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13. ABSTRACT (Maximum 200 words)

This document is the final report of a successful research program in the area of quantum and nonlinear optical imaging. This research area implements ideas and techniques from the fields of quantum optics and quantum information science to perform image formation with sensitivity and resolution exceeding that available using classical techniques. Examples of improved image formation addressed in this work included techniques to form images with resolution exceeding the traditional Rayleigh limit and techniques based on entangled photons to allow the formation of sharp images using photons that have never interacted with the object to be imaged. Quantum imaging systems can also be used to detect weak phase and amplitude objects in the presence of background noise with a sensitivity that exceeds the classical shot-noise limit. Possible long term implications of this work include their implementation in systems for quantum computing and quantum teleportation, thereby greatly increasing their information capacity by exploiting the parallelism intrinsic to image-bearing optical beams.

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Quantum and Nonlinear Optical Imaging
Final Report

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Year 1 Accomplishments

This project is aimed at developing quantum and nonlinear optical techniques for improving the performance of optical image forming systems. During this first funding period, we completed several theoretical projects and most importantly began the experimental portion of the research. We showed theoretically that the quantum statistical features of spontaneous parametric downconversion are largely retained in the much more intense output of a high-gain optical parametric amplifier. This conclusion is likely to have important practical implications for many quantum optical processes, including the realization of quantum lithography. A brief summary of this work appeared as a comment in Physical Review Letters, and more detailed versions of the theory have been written for publication. In addition, we have demonstrated experimentally that through control of the relative phases of the various input beams we can control the gain of the forward four-wave mixing process that leads both to self focusing and to the generation of quantum states of light. This work is likely to have important implications for the control of quantum optical processes. We have also provided experimental evidence that the technique of "coincidence imaging" can be performed using classically correlated beams of light; a recent article in PRL claimed that only quantum entanglement could lead to this effect. During the coming year we will continue these projects, pushing especially hard on the experimental projects.

Year 2 Accomplishments

We obtained a very significant result during the past funding cycle that was published in Physical Review Letters. This result pertains to the role of the quantum features of light in enabling the process of coincidence imaging (or ghost imaging). In brief summary, earlier workers had shown that it is possible to use quantum-correlated beams of light to perform coincidence imaging. In this process, coincidence techniques are used to form an image of an object using photons that have never actually interacted with the object to be imaged. This technique has obvious potential for applications such as remote surveillance. Many researchers speculated that this process was possible only through use of quantum entanglement, and in fact two years ago a separate research group published (again in Physical Review Letters) a purported theoretical demonstration of this speculation. In our work, we showed that we could reproduce this earlier result through use of light fields that possess only classical correlations. This result is both very surprising to some people and also potentially very useful in that it shows that coincidence imaging can be implemented using much simpler procedures. Our work has stimulated additional work in this field, including a recent publication (A. Gatti et al., Phys. Rev. Lett. 90, 133603, 2002) by a group in Como that shows that certain types of coincidence imaging (which had not been considered by any of these previous groups) can be produced only using quantum sources. We are currently working on demonstrating this effect and have some very recent results that demonstrate this effect. We are currently preparing these results for publication.

Other work performed during the past funding period includes the completion and publication of a theoretical analysis shows how the use of squeezed light beams for precision measurements can be optimized by proper control over the mode structures of the various light beams. Also in progress is a careful laboratory study of means to implement sub-Rayleigh lithography through use of nonlinear optical methods.

Year 3 Accomplishments

We have had good success over the past year in the area of coincidence (ghost) imaging.

Background: In the 1990's, the group of Yanhua Shih at the University of Maryland developed a method that is called ghost or coincidence imaging. The idea of this method is to use entangled photons to form an image of an inaccessible object. The idea is illustrated in Fig. 1. One photon of the photon pair illuminates the object. The light transmitted through or scattered from the object is detected by a bucket detector, which provides no spatial resolution. The other photon of the photon pair (biphoton) illuminates an imaging detector array. A coincidence circuit ensures that the output of the imaging detector is registered only if a photon is detected by the bucket detector. In papers published at that time (Strekalov et al, 1995; Pittman et al. 1995), these authors demonstrated that this technique could be used to form images and diffraction patterns of objects even though the photons that struck the imaging detector had never interrogated the object being investigated.

