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Entangled-Photon Sensing and Imaging

Bernard M. Gordon Center for Subsurface Sensing and Imaging Systems (Gordon-CenSSIS)

Year Eight Project Report

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Title: Entangled-Photon Sensing and Imaging

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I. Brief Overview of the Project and Its Significance

The goal of this project has been to develop subsurface sensing and imaging methods and applications based on light beams exhibiting quantum entanglement. Such beams are generated by use of spontaneous parametric down conversion (SPDC) in a nonlinear optical crystal, and they have the property that photons are emitted in pairs endowed with strong temporal and spatial correlations. Applications include metrology, imaging, ellipsometry, microscopy, and lithography. This project has focused on axial imaging, a novel two-beam quantum interferometry technique that is a quantum version of optical coherence tomography (OCT). In quantum OCT (Q-OCT), a quantum interferogram based on the photon coincidence rates is used to extract range information. The primary advantage is the inherent insensitivity to the dispersion of the medium. Dispersion sets the limit on axial resolution in conventional high-resolution OCT. Theoretical studies of Q-OCT have been undertaken and an experimental facility has been founded. Axial imaging has been demonstrated for multi-layered media. Dispersion cancellation has been demonstrated experimentally for the first time. A method for measurement of the dispersion coefficient of the interstitial media between parallel boundaries has been developed and tested. A statistical analysis of the accuracy of measurement has been conducted. Data processing tools appropriate for Q-OCT have being developed in collaboration with the Gordon-CenSSIS R2 group. A number of difficult challenges are being addressed and transition to B-scans of biological samples is being pursued.

II. State-of-the-Art, Major Contributions, and Technical Approach

Optical coherence tomography (OCT) has become a well-established imaging technique [1–4] with applications in ophthalmology [5], intravascular measurements [6, 7], and dermatology [8]. It is a form of range-finding that makes use of the second-order coherence properties of a classical optical source to effectively section a reflective sample with a resolution governed by the coherence length of the source. OCT therefore makes use of sources of short coherence length (and consequently broad spectrum), such as superluminescent diodes (SLDs) and ultrashort-pulsed lasers. As broad bandwidth sources are developed to improve the resolution of OCT techniques, material dispersion has become more pronounced. The deleterious effects of dispersion broadening limit the achievable resolution, as has been recently emphasized [9].

To further improve the sensitivity of OCT, techniques for handling dispersion must be implemented. In the particular case of ophthalmologic imaging, one of the most important applications of OCT, the retinal structure is located behind a comparatively large body of dispersive ocular media [10]. Dispersion increases the width of the coherence envelope of the probe beam and results in a reduction in axial resolution and fringe visibility [11]. Current techniques for depth-dependent dispersion compensation include the use of dispersion-compensating elements in the optical setup [10, 12] or employ *a posteriori* numerical methods [13, 14]. For these techniques to work, however, the object dispersion must be known and well-characterized so that the appropriate optical element or numerical algorithm can be implemented.

Over the past several decades, a number of non-classical (quantum) sources of light have been developed and applied to metrology, ellipsometry, and optical imaging [15-19]. Our lab was the first to introduce the concept of quantum tomographic imaging [20], based on SPDC in a nonlinear crystal, and to demonstrate dispersion immunity of these tomographic measurements in comparison to standard OCT techniques [21, 22].

A. Technical Approach

Quantum Optical Coherence Tomography (Q-OCT) is a novel technique for axial imaging based on quantum interference of entangled-photon beams. The interferometer uses a beam splitter in the Hong-Ou-Mandel (HOM) configuration (shown in Figure 1) as opposed to the conventional interferometer. One beam travels through the sample and the other through a controllable delay τ before reflection/transmission through the interferometer. The rate of coincidence of photons at the output ports of the beam splitter is measured as a function of τ by use of two photon-counting detectors and a coincidence counter. Because of quantum destructive interference, when the optical path lengths are equal, the coincidence rate exhibits a sharp dip of width equal to the width of the photon wave packet, which is as small as 10 fs. This is used to monitor the range (depth) with good resolution. An image of the backscattered light is obtained by scanning in the transverse direction.

