and will therefore be unlikely to provide high-fidelity in the near future. An exception to this rule is the recently demonstrated “stopped” light storage technique. Previous demonstrations of ultra-slow and stopped light were performed in ultra-cold and warm atomic vapors. While these materials demonstrate the principle, they do not have the inherent scalability of solid state systems. To address this problem, I have succeeded in producing ultra-slow and stopped light in a crystal of Pr doped Y_2SiO_5, which is commonly used for spectral hole burning (SHB) memories. The observed performance is similar to that of the atomic vapor. Now I am developing the techniques to manipulate the light group velocity of individual photons. The goal is to develop a robust quantum storage device that can be used to develop near-term quantum communication and computing systems.

Applications: The primary application is to quantum storage, which is essential for most quantum computing and communication schemes.

Room temperature slow-light in solids:
Background: Slow and stopped light has the promise to provide tunable optical delays for applications such as radar beam steering and optical buffer memories for all-optical routing. In radar systems, tunable delay lines are needed to suppress “squint” which can severely limit the ability to discriminate between signal and jamming sources. In high-speed fiber communication systems, the need to convert the optical signal into an electronic signal and then back into an optical signal, in order to accomplish routing, is a major speed-limiting bottleneck. To solve this problem, all optical routers are needed. Promising approaches exist for most router elements, with the exception of buffer memories. Slow light can potentially solve this problem by providing a real-time adjustable propagation delay. For both of these applications, slow light must be implemented in a room temperature solid state system. So far, a few techniques have been demonstrated, including my own approach, which involves two-beam coupling in photorefractive crystals. However, until now, all room temperature materials have suffered from a poor time-bandwidth product (TBP), on the order of one, whereas most applications require TBP of 100 to 1000 or more. To solve this problem, I demonstrated that an artificial inhomogeneous broadening, for example Bragg matched gratings, has the potential to solve this critical problem.

Applications: The primary applications are to optical buffer memories for all-optical routers and to true-time delay lines for radar beam steering.

Novel materials for the implementation of dark resonance techniques:
Background: Recently, there has been considerable interest in the use of “dark resonances” in optically dense material for applications such as nonlinear frequency conversion, lasers without inversion, refractive index enhancement, electromagnetically induced transparency, and ultra-slow group velocities. However, as with many other areas of optics and physics, the potential applications of dark resonances has so far been limited by the lack of suitable materials. To gain widespread applicability, it is important to extend dark resonance techniques to solids. To this end, I started working with doped crystals such as Pr doped Y_2SiO_5. This proved to be very successful as the first solid material to exhibit dark resonances with enough contrast to be suitable for applications. I have also demonstrated the effect in NV diamond, and am currently looking at doped semiconductors.

Applications: Specific applications for the short-term research are already being investigated and will be detailed below. For the long-term research the potential payoff for is large, especially in the areas of nano-scale semiconductors and medicine/biology as mentioned above.

Novel classes of materials for low power nonlinear optics:
Background: Nonlinear optics, especially optical phase conjugation, has numerous applications ranging from optical correlation and aberration correction to spatially broadband squeezed light generation. For many of these applications it is important to have a nonlinear material that is both fast and efficient at low optical pump intensities. Resonant systems are a natural choice because of the large resonant enhancement of their nonlinearities. However, the competing effects of resonant absorption and nonlinear refraction have so far limited how much resonance enhancement can be realized in these systems. To eliminate these problems, Raman "dark resonances" have been exploited. For example, using dark resonances in sodium vapor, a factor of 10 improvement in optical gain was observed at more than 100 times lower pump intensity than in previous work. Moreover, it was shown that large gains on the order of 30 could be achieved with almost no optical aberrations due to self-focussing and beam filamentation. Strong classical noise correlation under high gain conditions has also been observed. Recently, it was shown that this technique give quantum noise correlations, and quantum memory, as well. My prior proof-of-principle experiments showed that the this process can be used to correct optical aberrations caused by a high speed turbulent flow while maintaining high gain and low pump intensities. Extension of this technique to rubidium vapor has been demonstrated. Here it should be possible to use semiconductor lasers to replace the dye lasers needed to excite sodium vapor. Theoretical predictions show that this technique should also work well in solid-state stimulated Brillouin systems.

Applications: Optical phase conjugation, especially in stimulated Brillouin systems has numerous commercial and military applications, for example, aberration correction and beam cleanup is important for master-oscillator-power-amplifier (MOPA) laser sources and infrared-missile-countermeasures (IRCM). Since, these applications are currently limited by the high pump intensity requirement of conventional stimulated Brillouin phase conjugation, dark resonances promise to significantly advance development of such systems.

Materials for ultra-high capacity optical memory:
Background: There is considerable interest in the development of novel materials for ultrahigh-density data storage. Holographic optical materials have shown promise in this area. Among these, polymer-based materials, originally developed in Russia, have shown the best promise so far. However, for demanding applications such as real time target recognition systems, a material with far more storage capacity is needed. A promising class of materials for these more demanding applications is based on optical spectral hole burning (SHB). In SHB materials, a high storage density is achieved by augmenting the spatial degrees freedom with the ability to selectively excite a large number of frequency channels. This material also allows the use of spatial-temporal techniques for all-optical high-speed header recognition and routing. The key requirement is a large ratio of optical inhomogeneous to homogeneous linewidth. Unfortunately, materials exhibiting a large ratio generally require low temperatures, near that of liquid helium, to operate. This is because phonon interactions rapidly broaden the optical homogeneous linewidth. In contrast, spin transitions are much less sensitive to broadening at high temperatures, but the direct r.f. excitation of spin coherences does not give a large storage density because of the large r.f. wavelength. To solve these problems, I have been exploring the use of Raman excited spin echoes. Here, optical Raman excitation is used to create the "dark" ground state coherences in such a way that the information encoded on the optical fields is stored in a spin coherence that in turn is stable at higher temperatures than an optical coherence. In my first experiments, in a rare-earth doped crystal, I demonstrated a significant increase in operating temperature for spectral-hole burning optical memory.

Applications: For the polymer-based holographic materials, spin-off applications may be more important than memory applications. For example, ultra-narrow holographic filters can be used for dense WDM multiplexers/demultiplexers. Similar techniques can be used to fabricate beam combiners to enable fiber amplifiers to be pumped with much higher laser power. For the spectral holeburning materials, the extra degree of freedom provided by spin coherences, in addition to optical coherences, significantly expands capability. For example, in a high-performance spectral holeburning material, if the optical and spin degrees of freedom are independent, it should in principle be possible to independently address each active atom in the crystal.