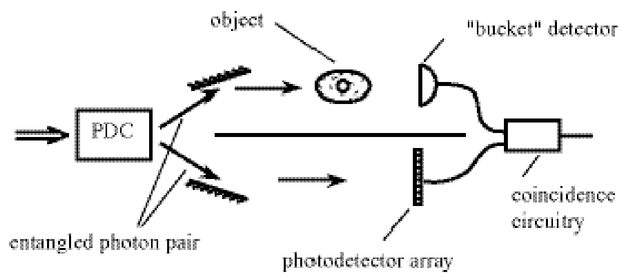

Fig. 1. Illustration of the process of coincidence imaging.

In these initial papers, the authors commented that it was not clear whether ghost imaging required the use of quantum entanglement or whether other types of correlation (such as classical correlations) could be used. This question was addressed by a more recent paper (Abouraddy et al., 2001), which concluded that the ability to perform ghost imaging was a manifestation of the quantum nature of light and that classically correlated light waves could not be used to perform ghost imaging. Our group felt that this conclusion was in error, and we performed an experiment to demonstrate that the results of the University of Maryland experiments could be reproduced through use of a demonstrable classical light source. This experiment was successful and was published in Physical Review Letters in 2002 (Bennink, 2002). Our experimental work motivated the theory group of Lugiato in Como to perform a more detailed analysis of this system (Gatti et al, 2003). They concluded that classical correlations could be used to perform ghost imaging only for one particular object plane. However, if quantum entangled photons were used, ghost imaging could be performed for an object in any object plane. The reason is that quantum mechanically a photon can be emitted and only later does one need to decide whether to measure the position or the transverse momentum of the photon. Thus, according to the model of Gatti et al, the true signature of quantum aspects of ghost imaging is to be able to obtain sharp images of an object that can be in either the near or the far field of the entangled light source.

We have performed an experiment to verify the predictions of this model. These results were very recently published in PRL (Bennink et al, 2004). In particular, we found that by using a source of quantum entangled photons we were able to form sharp images of an object in either the near or the far field of the light source. However, when we used a source that showed only classical correlations, we were able to obtain sharp coincidence images either in the near field or the far field but not in both. In setting up such an experiment, one has to construct the correlated light source to produce correlations in the plane in which the object is to be located.

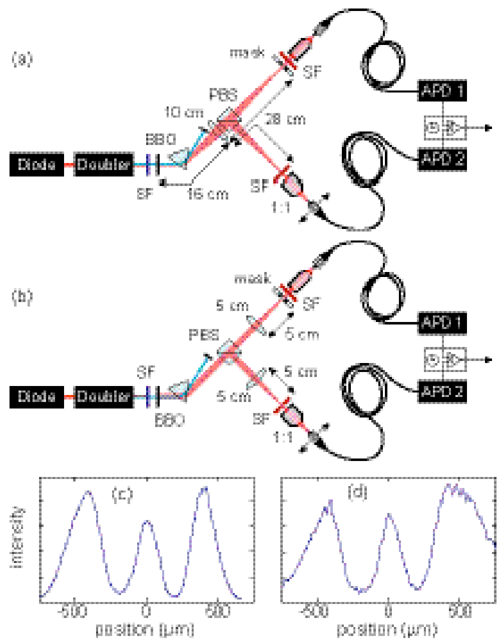

Fig. 2. Experimental setups (a,b) and measurements (c,d) showing coincidence images of a two-bar masks in both the near (a,c) and far (b,d) fields.

The significance of this work includes the following. (1) Coincidence imaging is a method that may lead to practical applications in the fields of remote sensing, surveillance, and imaging through tissue for medical applications. (2) Our experiment helps provide a crisp answer to the question of which sorts of quantum correlations can and which cannot be mimicked by a classical source. (3) Our results in a sense constitute a manifestation of the Einstein-Podolsky-Rosen (EPR) effect in the position-momentum basis originally formulated by EPR.

In our future research on this topic, we will address the following topics: (1) Can these techniques provide an exacting test of the predictions of quantum mechanics to better rule out the possibility of "hidden variable" interpretations? In this context, it is crucial to note that the vast majority of experimental searches for hidden variables in quantum mechanics have made use of the polarization degree of freedom of photons. In contrast, our method studies entanglement involving continuous variables (position and momentum) where one might hope to find more subtleties in the underlying physics. We also note that the few prior studies of entanglement of continuous variables (e.g., Ou et al., 1992) made use of the quadrature components of the electric field amplitude and not the position and momentum, which are the variables considered by EPR. (2) We will perform studies aimed at determining exactly how sharp the image formed though coincidence techniques can be. This question is important because of the potential of this method for practical applications, as outlined above. There are a number of considerations that need to be addressed in optimizing the process of coincidence imaging, such as the degree of collimation of the pump laser that produces the entangled photon pair and fundamental limitations (the Heisenberg limit) that cannot be violated. There are also very practical issues that need to be addressed in a realistic implementation of this technique, such as the fact that the bucket detector will certainly not be able to detect all of the photons not absorbed by the object. The consequence of this fact on the system performance of ghost imaging methods will be studied as part of our research program.