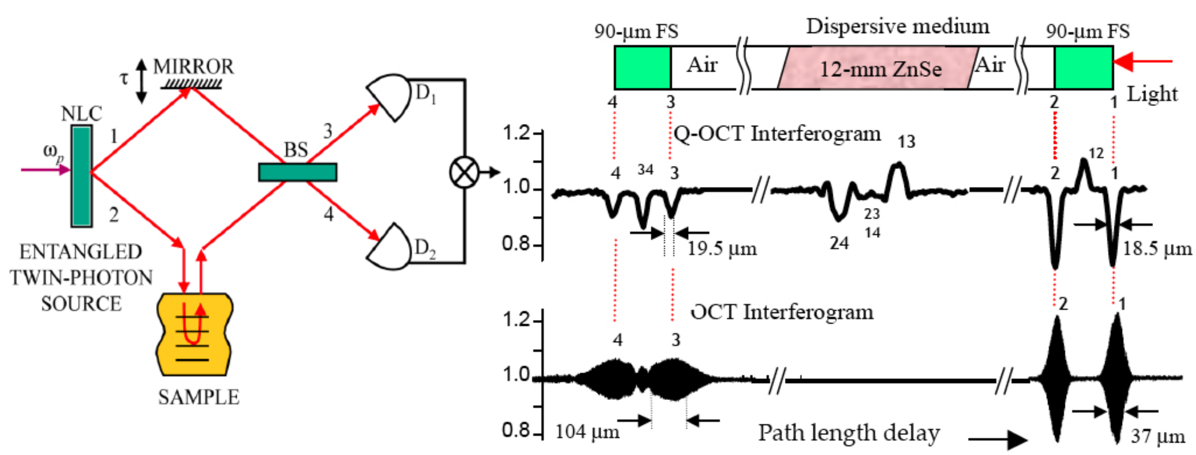

Figure 1. Left: The Q-OCT apparatus. Right: Measured quantum (Q-OCT) interferograms and classical (OCT) for a four-boundary medium made of two 90µm slabs of fused silica in air. A 12-mm slab of ZnSe, which is highly dispersive, is placed between. In classical OCT, each boundary corresponds to interference fringes that last for a coherence length (37µm in this case). The interferogram of the lower slab (left) is broadened by dispersion to 104 µm. In Q-OCT, each boundary corresponds to an interference of duration equal to the entanglement length (18.5 µm). The interferogram of the lower slab is broadened only slightly (19.5 µm). This demonstrates dispersion cancellation. Cross interference between reflections from each pair of boundaries leads to humps or dips at mid points.

B. Challenges

A fundamental limitation of conventional OCT is the reduced axial resolution caused by sample dispersion. Q-OCT is inherently insensitive to even-order dispersion of the medium surrounding the target. However, current implementations have not yet reached Q-OCT's theoretical potential because of the relatively narrow spectral width of existing sources. Another principal challenge facing Q-OCT, and all quantum optical technology, has been the low entangled-photon flux of existing sources, and the need for photon-counting detectors at long wavelengths. Although we have demonstrated Q-OCT in simple planar samples with parallel layers of non-scattering material at 800 nm, a greater challenge is the application of the technique to more realistic media, including tissue and other biological samples. Yet another technical challenge is the development of a system with combined axial and transverse scanning, i.e., construction of a quantum optical coherence microscope.

C. Major Contributions

1. Development of Q-OCT Theory

We have demonstrated theoretically [20, 21] that Q-OCT has the following advantages over conventional OCT: 1) The signal-to-background ratio is greater; 2) Resolution is greater by a factor of 2 for the same source bandwidth; 3) The measured interferogram has components that are insensitive to even-order dispersion of the medium, which permits deeper subsurface sensing in dispersive media; 4) The measured interferogram also has components that are sensitive to dispersion of the medium, which permits measurement of the dispersive properties of layered media with greater accuracy. Another recent theoretical study of noise in quantum imaging has laid the foundations for determining the statistical accuracy of quantum imaging, in general, and Q-OCT in particular [30].