Novel semiconductor materials for uncooled infrared detectors and single photon switching:
Background: Recently dark resonances have been proposed for use as optical switches that are sensitive at the single photon level. Ideally, such a switch would absorb pairs of photons, but not single photons. Such a device would also work well as an uncooled infrared detector. By arranging for a visible or near infrared probe laser to only be absorbed when a far infrared photon is present, image upconversion can be realized. The advantage over other two-photon upconversion techniques is that the dark resonance process would have a much lower threshold and would not require phase matching.

Applications: Uncooled or much higher operating temperature infrared detectors that are sensitive to single photons will have numerous military and commercial applications. This is because cryogenics are a major source of system cost and complexity that increases rapidly as operating temperature decreases.

Quantum communication:
Background: A project seeks to demonstrate high-fidelity quantum communication over lossy channels. To do this, polarization-entangled photon pairs will be transmitted down optical fibers to distant Rb atoms held in a far off-resonance optical trap. The polarization-entanglement will then be transferred to spin-entanglement in the atoms using polarization selective Raman transitions and high-Q optical cavities. Once it has been verified that both cavities have captured photons from an entangled pair, the quantum information will then be teleported. The Bell-state measurements required for teleportation will be accomplished by first transferring the quantum information to one of the entangled atoms, using previously proposed cavity QED techniques. Raman transitions will then be used to rotate atomic ground-state superpositions so as to project the Bell state amplitudes onto bare atom states. These bare atom amplitudes can then be measured one at a time using cycling transitions. Finally, teleportation is completed by using Raman transitions to modify the state of the receiving atom.

Applications: The primary application is secure communications.

Atomic clocks and magnetometers based on Raman transitions:
Background: Work was done several years ago to determine the feasibility of using optical Raman interactions to interrogate atomic clock transitions. The advantages include eliminating the need for microwave cavities and state selection and detection magnets. This has the potential to significantly reduce the size and weight of atomic clocks, thereby expanding their applications. For example, improved portable clocks have gained renewed interest in the context of GPS receivers. This work included the observation of Ramsey fringes on the clock transition in a sodium atomic beam and a systematic study of potential clock frequency error sources, such as light shifts. Techniques to reduce these errors to acceptable levels were also developed. As a step toward development of a portable clock, it was shown that the clock transition in a cesium beam could be driven with a high signal to noise, using only a single microwave-frequency modulated semiconductor laser.

Applications: This technique will likely be the basis of the atomic clocks to be included in the next generation of portable GPS receivers.

Self organized grating-assisted optical gain:
Background: The ability of a collection of atoms, having only optical interactions, to spontaneously organize grating-like structures was observed. These grating structures were shown to enhance the optical gain experienced by a counter propagating probe wave. Spontaneous cavity-assisted lasing was also observed when these gratings were formed. Potential applications of this effect include the generation of high power X-rays by using the internal degrees of freedom in atoms (or other particles) to enhance the grating-like structures produced in free-electron lasers.

Optoelectronic systems employing feedback:

Background: In electronics, real-time feedback is key element in numerous devices and systems. However, in opto-electronics, it is rarely used, especially in imaging systems. To demonstrate the potential advantages of using optical feedback, experiments were performed using a smart pixel array, consisting of a liquid crystal modulator array, with multiple detectors per pixel, and a lens array. Experiments with positive feedback were used to demonstrate several logic operations on an array scale. Negative feedback was used to suppress nonlinearities, including pixel-to-pixel variations, in the operation of a detector array.

New and Continuing Research Directions

Novel imaging schemes for sub-Rayleigh and sub-wavelength imaging
Quantum imaging and lithography with classical light
Ultra-sensitive magnetometry using nitrogen-vacancy (NV) diamond
Indestructible fluorescent markers for sub-wavelength cellular probing
Nanotechnology and nanoscale optics
Ultrasound modulated optical tomography (UOT) with spectral hole burning (SHB) materials
Room temperature few-qubit solid state quantum computers in diamond

Refereed Journal Publications:

1. “Thickness Effect on K-Alpha-K-Beta Ration of Tin,” RE..Mohler, PR. Hemmer, MJ. Heitbrin, CR. Cothern, **B. Am. Phys. Soc. 18,** 888 (1973).

2. “Computer Fits of Calculated Raman-spectra of N2 to Observed Spectra,” PR Hemmer, PP Yaney, WM Roquemore, **B. Am. Phys. Soc. 22,** 1039-1040 (1977)

3. “Effect of Variations in Instrument Function on Temperature Calculated from Raman-Spectrum on N2,” TH Hemmer, PP Yaney, PR Hemmer, **B. Am. Phys. Soc. 23,** 162-162 (1978)

4. “High-resolution Studies of the AC Stark Effect in an Atomic Beam and the Influence of Atomic Recoil, **J. Opt. Soc. Am 70**, 625-626 (1980)

5. “Influence of Atomic Recoil on Power Broadened Lineshapes in Two-Level Atoms,” P. R. Hemmer, F. Y. Wu, and S. Ezekiel, **Optics Communications, 38,** 105 (1981).

6. “Precision Atomic Beam Studies of Atom-Field Interactions,” P. R. Hemmer, B. W. Peuse, F. Y. Wu, J. E. Thomas, and S. Ezekiel, **Optics Letters, 6,** 531 (1981).

7. “Two Laser Raman Differences Technique Applied to High Precision Spectroscopy,” R. E. Tench, B. W. Peuse, P. R. Hemmer, J. E. Thomas, S. Ezekiel, C. C. Leiby, Jr., R. H. Picard, and C. R. Willis, Third Symposium on Frequency Standards and Metrology, **Journal de Physique, 42,** C8-45 (1981).

8. “Observation of Ramsey Fringes using a Stimulated Resonance Raman Transition in a Sodium Atomic Beam,” J. E. Thomas, P. R. Hemmer, S. Ezekiel, C. C. Leiby, Jr., R. H. Picard, and C. R. Willis, **Physical Review Letters, 48,** 867 (1982).

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14. “Alignment-Insensitive Technique for Wideband Tuning of an Unmodified Semiconductor Laser,” B. E. Bernacki, P. R. Hemmer, S. P. Smith, and S. Ezekiel, **Optics Letters 13,** 725 (1988).