1.a Manuscripts published in peer-reviewed journals during the award period

Comment on "Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit," G. S. Agarwal, R. W. Boyd, E. M. Nagasako, S. J. Bentley, Phys. Rev. Lett., 86, 1389, 2001

Nonclassical two-photon interferometry and lithography with high-gain parametric amplifiers, E. M. Nagasako, S. J. Bentley and R. W. Boyd, and G. S. Agarwal, Phys. Rev. A, 64, 043802 (2001).

Honeycomb Pattern Formation by Laser-Beam Filamentation in Atomic Sodium Vapor, R S. Bennink, V. Wong, A. M. Marino, D. L. Aronstein, R. W. Boyd, C.R. Stroud, Jr., S. Lukishova, and D. J. Gauthier, December 2002 issue of Optics and Photonics News, entitled "Optics in 2002

"Slow" and "Fast" Light, R. W. Boyd and D. J. Gauthier, a book chapter to appear in Progress in Optics, 2002.

Parametric downconversion vs. optical parametric amplification: a comparison of their quantum statistics, E. M. Nagasako, S. J. Bentley and R. W. Boyd, and G. S. Agarwal, J. Mod. Optics, 49, 529 2002.

"Two-Photon" Coincidence Imaging with a Classical Source, R S. Bennink, S. J. Bentley, and R. W. Boyd, Phys. Rev. Lett. 89, 1130601, 2002.

Stabilization of the propagation of spatial solitons, M. S. Bigelow, Q-Han Park, and R. W. Boyd, Phys. Rev. E., 66, 046631, 2002.

Improved measurement of squeezed light via an eigenmode approach, Ryan S. Bennink and Robert W. Boyd, Phys. Rev. A 66, 053815 (2002).

Cumulative birefringence effects of nanosecond laser pulses in dye-doped planar nematics liquid crystal layers, S.G. Lukishova, R.W. Boyd, N. Lepeshkin, and K.L. Marshal, Special issue of the *Jour. Nonl. Opt. Phys* & Mater, **11**, No 4 (2002)

Influence of damping on the vanishing of the electro-optic effect in chiral isotropic media, G.S. Agarwal and R. W. Boyd, Phys. Rev. A, 67 043821, 2003.

Observation of Ultra-Slow Light Propagation in a Ruby Crystal at Room Temperature M. S. Bigelow, N. N. Lepeshkin, R. W. Boyd, Phys. Rev. Lett. 90, 113903 (2003). A news article published in Nature describing this work can be found at the following web address http://www.nature.com/nsu/030324/030324-4.html (ONR, ARO, DoE, AFOSR)

Superluminal and Slow Light Propagation in a Room-Temperature Solid, M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, Science, 301, 200, 2003. (ONR, ARO, DoE, AFOSR)

Superluminal and Ultra-Slow Light Propagation in Room-Temperature Solids, R. W. Boyd, M. S. Bigelow, and N. N. Lepeshkin, *Laser Spectroscopy, Proceedings of the XVI International Conference,* pp. 362-364, edited by P. Hannaford, A. Sidorov, H. Bachor, and K. Baldwin, World Scientific Publishing Company, Singapore, 2004.

Novel Photonic Materials for Advanced Imaging Applications, R. W. Boyd. Journal of the Korean Physical Society, 43, 603, 2003.

Chirality and Polarization effects in Nonlinear Optics, R. W. Boyd, J. E. Sipe, and P. W. Milonni, Journal of Optics A, 6, S14-S17 (2004).

Equivalence of Interaction Hamiltonians in the Electric Dipole Approximation, K. Rzazewski and R.W. Boyd, J. Mod. Optics, 51, 1137 (2004).

Breakup of Ring Beams Carrying Orbital Angular Momentum, M.S. Bigelow, P. Zerom, and R.W. Boyd, Phys. Rev. Lett. 92, 03902, 2004.

Quantum and Classical Coincidence Imaging, R.S. Bennink, S. J. Bentley, R. W. Boyd, and J. C. Howell, Phys. Rev. Lett. 92, 033601 (2004).