2. First Proof-of-Concept Experiments

We have conducted experiments to demonstrate the viability of the Q-OCT technique and to verify its dispersion-canceling property [22-23]. The experimental setup (Figure 1) includes a source of entangled photons using a nonlinear crystal operated in Type-I SPDC. For the purpose of comparison, one of the down-converted beams was used as a broadband source for conventional OCT from the same sample and in the same apparatus. Figure 1 also shows one example of our experimental results demonstrating conventional OCT and Q-OCT interferograms for two 90 μm fused-silica-glass layers separated by a thick layer of dispersive material (ZnSe). A factor of 2 enhancement of resolution predicted by the theory was experimentally demonstrated. As shown in Figure 1, the axial resolution in conventional OCT is diminished by the presence of the dispersive layer, whereas Q-OCT is practically insensitive to dispersion. This is the first demonstration of dispersion cancellation in Q-OCT. As shown in Figure 1, each layer corresponds to one sharp dip in the quantum interferogram. However, a dip or a hump appears between each pair of dips as a result of cross-interference between inter-boundary reflections.

3. Measurement of Dispersion Coefficient of Interstitial Layers

As mentioned before, one feature of Q-OCT is the appearance of dispersion-sensitive inter-boundary interference dips/humps, which permits the direct measurement of group velocity dispersion (GVD) coefficients of the interstitial media between reflecting boundaries. The Q-OCT interferogram in Figure 1 was used to accurately determine the group velocity dispersion (GVD) coefficient of ZnSe [23]. The GVD coefficient can be used to identify different materials constituting a subsurface object.

4. Extension to Polarization Sensitive Q-OCT

We have also developed a polarization-sensitive quantum-optical coherence tomography (PS-Q-OCT) technique that provides axial optical sectioning with polarization-sensitive capabilities [24]. This technique provides a means for determining information about the optical path length between isotropic reflecting surfaces, the relative magnitude of the reflectance from each interface, the birefringence of the interstitial material, and the orientation of the optical axis of the sample. PS-Q-OCT is also immune to sample dispersion and therefore permits measurements to be made at depths greater than those accessible via conventional OCT. A general Jones matrix theory for analyzing PS-Q-OCT systems has been demonstrated and an experimental procedure for carrying out such measurements is ongoing. We have also developed quantum ellipsometry as a tool for measuring polarization properties of thin films [26].

5. Miniaturized Q-OCT System with Improved Axial Resolution and Greater Photon Flux

Earlier Q-OCT systems developed in our laboratory were limited by poor axial resolution (approximately 18.5 μm) and low flux of photon pairs, which means that the time necessary to construct a Q-OCT interferogram with an acceptable signal-to-noise ratio is too long. An initial change of the layout brought the resolution down to 13 μm. A more comprehensive redesign of the system layout compressed all distances and miniaturized the system, thereby offering enhancement in the spatial resolution by a factor of 2 and of the photon flux by a factor of 4. Subsequent enhancements of the system have yielded an axial resolution of 3.5 μm.

6. Enhancement of Resolution by Manipulation of Pump Spatial Distribution

A spin-off of our development of Q-OCT has been the discovery that SPDC provides an excellent broadband source for conventional OCT. We have shown, both theoretically and experimentally, that the spectral distribution of the signal or the idler beams in non-collinear parametric down-conversion can be controlled by changing the spatial distribution of the pump beam in an almost one-to-one mapping. A pump beam with small diameter generates down-converted light with spectral distribution sufficiently broad (greater than 200 nm) to result in submicron-resolution OCT. OCT interferograms from a 2-μm pellicle confirmed this new technology [25, 27].