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14. “Scalable Quantum Computing in Diamond,” Philip Hemmer, Jerog Wrachtrup, Fedor Jelezko, Philippe Tamarat, Steven Prawer, Mikhail Lukin. **Photonics West 2007**, San Jose, CA (Jan 2007).
15. “Diamond based quantum registers at room temperature,” P. R. Hemmer and M. D. Lukin, **Frontiers of Nonlinear Physics,** Nizhny Novgorod, Russia (July 2007)
16. “Optical and RF EIT for imaging single NV centers,” Philip Hemmer, Joerg Wrachtrup and Fedor Jelezko, **Photonics West 2008**, San Jose, CA (Jan 2008).
17. “Sub-wavelength imaging with Dopplerons,” Philip Hemmer and Suhail Zubairy, **Photonics West 2008**, San Jose, CA (Jan 2008).
18. “Room-Temperature Solid-State Quantum Processors in Diamond,” Philip Hemmer and Mikhail Lukin, **SPIE Defense & Security Conference**, Orlando, FL (Mar 2008).
19. **“**Quantum optical techniques for sub-wavelength imaging,”**,** Philip Hemmer**, XII International Conference on Quantum Optics and Quantum Information (ICQO'2008)** Vilnius, Lithuania, September 20-23, 2008.
20. **“**Quantum optics for subwavelength imaging,” Philip Hemmer, Changdong Kim, Joerg Wrachtrup and Fedor Jelezko, **Photonics West 2009**, San Jose, CA (Jan 2009).
21. “Tradeoffs of spectral hole burning memories for bio-imaging applications,” Philip Hemmer and Huiliang Zhang, Lihong V. Wang and Youzhi Li, **Photonics West 2009**, San Jose, CA (Jan 2009).
22. “Ultimate limits of subwavelength imaging with NV diamond,” **Quantum Communications and Quantum Imaging VIII,SPIE Photonics & Optics (OPTO 10),** (San Diego, CA, Aug 3-5, 2010)

Invitation-Only Conference/Meeting Presentations:

1. **“**Low Threshold Optical Phase Conjugation using Inversionless Gain in the Double-Lambda System,” P.R. Hemmer, M.S. Shahriar, P. Kumar, J. Donoghue, and M. Cronin-Golomb, **Quantum Coherence and Interference in Fundamental and Applied Physics,** Crested Butte, CO (Aug 1994).
2. **“**Optical Phase Conjugation using Coherent Population Trapping,” P.R. Hemmer, M.S. Shahriar, P. Kumar, D.P. Katz, J. Donoghue, and M. Cronin-Golomb, **25th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 1995).
3. **“**Optical Phase Conjugation in the Double Raman System,” P.R. Hemmer, M.S. Shahriar, P. Kumar, and M. Cronin-Golomb, **7th Rochester Conference on Coherence and Quantum Optics,** Rochester, NY (Jun 1995).
4. “Generation of Squeezed States via Non-Degenerate Four Wave Mixing in an Ideal Λ System,” M. S. Shahriar and P. R. Hemmer, **7th Rochester Conference on Coherence and Quantum Optics,** Rochester, NY (Jun 1995).
5. “Grating Enhanced Gain and Reverse Oscillations in a Sodium Vapor Laser: Evidence for Collective Atomic Recoil Lasing (CARL),” P. R. Hemmer, M. S. Shahriar, D. P. Katz, R. Bonifacio, E. J. D’Angelo, and N. P. Bigelow, **7th Rochester Conference on Coherence and Quantum Optics,** Rochester, NY (Jun 1995).

6. **“**Optical Processing with Coherent Population Trapping,” P. Hemmer, **Quantum Coherence and Interference in Fundamental and Applied Physics,** Alta WY (August 1995).
7. “Gain, Noise Correlation & Propagation Effects in the Double Lambda System,” P.R. Hemmer, M. S. Shahriar, T. Grove, P. Kumar, **26th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 1996).
8. “Noise Correlation and Suppressed Self-focusing in the Double Lambda System,” P.R. Hemmer, M.S. Shahriar, P. Kumar, M. Cronin-Golomb, **Texas Conference on Foundations of Quantum Electrodynamics,** Bellingham WA (Aug 1996)
9. “Quantum Coherence in the Double Lambda System and Applications,” P.R. Hemmer, **27th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 1997).
10. “Turbulence aberration correction with high-speed, high-gain optical phase conjugation in sodium”, V.S. Sudarshanam, M. Cronin-Golomb, P.R. Hemmer, and S. Shahriar, **Electromagnetics Research Symposium 1997,** Boston, MA (Jul 1997)
11. “Electromagnetically Induced Transparency in Pr Doped YSO Crystals,” P.R. Hemmer, **Taos Summer School,** Taos, NM (Aug 1997).
12. “Phase Conjugation and Atomic Coherence,” P.R. Hemmer, **28th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 1998).
13. “Atomic Coherence for Phase Conjugation, Optical Memory and Quantum Computing,” P.R. Hemmer, **29th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 1999).
14. “Progress in Raman Excited Spin Coherences for High Temperature Spectral Hole Burning,” P.R. Hemmer, **Applications of Spectral Hole Burning,** Montana State University, Bozeman, MT (Mar 1999).
15. “Quantum Coherence Effects for Optical Memory, Aberration Correction and Quantum Computing,” P.R. Hemmer, **1999 TAMU-ONR Workshop on Quantum Optics,** Jackson, WY (Aug 1999).
16. “Applications and Prospects for Electromagnetically Induced Transparency in Solids,” P.R. Hemmer, **Physics and Applications of Slow Light, ITAMP Workshop**, Cambridge, MA (Apr 2000).
17. “Dark Resonances in Spectral Hole Burning Materials,” P. R. Hemmer, **Applications of Spectral Hole Burning,** Big Sky, MT (Jul 2000).
18. “Applications and Prospects for Dark Resonances in Solids,” P.R. Hemmer, **2000 TAMU-ONR Workshop on Quantum Optics,** Jackson, WY (Aug 2000).
19. “First Observation of Ultraslow Group Velocity of Light in a Solid,” V.S. Sudarshanam, M.S. Shahriar, and P.R. Hemmer, **31st Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2001).
20. “Dark Resonances in Solids: Materials Issues and Applications,” P.R. Hemmer and M.S. Shahriar, **31st Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2001).
21. “Dark Resonances in Solids for Quantum Computing and Slow Light,” P.R. Hemmer, **8th Conference on Quantum Optics (CQO8),** University of Rochester, NY (June 2001).
22. “Dark Resonances in Solids: Methods and Applications,” P.R. Hemmer, **2001 TAMU-ONR Workshop on Quantum Optics,** Jackson, WY (Aug 2001).
23. “Quantum Coherence in the Double Lambda System and Applications from Optical Memory to Quantum Computing,” P.R. Hemmer, **1998 TAMU/ONR Workshop on Quantum Optics,** Jackson, WY (Aug 1998).
24. “Ultra-slow and Stopped Light Pulses in a Solid,” P.R. Hemmer **, 32nd Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2002).
25. “Type II Quantum Computing with Optically Addressed Spins in Solids,” **Quantum Computation for Physical Modeling Workshop**, Martha’s Vineyard, MA (May 2002).
26. “Solid State Quantum Computing and Storage using Optically Addressed Spins,” P.R. Hemmer, M.S. Shahriar, **Progress in Electromagnetics Research Symposium**, Boston, MA (July 2002).
27. “Optical Raman Dark Resonances for Quantum Computing in NV Diamond,” P.R. Hemmer, M.S. Shahriar, **8th International Conference New Diamond Science and Technology 2002**, Melbourne, Australia (July 2002).
28. “Ultraslow and Stopped Light in Rare Earth Doped Crystal,” P.R. Hemmer, **Quantum Optics Miniprogram at the Institute for Theoretical Physics in Santa Barbara**, Santa Barbara, CA (July 2002).