Dramatic Enhancement of Third-Harmonic Generation in 3-D Photonic Crystals, P. Markowicz, H. Tiryaki, H. Pudavar, P. N. Prasad, N.N. Lepeshkin, and R.W. Boyd, Phys. Rev. Lett. 92, 083903, 2004.

Momentum-position realization of the Einstein-Podolsky-Rosen Paradox, J. C. Howell, R.S. Bennink, S. J. Bentley, and R. W. Boyd, Phys. Rev. Lett. 92, 210403 (2004).

1.b Papers published in conference proceedings

Quantum Entanglement for Optical Lithography and Microscopy Beyond the Rayleigh Limit, S. J. Bentley, R. W. Boyd, E. M. Nagasako, and G. S. Agarwal, presented at CLEO/QELS 2001, Baltimore MD May 6-11, 2001.

Honeycomb Pattern Formation by Laser-Beam Filamentation in Atomic Sodium Vapor, R. S. Bennink, V. Wong, D. L. Aronstein, R. W. Boyd, S. G. Lukishova, A. M. Martino, and C. R. Stroud, Jr., presented at CLEO/QELS 2001, Baltimore MD May 6-11, 2001.

Honeycomb Pattern Formation by Laser Beam Filamentation in Atomic Sodium Vapor, R. S. Bennink, V. Wong, D. L. Aronstein, R. W. Boyd, S. G. Lukishova, A. M. Marino, and C. R. Stroud, Jr., presented at the Eighth Conference on Coherence and Quantum Optics, Rochester, NY, 2001.

Nonclassical, Two-Photon Interferometry and Lithography with High-Gain Optical Parametric Amplifiers, R. W. Boyd, E. M. Nagasako, S. J. Bentley, and G. S. Agarwal, presented at the Eighth Conference on Coherence and Quantum Optics, Rochester, NY, 2001.

1.c Papers presented at meetings, but not published in conference proceedings

Quantum and Nonlinear Optical Imaging, 31st Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, January 7-10, 2001.

Colloquium, New Concepts and Materials for Nonlinear Optics, Optical Sciences Center, University of Arizona, Tucson, Arizona, Feb 15, 2001.

Slow Light, Induced Dispersion, Enhanced Nonlinearity, Self-Steepening, and Optical Solitons in a Side-Coupled Integrated Spaced Sequence Of Resonators , J. E. Heebner and R. W. Boyd, Topical Meeting on Nonlinear Guided Waves, Clearwater, Florida, March 25-29, 2001.

New Concepts and Materials for Nonlinear Optics, Physics Department Colloquium, University of Hawaii, Manoa, April 5, 2001

New Concepts and Materials for Nonlinear Optics, Third Annual Cross-Border Workshop on Laser Science, Toronto, Ontario, May 24, 2001.

New Concepts and Materials for Nonlinear Optics, Physics Department Colloquium, Texas A&M University, College Station, Texas, June 7, 2001

Quantum and Nonlinear Optical Imaging, Workshop on Laser Physics and Quantum Optics, Jackson Hole, Wyoming, July 29-August 3, 2001. *

Reducing the Effect of Laser Beam Filamentation, Sean J. Bentley and Robert W. Boyd, presented at OPTO-Canada 2002, Ottawa, Canada, May 10, 2002.

Quantum and Nonlinear Optical Imaging, Presented at the ARO Optics Workshop, October 16, 2002.

Quantum and Nonlinear Optical Imaging, Presented at the Workshop on Quantum Imaging and Metrology, Pasadena, CA November 14-15, 2002.

Colloquium talks at SUNY Stony Brook, Ewha Womans University and Korea University, 2002.

Slow Light, Enhance Optical Nonlinearities, and Photonic Biosensors based on Quantum Coherence and on Artificial Optical Materials, presented at the 33rd Winter Colloquium on the Physics of Quantum Electronics, Snowbird Utah, January 9, 2003

New Materials and Interactions for Nonlinear Optics, presented February 4, 2003 as the Physics Colloquium at Ohio State University.

New Materials and Interactions for Nonlinear Optics, presented February 18, 2003 at Los Alamos National Laboratory.

New Materials and Interactions for Nonlinear Optics, presented as a seminar for first year graduate students at the University of Rochester Department of Physics and Astronomy, April 4, 2003.

Slow Light, Enhance Optical Nonlinearities, and Photonic Biosensors based on Quantum Coherence and on Artificial Optical Materials,, presented April 9, 2003 at the joint Harvard University ITAMP, Atomic, Molecular, and Optical Physics Colloquium.