We have also demonstrated experimentally that a similar approach permits the generation of entangled photon pairs with a broad joint spectrum. Such spectral properties are mediated by the geometry of non-collinear SPDC and by selecting the appropriate spatial profile of the pump laser radiation. The width of both (i) the joint spectrum of the entangled photon pairs and (ii) the spectrum of the individual signal and idler photons are tailored over a large range of values, which renders this technique of great value for many quantum optics applications. Reference [32] describes recent experimental results demonstrating an axial resolution of 1 μm.

7. Enhancement of Resolution and Entangled-Photon Flux by Periodic Poling of Crystal

Our initial research in this project was focused on the demonstration of entangled-photon microscopy (EPM). An experimental facility was set up and optimal photon delivery systems were investigated. We have experimentally demonstrated entangled-photon photoemission, but the signal was very weak. A major impediment has been the weakness of the available entangled-photon flux generated by the process of SPDC in bulk crystals. To address this problem and to also come up with a more intense source for Q-OCT, we have launched an experimental effort to investigate sources of high-flux entangled photons using quasi-phase matched parametric down-conversion in periodically poled materials (PPLN). This provides flexibility to use larger nonlinear coefficients and thus enhance the rate of generation of entangled-photon flux [25].

8. Enhancement of Resolution by Use of SSPD Detectors

The limited spectral width of conventional photon counting avalanche photodiodes (APDs) can be circumvented by use of a new class of superconducting single-photon detectors (SSPDs). These devices are made of 3-10 nm-thick niobium nitride meandering microstripes sputtered on sapphire substrate. They are operated at temperatures under 4°K and are responsive over a band ranging from visible to IR with quantum efficiency of the order of 10%. Light is coupled to the detectors via a single-mode fiber. We have replaced our conventional APD detectors with this new technology, and preliminary results are promising.

9. Enhancement of Transverse and Axial Resolution: Quantum Optical Coherence Microscopy

Since we have succeeded in bringing the axial resolution of Q-OCT to the few-micrometer range, the next step in generating B-scan images is to consider the resolution in the transverse direction. Conventional interferometers are based on the interference of a plane waves probing the sample with a plane-wave reference. In order to localize information in the transverse plane, focused beams must be used instead of plane waves. This is implemented in conventional interferometry by use of a lens. We have investigated the use of a lens in Q-OCT. Placement of a single lens in the probe beam broadens the interference dip substantially and ruins the axial resolution of the system. Fortunately, we have found that the use of two lenses in the reference beam in a collimating configuration (3 lenses total) can reverse this broadening.

10. Algorithms for Image Reconstruction in Q-OCT

Research on data processing to extract axial images from Q-OCT interferograms has also been pursued. In collaboration with Professor Clem Karl of BU, we formulated the problem in the special case of layered samples. In her completed Ph.D. dissertation, Julia Pavlovich tested new algorithms for solving this problem using least-square error estimation techniques. The program estimates the positions and reflectances of the layers. The problem is challenging, particularly when the layers are not well separated. Her new algorithm dealt with a large number of interacting layers.

D. More Recent Developments

A byproduct of research on the periodically-poled entangled-photon source has been the discovery of a new method of enhancing the axial resolution of Q-OCT by use of aperiodic (chirped) quasi-phase-matching structures (C-PPLN) [25]. Using crystals fabricated for this purpose by collaborators at Stanford University, the Gordon-CenSSIS team was able to generate biphotons of 300-nm bandwidth via SPDC. These ultrabroadband biphotons were used to generate the narrowest HOM dip to date, having a full width at half maximum (FWHM) of 7.1 fsec, corresponding to axial resolution of 1.1 μm in a Q-OCT experiment. This landmark advance in the area of quantum imaging is described in a paper submitted recently to the *Physical Review Letters* [J4].