29. “Progress toward Quantum Computing and Stopped Light Quantum Storage using EIT in Solids,” P.R. Hemmer **, 33nd Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2003).
30. “Applications of Electromagnetically Induced Transparency in Doped Solids,” P.R. Hemmer **, 34nd Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2004).
31. “Very Large Scale (VLSI) Quantum Computer in Diamond,” P.R. Hemmer **, 35th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2005).
32. “Solving the Delay-Time-Bandwidth Problem in Slow Light,” P Hemmer, M Scully, S Zubairy De-Kui Qing, Z Deng, R Ooi, **36th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2006).
33. “Fundamentals of solid state quantum computing with spin systems,” “Solid state quantum computing with a photonic interface,” P. Hemmer, **International Workshop on Quantum Informatics and Quantum Devices,** Nathiagali, Pakistan (Jun 2006)
34. “Solid state quantum computing,” Philip Hemmer, Steven Prawer, Jerog Wrachtrup, Fedor Jelezko, Neil Manson, and Matthew Sellars, **International Conference on Coherent Control of the Fundamental Processes in Optics and X-ray-Optics,** Nizhny Novgorod Russia (Jul 2006)
35. “Progress toward scalable quantum computers in diamond,” P Hemmer, **37th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2007).
36. “Sub-wavelength single-molecule imaging using quantum optics,” P Hemmer, **38th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2008).
37. “EIT, dopplerons, and other quantum optical techniques for sub-wavelength imaging,” Philip Hemmer, **17th International Laser Physics Workshop (LPHYS’08)**, Trondheim, Norway, June 30 – July 4, 2008
38. “Limits of subwavelength imaging,” P Hemmer, **39th Winter Colloquium in Quantum Electronics,** Snowbird, Utah (Jan 2009).
39. “Practical Limits to Sub-Wavelength Imaging,” P Hemmer, **The 10th International Meeting on Hole Burning, Single Molecule, and Related Spectroscopies: Science Applications (HBSM 2009),** Palm Cove, Australia on 22 to 27 June 2009
40. “Practical limits to sub-wavelength imaging,” P. Hemmer, **18th INTERNATIONAL LASER PHYSICS WORKSHOP** (Barcelona, July 13 - 17, 2009)
41. “Limits to subwavelength imaging,” Coherent **Raman Scattering Microscopy (microCARS2010),** (Physikzentrum Bad Honnef, Germany, October 18 – 20, 2010)
42. “Practical limits to sub-wavelength imaging,” **19th International Laser Physics Workshop (LPHYS’10),** (Foz do Iguaçu, Brazil, July 5 – 9, 2010)
43. “High Resolution Single Spin Imaging with NV Diamond,” **IV International Conference Frontiers of Nonlinear Physics,** (Nizhny Novgorod, Russia, July 13-20, 2010)
44. “Spectral Hole Burning Solids for Advanced Ultrasound Imaging,” **International Symposium on Optical Manipulation of Quantum Information in Solids,** (Paris, May 26-28, 2010)

Contributed Conference Presentations:

1. “Performance of a Microwave Clock Based on a Laser Induced Stimulated Raman Interaction,” (with S. Ezekiel et al), presented at the **International Quantum Electronics Conference,** Anaheim, CA (June, 1984)
2. “Performance of a Laser-Induced Resonance Raman Clock,” (with S. Ezekiel et al), presented at the **39th Annual Frequency Control Symposium,** Philadelphia, PA (May 1985)
3. “Laser Raman Microwave Clock,” **Quantum Electronics Series,** Massachusetts Institute of Technology, Cambridge, MA (March 1986)
4. “Study of Several Error Sources in a Laser Raman Clock,” (with B. Bernacki and S. Ezekiel et al), presented at the **41st Annual Frequency Control Symposium,** Philadelphia, PA (May, 1987)
5. “Microwave Phase Dependent Optical Absorption,” (with M. S. Shahriar), **International Quantum Electronics Conference,** Anaheim, CA (May 1990)
6. “Bloch Vector Model for Dressed States of Resonant Raman Interaction,” (with M. S. Shahriar), **Optical Society of America 1990 Annual Meeting,** Boston, MA (Nov. 1990)