Nonlinear Optical Physics, Physics Colloquium, San Diego State University, May 2, 2003

Nonlinear Optical Physics, Physics Colloquium, University of California at Berkeley, May 5, 2003

Nonlinear Optical Physics, DAMOP Annual Meeting, Boulder Colorado, May 22, 2003.

Super-resolution by Nonlinear Optical Lithography, S. J. Bentley and R. W. Boyd, Demonstration of a Room-Temperature Single-Photon Source, S. G. Lukishova, A. W. Schmid, A. J. McNamara, R. W. Boyd, and C. R. Stroud, Jr., Quantum and Classical aspects of Coincidence Imaging, R. S. Bennink, S. J. Bentley, and R. W. Boyd, Observation of Superluminal Pulse Propagation in Alexandrite, M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, CLEO/QELS, Baltimore, Maryland, June 1-6, 2003.

Honeycomb Pattern Formation by Laser-Beam Filamentation in Atomic Sodium Vapor. R.S. Bennink, V. Wong, A.M. Marino, D.L. Aronstein, R.W. Boyd, C.R. Stroud, Jr., S. Lukishova, and D.J. Gauthier, European Quantum Electronics Conference, Munich Germany, June 24, 2003.

Chirality and Polarization Effects in Nonlinear Optics, R. W. Boyd, presented at the ICO Conference on Polarization Optics, Joensuu, Finland, June 30, 2003.

Ultra-Slow Light Propagation in Room Temperature Solids, R. W. Boyd, presented at the Laser-Optics Conference, St. Petersburg, Russia, July 3, 2003.

Ultra-Slow Light Propagation in Room Temperature Solids, R. W. Boyd, M. S. Bigelow, and N. N. Lepeshkin, presented at the International Conference on Laser Spectroscopy, Palm Cove, Australia, July 13-18, 2003.

Superluminal and Ultra-Slow Light Propagation in Room Temperature Solids, presented the Gordon Research Conference on Nonlinear Optics and Lasers, July 27 through August 1, 2003.

Coherent control of four-wave mixing gain, S. J. Bentley and R. W. Boyd; Efficient room temperature single photon source for quantum information, S. G. Lukishova, A. W. Schmid, A. J. McNamara, R.W. Boyd, and C. R. Stroud, Jr; Polarization Properties of Photons Generated by Two-Beam Excited Conical Emission, M S. Bigelow, S. J. Bentley, A. M. Marino, R. W. Boyd, and C. R. Stroud, Jr.; presented at the joint OSA Annual Meeting and APS Laser Science Meeting, Tucson Arizona, October 5-9, 2003.

New Materials and Interactions for Nonlinear Optics, presented at RIT, October 22, 2002.

Superluminal and Ultra-Slow Light Propagation in Room Temperature Solids, presented the Department of Physics, University of Toronto, October 27, 2003.

New Materials and Interactions for Nonlinear Optics, presented at the University at Buffalo, November 5, 2003.

Slow Light and Enhanced Nonlinear Optical Response of Novel Materials, presented at Bryn Mawr College, November 17, 2003.

Ultra-Slow (and Superluminal) Light Propagation in Room Temperature Solids, presented at the Naval Research Laboratory QUIC Seminar, November 19, 2003.

Fundamentals and Applications of Ultra Slow Light Propagation in Room Temperature Solids, Presented at the DARPA Slow Light / EIT Workshop, December 2, 2003, Orlando, Florida.

1.d Manuscripts submitted but not published during the award period

none

2. Scientific Personnel supported by this project

Elna M. Nagasako completed her Ph.D. during this award period.

Robert W. Boyd was promoted to a chaired professorship at the University of Rochester and received a joint appointment in the Department of Physics and Astronomy during this award period.

Ryan Bennink completed writing and defending his PhD thesis during Spring 2004 and is currently working at Oar Ridge National Laboratory.

Sean Bentley completed writing and defending his PhD thesis during Spring 2004. He has taken a position as Assistant Professor at Adelphi University.

3. Inventions - none

4. Scientific Progress and Accomplishments

Accomplishments are described in the publications listed in part 1.

5. Technology transfer

Our research group has collaborative research programs with JPL, with Brookhaven National Laboratory, and with the US Navy PAX River laboratory.

Robert W. Boyd presented a seminar at Dow Corning and began a joint research project.

Robert Boyd has received support from the National Science Foundation for work on Slow Light that was started under ARO support.