The experimental results of this work are shown in Figure 2. In Figure 2(a), for the smallest chirp coefficient ($\alpha = 0.02\,\mathrm{nm}^{-2}$) the interferogram exhibits a FWHM of 130 fsec, whereas in Figure 2(b), for the largest chirp coefficient ($\alpha = 9.7\,\mathrm{nm}^{-2}$), the FWHM is 7.87 fsec. The corresponding power spectral densities, obtained from the Fourier transform of the measured interferograms, are presented in Figure 2(c). The emission from the highest chirped grating exhibits an ultrabroadband power spectral density $S(\Omega)$ (plotted vs. wavelength λ) that spans approximately 300 nm about the degenerate wavelength (812 nm). However, this salutary spectral broadening is unfortunately accompanied by a decrease in the entangled-photon flux, as indicated in Figure 2(d).

Finally, we demonstrate the ultra-narrow dip that can be attained using these biphotons when they are employed in an HOM interferometer [1]. The normalized coincidence rates, $N_c(\tau)$, are depicted in Figure 3 for biphotons generated by chirped gratings with chirp coefficients α = 0.02, 1.0, and 9.7 nm^{-2}. The effect of chirping is clearly evident, as the HOM dip narrows from a FWHM of 77 fsec for a weakly chirped grating to 7.16 fsec for the highest-chirped grating. This observed narrow dip translates to an ultra-high axial resolution of 1.1 μm in a Q-OCT experiment.

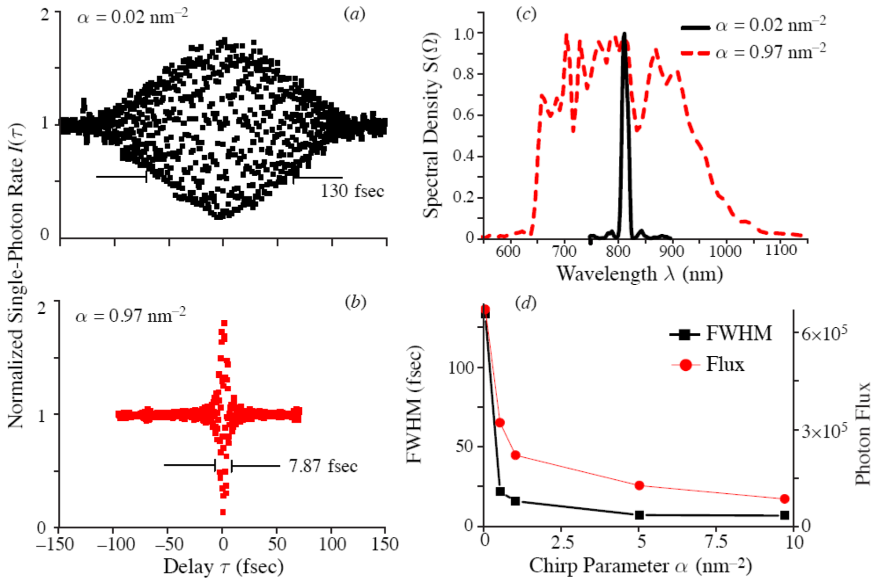

Figure 2. Normalized interferogram $I(\tau)$ for collinear SPDC. Emission from a C-PPSLT grating with (a) α = 0.02 nm^{-2} exhibits a FWHM of 130 fsec, and (b) α = 9.7 nm^{-2} exhibits a FWHM of 7.87 fsec. (c) The power spectral densities $S(\Omega)$, plotted vs wavelength λ, for the data shown in panels (a) and (b). (d) The FWHM (squares) of the measured interferograms for gratings of different chirp coefficients are plotted on the left ordinate. The biphoton flux per mW of pump power (circles) are plotted on the right ordinate.

It should be pointed out that the semiconductor single-photon APDs that have been used in our experiments (EG&G-SPCM-AQR-15) have a limited bandwidth, particularly in the near-infrared region. An even narrower HOM dip would emerge if we use of broader bandwidth devices, such as SSPDs. Note also that the biphotons that were employed in our experiments were far from being transform-limited. Conversion to transform-limitedness by use of the pulse compression techniques that are used routinely in ultra-fast optics would significantly compress the biphoton wave function.