7. **"**Forces on Three Level Atoms including Trapped-state Contributions," (with M. S. Shahriar, N. P. Bigelow, and M. G. Prentiss), **Quantum Electronics and Laser Science Conference (QELS '91),** Baltimore, MD (May 1991)
8. **"**Optical Phase Conjugation with a Sodium Raman Laser," (with J. Donoghue and J. S. Kane), **Quantum Electronics and Laser Science Conference (QELS'91),** Baltimore, MD (May 1991)
9. **"**Gigahertz Optical Lock-in Demultiplexer" (with J. Khoury and C. Woods et al), **Conference on Lasers and Electro-optics (CLEO),** Baltimore, MD (May 1991). Post-deadline.
10. **"**Binary Phase Only Filter Associative Memory," (with J. S. Kane, C. Woods, and J. Khoury), **S.P.I.E. No. 1564 "Optical Information Processing Systems and Architecture III",** San Diego, CA (July 1991).
11. **"**Forces on Three Level Atoms in Standing Wave Excitation Fields," (with K. Berggren, N. Bigelow, S. Ezekiel, J. Mervis, M. G. Prentiss and M. S. Shahriar), **Enrico Fermi International School of Physics Course CXVIII "Laser Manipulation of Atoms and Ions",** Milan, Italy (July 1991).
12. **"**Observation of the Deflection of Three-Level Atoms due to Two Standing-Wave Optical Fields," P.R. Hemmer, M.S. Shahriar, M.G. Prentiss, D.P. Katz, K. Berggren, J. Mervis, and N.P. Bigelow, **Conference on Quantum Electronics and Laser Science (QELS),** Anahiem, CA (May 1992).
13. **"**Bi-directional Oscillation and Phase Conjugation in a Sodium Vapor Ring Resonator," J. Kane, P.R. Hemmer, J. Donoghue, and M. Cronin-Golomb, **Conference on Quantum Electronics and Laser Science (QELS),** Anahiem, CA (May 1992).
14. **"**Optical Data Storage with Raman Excited Microwave Spin Echoes," P.R Hemmer, M.S. Shahriar, **Conference on Quantum Electronics and Laser Science (QELS),** Anahiem, CA (May 1992). Postdeadline.
15. **"**Raman Gain in a Λ-three-level System with Closely Spaced Ground States," M.S. Shahriar, P.R. Hemmer, J. Donoghue, M. Cronin-Golomb, P. Kumar, **Optical Society of America Annual Meeting (OSA),** Albuquerque, NM (Sept 1992).
16. **"**Raman Excited Microwave Spin Echoes for Optical Data Storage," M.S. Shahriar, P.R. Hemmer, M. Kim, **Optical Society of America Annual Meeting (OSA),** Albuquerque, NM (Sept 1992).
17. **"**Four-level Closed-loop Model for Calculation of Thresholdless Raman Gain without Inversion in Alkali-metal Vapors," J. Donoghue, P. Hemmer, M.S. Shahriar, M. Cronin-Golumb, **Optical Society of America Annual Meeting (OSA),** Toronto, Canada (Oct 1993).
18. **"**Velocity-selective Coherent Population Trapping in Conjunction with Pol-grad Cooling in a Folded Three-level System under Standing Wave Excitation," D.P. Katz, M.S. Shahriar, P.R. Hemmer, M. Prentiss, N.P. Bigelow, **Optical Society of America Annual Meeting (OSA),** Toronto, Canada (Oct 1993).
19. **"**Suppression of Absorption of Resonance Fluorescence in a Folded Three-level Atom," M.S. Shahriar, M. Prentiss, P.R. Hemmer, **International Quantum Electronics Conference (IQEC),** Anahiem, CA (May 1994).
20. **"**Optical Phase Conjugation via Gain Without Inversion in the Double Λ System," P.R. Hemmer, J. Donoghue, M.S. Shahriar, P. Kumar, M. Cronin-Golomb, **Optical Society of America Annual Meeting (OSA),** Dallas, TX (Oct 1994).
21. **"**Transient Heating and Cooling in Traveling-wave Velocity-selective Coherent Population Trapping," M.S. Shahriar, M.G. Prentiss, and P.R. Hemmer, **Optical Society of America Annual Meeting (OSA),** Dallas, TX (Oct 1994).
22. **"**Resonance Fluorescence, Gain, and Momentum Diffusion of Atoms Moving in Standing Waves of Optical Fields," M.S. Shahriar, D.P. Katz, M.G. Prentiss, and P.R. Hemmer, **Optical Society of America Annual Meeting (OSA),** Dallas, TX (Oct 1994).
23. **"**Possible Evidence for Collective Atomic Recoil Lasing," P.R. Hemmer, M.S. Shahriar, D.P. Katz, N.P. Bigelow, R. Bonifacio, and E.J. D'Angelo, **Quantum Electronics and Laser Science Conference,** Baltimore, MD (May 1995). Postdeadline.
24. **"**Possible Observation of Collective Atomic Recoil Lasing," N.P. Bigelow, P.R. Hemmer, M.S. Shahriar, R. Bonifacio, and E.J. D'Angelo, **Enrico Fermi International School of Physics Course CXXXI "Coherent and Collective Interactions of Particle and Radiation Beams",** Milan, Italy (July 1995).

25. **“**Intensity Noise Correlation in Phase Conjugation using a Double Raman System,” M.S. Shahriar, P.R. Hemmer, P. Kumar, **Optical Society of America Annual Meeting (OSA),** Portland, OR (Sep 1995).
26. “Optical Forces on Λ system due to optical phase conjugation via electromagnetically induced transparency,” M.S. Shahriar, P.R. Hemmer, **Optical Society of America Annual Meeting (OSA),** Portland, OR (Sep 1995).
27. “Unbounded Cooling Force in Traveling Waves Excitation on a Four Level System,” M.S. Shahriar and P.R. Hemmer, **Quantum Electronics and Laser Science Conference,** Anaheim, CA (Jun 1996)
28. “Diffraction-limited Propagation and High Gain in Optically Dense Sodium Vapor at Low Pump Intensity,” M.S. Shahriar, T. Grove, P.R. Hemmer, M. Cronin-Golomb, **Quantum Electronics and Laser Science Conference,** Anaheim, CA (Jun 1996)
29. “Implementing Optical Feedback with a Smart Pixel Spatial Light Modulator,” J.S. Kane, P.R. Hemmer, T.G. Kincaid, **Optical Society of America Annual Meeting (OSA),** Rochester, NY (Sep 1996)
30. “High-speed Turbulence Aberration Correction with High-Gain Optical Phase Conjugation in Sodium,” V.S. Sudarshanam, M. Cronin-Golomb, P.R. Hemmer, M.S. Shahriar, **Conference on Lasers and Electro-Optics (CLEO),** Baltimore, MD (Jun 1997)
31. “Efficient, Fast, Low-power Optical Phase Conjugation using Two-photon Induced Zeeman Coherence in Rubidium,” T.T. Grove, E. Rousseau, Xiao-Wei Xia, M.S. Shahriar, and P.R. Hemmer, **Quantum Electronics and Laser Science Conference (QELS),** Baltimore, MD (Jun 1997)
32. “Observation of Enhanced Nondegenerate Four-wave Mixing and Efficient Electromagnetically Induced Transparency in a Optically Dense Rare-Earth Doped Crystal”, B.S. Ham, P.R. Hemmer, and M.S. Shahriar, **Optical Society of America Annual Meeting (OSA),** Long Beach, CA (Oct 1997)
33. “Air Force Applications of Long-Lived Quantum Coherence,” P.R. Hemmer, M.S. Shahriar, B.S. Ham, V.S. Sudarshanam, and M. Cronin-Golomb, **American Physical Society, New England Section Fall Meeting,** Hanscom AFB, MA (Oct 1997).
34. “Optical data storage by electromagnetically induced transparency and nondegenerate four-wave mixing in a spectral hole-burning solid,” B.S. Ham, M. S. Shahriar, M.K. Kim, and P. R. Hemmer, **Conference on Lasers and Electro-Optics (CLEO),** San Francisco, CA (May 1998)
35. “High gain optical phase conjugation using degenerate four wave mixing via coherent population trapping in moving atoms,” X. Xia, D. Hsiung, M. S. Shahriar, T. T. Grove, and P. R. Hemmer, **Conference on Lasers and Electro-Optics (CLEO),** San Francisco, CA (May 1998)
36. “Intracavity high-speed turbulence aberration correction in a phase-conjugate resonator,” V. S. Sudarshanam, M. Cronin-Golomb, P. R. Hemmer, and M. S. Shahriar, **Optical Society of America Annual Meeting (OSA),** Baltimore, MD (Oct 1998)
37. “Nonlinear optics in resonant systems applied to signal processing,” P. R. Hemmer, and M. S. Shahriar, **Optical Society of America Annual Meeting (OSA),** Baltimore, MD (Oct 1998). Invited.
38. “RF-induced gain of optical laser beam in an optically dense rare-earth-doped solid,” B.S. Ham, M. S. Shahriar, and P. R. Hemmer, **Optical Society of America Annual Meeting (OSA),** Baltimore, MD (Oct 1998).
39. “Limits on the sensitivity of an atomic interferometer imposed by the phase noise of a blazed grating optical beam splitter,” Y. Tan, M. S. Shahriar, and P. R. Hemmer, **Optical Society of America Annual Meeting (OSA),** Baltimore, MD (Oct 1998).
40. “Angle and space multiplexed holographic optical memory using thick, diffusion amplified photopolymer,” L. Wong, M. Bock, M.S. Shahriar, P.R. Hemmer, M. Henrion, J. Ludman, **Optical Society of America Annual Meeting (OSA),** Baltimore, MD (Oct 1998).
41. “Quantum computing via cavity-coupled bands in a spectral hole-burning solid, J. Bowers, M.S. Shahriar, S. Lloyd, A. Craig, and P.R. Hemmer, **Optical Society of America Annual Meeting (OSA),** Baltimore, MD (Oct 1998).
42. “Efficient phase conjugation using Raman dark resonance in an optically dense crystal,” B. S. Ham, P. R. Hemmer, and M. S. Shahriar, **Conference on Lasers and Electro-Optics (CLEO),** Baltimore, MD (May 1999).
43. “Electromagnetically induced transparency over spectral hole-burning temperature in an inhomogeneously broadened solid,” B. S. Ham, P. R. Hemmer, M. K. Kim, and M. S. Shahriar, **Quantum Electronics and Laser Science Conference (QELS),** Baltimore, Maryland (May 1999).

44. "Raman Excited Spin Coherences for High Temperature Spectral Hole Burning Memories," P. R. Hemmer, M. S. Shahriar, and A.V. Turukhin, **Conference on Lasers and Electro-Optics (CLEO),** San Francisco, CA (May 2000).
45. "Raman Excited Spin Coherences in N-V Diamond," P. R. Hemmer, A.V. Turukhin, M. S. Shahriar, and J.A. Musser**, Conference on Lasers and Electro-Optics (CLEO),** Baltimore, MD (May 2001).
46. "First Observation of Ultraslow Group Velocity of Light in a Solid," A.V. Turukhin, V.S. Sudarshanam, M.S. Shahriar, J.A. Musser, and P.R. Hemmer, **Conference on Lasers and Electro-Optics (CLEO),** Baltimore, MD (May 2001).
47. "First Observation of Ultraslow Group Velocity of Light in a Solid," A. V. Turukhin, V.S. Sudarshanam, M. S. Shahriar, J.A. Musser, P.R. Hemmer, **The International Symposium on Optical Science and Technology, SPIE's 46th Annual Meeting,** San Diego, CA (Aug 2001).
48. "Raman Excited Spin Coherences in N-V Diamond," P.R. Hemmer, A.V. Turukhin, M.S. Shahriar, J.A. Musser, **The International Symposium on Optical Science and Technology, SPIE's 46th Annual Meeting,** San Diego, CA (Aug 2001).
49. "Investigation of room-temperature slow light in photorefractives for optical buffer applications," Z. Deng and P.R. Hemmer, **Advanced Optical and Quantum Memories and Computing, SPIE Symposium on Integrated Optoelectronic Devices 2004**, San Jose, CA (January 2004).
50. "Expanding the bandwidth of slow light by artificial inhomogeneous broadening," D Qing, Z Deng, P Hemmer, MO Scully, MS Zubairy, **Photonics West 2006**, San Jose, CA (Jan 2006).
51. "Ultrasound-modulated optical tomography using spectral hole-burning," Youzhi LI, Chulhong Kim, Huiliang Zhang, Kelvin H. Wagner, Philip R. Hemmer, Lihong V. Wang, **Photonics West 2008**, San Jose, CA (Jan 2008).
52. "Ultrasound-modulated optical tomography using fourwave mixing in photorefractive polymers," Huiliang Zhang, Philip R. Hemmer, Peng Wang, Shuji Rokutanda, Michiharu Yamamoto, Nitto Denko, **Photonics West 2008**, San Jose, CA (Jan 2008).
53. "Fast light in a photorefractive crystal for broadband gravitational wave detection with an augmented advanced-LIGO interferometer," Mary Salit, Max Kellner, Subramanian Krishnamurthy, Selim M. Shahriar, Northwestern Univ, Honam Yum, Philip R.Hemmer **Photonics West 2009**, San Jose, CA (Jan 2009).
54. "Buffering and sensing applications of SBS induced fast light in a fiber resonator," Honam Yum, Philip R. Hemmer, Mary Salit, Selim M. Shahriar, **Photonics West 2009**, San Jose, CA (Jan 2009).

Supervisory Experience

- Supervised four Ph.D. theses that have been completed for graduate students from M.I.T., Harvard, Tufts University, and Boston University.
- Supervised six Post-docs for more than 2 years each.
- Supervised two Ph.D.-level staff researchers, one military officer, and one technician for more than 2 years each.
- Supervised several Masters theses that have been completed.

After arriving at TAMU

- Supervised Masters thesis for Honam Yum "A 6-beam combiner using superimposed volume index holographic gratings" 2004
- Supervised Doctorate thesis for Zhijie Deng, "Novel Optical Devices for Information Processing," May 2006
- Supervised Doctorate thesis for Mughees Kahn, "Fabrication and testing of nano-optical structures for advanced photonics and quantum information applications," December 2005
- Supervised Doctorate thesis for Changseok Shin, "One dimensional electron spin imaging for single spin deterdction and manipulation using gradient field," January 2008
- Supervised Doctorate thesis for Honam Yum, "Study of white light cavity effect via stimulated Brillouin scattering induced fast light in a fiber ring resonator," August 2009

- Supervised Doctorate thesis for Changdong Kim, “Ultrasensitive Magnetometry and Imaging with NV Diamond ,” December 2009.
- Supervised Doctorate thesis for Huilang Zhang, “Novel Nonlinear Optics and Quantum Optics Approaches for Ultrasound-Modulated Optical Tomography in Soft Biological Tissue,” August 2010.
- Supervised Masters student: Nakul Butta
- Current PhD students: Todd Zapata
- Current Masters students:, Jeson Chen

Teaching-Related Experience

- Wrote a paper explaining the basic physics of dark resonances in simple terms. This model has been used by numerous university professors to teach graduate students.
- Wrote or co-authored several review papers and sections of books.
- Gave numerous tutorial-level presentations to military and civilian audiences.

At TAMU

- Developed and taught graduate-level course on quantum and optical computing.
- Developed and taught graduate-level laboratory course on basic experimental optics techniques. This course give students “hands on” experience with both optics and electronics and teaches them how to do set up challenging laboratory experiments starting from scratch.
- Successfully transitioned experimental optics course to the undergraduate level.

Professional Service

- Optical Society of America, Sub-committee chair for Quantum Electronics and Laser Science Conference (QELS 02), major international conference in quantum optics with 1000s of attendees, Feb 2001 – May 2002.
- SPIE, Program committee member for Advanced Optical and Quantum Memories and Computing (OE14), international conference, Mar 2003 – Jan 2004.
- SPIE, Co-chair for conference on Fluctuations and Noise (FaN’04), international conference, June 2003 – May 2004.
- SPIE, Chair for conference on Fluctuations and Noise (FaN’05), international conference, June 2004 – May 2005.
- SPIE, Program committee member for Advanced Optical and Quantum Memories and Computing (OE15), international conference, Mar 2004 – Jan 2005.
- EE Coordinator for Homeland Security research, Appointed, College of Engineering Homeland Security committee, Jan. 2003 - present.
- SPIE, Co-chair for Advances in Slow and Fast Light (OE21), international conference, Mar 2007 – Jan 2008.
- SPIE, Co-chair for Advanced Optical Concepts in Quantum Computing, Memory, and Communication (OE19) international conference, Mar 2007 – Jan 2008.
- OSA, Session organizer for Quantum optics for information processing in 2008 Frontiers in Optics/ Laser Science XXIV, Rochester, Jan 2008 - Oct 2008
- SPIE, Co-chair for Advances in Slow and Fast Light (7226), international conference, Mar 2008 – Jan 2009.
- SPIE, Co-chair for Advanced Optical Concepts in Quantum Computing, Memory, and Communication (7225) international conference, Mar 2008 – Jan 2009.
- SPIE, Co-chair for Advances in Slow and Fast Light, Mar 2009 – Jan 2010.
- SPIE, Co-chair for Advanced Optical Concepts in Quantum Computing, Memory, and Communication, Mar 2009 – Jan 2010.
- SPIE, Co-chair for Advances in Slow and Fast Light, Mar 2010 – Jan 2011.

- SPIE, Co-chair for Advanced Optical Concepts in Quantum Computing, Memory, and Communication, Mar 2010 – Jan 2011.

Funding Activities

Air Force Internal Funding

Until ~1982 – 1994, most internal funding for basic research in the Air Force Research Laboratory, Hanscom AFB came from funding lines that had been in existence longer than 10 years. The title of the funding line was only loosely related to the work performed. However, the budget was automatically cut at least 10% per year and was subject to termination if not adequately defended at the annual review. I assumed the primary responsibility for defending the program that provided my primary support in the year it was pre-selected for termination. Since then, not only was the program not terminated, but was protected from the annual cut, ranging from 10 – 30 % per year for approximately 6 years.

After 1994, proposals were allowed to be sent directly to Air Force program managers. The following is a list of successful proposals since that time. Although I had to leave this funding behind, much of it is still in place.

Project/Proposal Title: Quantum Computing Materials Based on Spectrally Selective Solids
Principal Investigator: Philip Hemmer
Source of Support: US Air Force Office of Scientific Research
Total Award Amount: $540,000/ 1st 3 years **Total Period Covered**: 0/1/01-indeterminant
Number of postdocs supported: 1
Number of graduate students supported: 0

Project/Proposal Title: Quantum Devices for Computing and Communication
Principal Investigator: Philip Hemmer
Source of Support: US Air Force Office of Scientific Research
Total Award Amount: $675,000/ 1st 4 years **Total Period Covered**: 1/1/00-indeterminant
Number of postdocs supported: 1
Number of graduate students supported: 0

Project/Proposal Title: Laser Targeting through High Speed Turbulence
Principal Investigator: Philip Hemmer
Source of Support: Air Force Research Laboratory
Total Award Amount: $400,000/ 1st 4 years **Total Period Covered**: 10/1/98- indeterminant
Number of postdocs supported: 1
Number of graduate students supported: 0

Project/Proposal Title: Hybrid ATR Algorithms
Principal Investigator: Charles Woods **Co-Principal Investigator:** Philip Hemmer
Source of Support: Air Force Research Laboratory
Total Award Amount: $100,000 **Total Period Covered**: 10/1/98-10/1/99
Number of postdocs supported: 1
Number of graduate students supported: 0

Project/Proposal Title: Silicon Intersubband and Inversionless Lasers
Principal Investigator: Philip Hemmer **Co-Principal Investigator:** Richard Soref
Source of Support: US Air Force Office of Scientific Research
Total Award Amount: $540,000/ 1st 3 years **Total Period Covered**: 10/1/95-indeterminant
Number of postdocs supported: 2
Number of graduate students supported: 0

Project/Proposal Title: Aero-Optic Metrology and Image Reconstruction using Optical Raman Quantum Interference
Principal Investigator: Philip Hemmer **Co-Principal Investigator:** Charles Woods
Source of Support: US Air Force Office of Scientific Research
Total Award Amount: $480,000/ 1st 3 years **Total Period Covered**: 10/1/94-indeterminant
Number of postdocs supported: 1
Number of graduate students supported: 1

Past TAMU External Funding

Project/Proposal Title: Fractal-enhancement of photon bandgap cavities for quantum computing and other applications
Principal Investigator: Philip Hemmer
Source of Support: US Air Force Office of Scientific Research
Total Award Amount: $370,000 **Total Period Covered**: 8/1/02-7/31/05
Number of graduate students supported: 2

Project/Proposal Title: Quantum optics initiative
Principal Investigator: Marlan Scully, **Co-investigators:** Philip Hemmer and others
Source of Support: ONR
Total Award Amount: $75,000 (PI share) **Total Period Covered**: 3/15/03-12/31/05
Number of graduate students supported: 0

Project/Proposal Title: Investigation of NV diamond for quantum repeater applications
Principal Investigator: Mikhail Lukin, Harvard **TAMU PI:** Philip Hemmer
Source of Support: Harvard (DARPA Prime)
Total Amount: $44,526 **Total Period Covered**: 9/1/04-12/31/04
Number of graduate students supported: 0

Project/Proposal Title: Plasmon resonators for quantum computing
Principal Investigator: Philip Hemmer
Source of Support: US Air Force Office of Scientific Research
Total Award Amount: $255,000 **Total Period Covered**: 4/1/04-10/1/06
Number of graduate students supported: 2

Project/Proposal Title: Real-Time Stand-Off Detection of Anthrax via FAST CARS and Gain-Swept Super-Radiance
Principal Investigator: Marlan Scully
Source of Support: Sandia National Lab/DARPA
Total Amount: $900,000 **Total Period Covered**: 9/30/05-9/30/06
Number of graduate students supported: 0.

Project/Proposal Title: Spin-Based Lattice-Gas Quantum Computers in Solids using Optical Addressing
PI: Marlan Scully
Involvement: Conceived research plan, wrote proposal and currently managing/defending program
Source of Support: DARPA, QuIST, managed by US Air Force Office of Scientific Research
Total Award Amount: $2,100,000 base **Total Period Covered**: 9/30/01-9/30/04
Total Option Amount: $700,000 **Total Option Period**: 9/30/04-1/30/06
Number of postdocs supported: 2
Number of graduate students supported: 2

Project/Proposal Title: Quantum Computing in Diamond
Principal Investigator: Steven Prawer, Univ of Melbourne **TAMU PI:** Philip Hemmer
Source of Support: Univ Melbourne/ARO
Total Amount: $50,000 **Total Period Covered**: 9/30/05-9/30/06

Number of graduate students supported: 0.

Project/Proposal Title: Support for Slow Light in Semiconductor Quantum Well Waveguides
Principal Investigator: Connie Chang-Hasnain, UC Berkeley **TAMU PI:** Philip Hemmer
Source of Support: University of California, Berkeley (AFOSR Prime)
Total Amount: $62,500 **Total Period Covered**: 6/1/04-5/31/07
Number of graduate students supported: 0

Project/Proposal Title: Development of a System of Nonlocally Interconnected Spin Qubits for Quantum Computation
Principal Investigator: Hemmer
Source of Support: Harvard University (ARO funds)
Total Amount: $198,000 (TAMU share) **Total Period Covered**: 6/1/06-12/31/08
Number of graduate students supported: 0

Project/Proposal Title: NV diamond micro-magnetometer baseline studies
Principal Investigator: Hemmer
Source of Support: ARO (DARPA funds)
Total Amount: $300,000 **Total Period Covered**: 5/1/08-4/30/09
Number of graduate students supported: 1

Project/Proposal Title: Indestructable Fluorescent Markers in Diamond Nanocrystals with Nanometer Distance-Scale Distinguishability
Principal Investigator: Hemmer
Source of Support: NIH
Total Amount: $473,280 **Total Period Covered**: 7/1/08-6/30/10
Number of graduate students supported: 1

Project/Proposal Title: Controlled Assembly of Metallic Clusters for High-Performance Optical Devices
Principal Investigator: Hemmer
Source of Support: NSF (Sandia funds)
Total Amount: $240,000 **Total Period Covered**: 3/1/07-5/30/10
Number of graduate students supported: 1

Current External Funding

Project/Proposal Title: Solid state quantum information system based on optically coupled few qubit registers
Principal Investigator: Hemmer
Source of Support: Harvard University (NSF funds)
Total Amount: $180,000 (TAMU share) **Total Period Covered**: 4/1/07-4/1/10
Number of graduate students supported: 0

Project/Proposal Title: Diamond Based Magnetometry for Quantum Information Processing Using Endohedral Fullerenes
Principal Investigator: Hemmer
Source of Support: Harvard University (DARPA funds)
Total Amount: $300,000 **Total Period Covered**: 11/1/09-10/31/12
Number of graduate students supported: 1

Project/Proposal Title: Magnetic resonance (MRI) and coherent imaging of single cells and proteins: A revolutionary new tool for biology, medicine and material science

Principal Investigator: Wrachtrup
Source of Support: University of Stuttgart (Deutsche Forschungsgemeinschaft funds)
Total Amount: €442,000 (Hemmer share) **Total Period Covered**: 7/15/09-7/14/12
Number of graduate students supported: 1