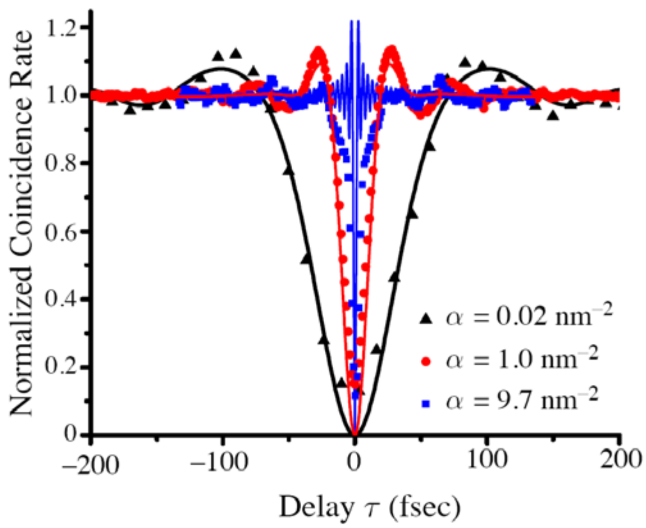

Figure 3. Normalized Hong-Ou-Mandel (HOM) coincidence interferograms (dips) for various values of the chirp coefficient α. The symbols represent the measured data points whereas the solid curves are the corresponding numerical simulations. The FWHM of the measured dips are 77, 19.1, and 7.16 fsec for three values of the chirp parameter α.

III. <u>Future Plans</u>

Our initial success in experimentally demonstrating the concept of Q-OCT in simple samples has been encouraging. However, a number of challenges have frustrated practical applications of the technique, including the limited axial resolution and the low flux of entangled-photon pairs produced by the source. These challenges have been addressed systematically by making modifications in the light source, the systems layout, and the detection system. As a result of this continuing research, the axial resolution of Q-OCT has been enhanced substantially (from 18.5-μm axial resolution reported in early experiments to 1.1 μm in this year's results). Likewise, the rate of entangled photon flux has increased by an order of magnitude. Combined enhancement of resolution and photon flux continues to be a challenge. We are presently working on measuring B-scan images from samples enhanced with gold nanoparticles. This is a new approach to circumventing the low photon flux density in Q-OCT. Earlier efforts at scanning in the transverse direction were not successful because of the substantial drop of visibility of the Q-OCT interferograms resulting from focusing the probe beam. A major study of this problem conducted last year has led to solutions based on compensating the lens effect in the probe beam with pairs of lenses in the reference beam. The solution of this problem last year has opened the door to B-scan measurement, a principal goal for this year. This will naturally be followed by imaging real biological samples, for which classical OCT has been successful. This ultimate goal of the project is being pursued in direct collaboration with Gordon-CenSSIS partners with biological expertise and facilities.

IV. Gordon-CenSSIS Strategic Goals and Legacy

The fundamental research pursued in this project complements efforts in the two principal areas of the Gordon-CenSSIS fundamental sensor research — nonlinear-wave imaging and dual-wave imaging. Also, because of the special nature of Q-OCT, the mathematics of signal recovery is different from that in conventional OCT, and the solution of related inverse problems can benefit from the tools of numerical modeling and image processing algorithms developed by the R2 group, and eventually the computer visualization algorithms pursued by the R3 group.

As a technique based on 3-D optical microscopy (scanning in the transverse direction and tomography in the axial direction), this project is fundamentally and practically related to the S1 driver. As soon as the practical capabilities of Q-OCT are established, a stronger link with S1 is expected. This will possibly take the form of adding Q-OCT as a new modality in the fusion microscope, or sharing expertise in algorithmic development.

It is not possible to realize the full potential of this new imaging tool in real subsurface imaging applications without the large resources and diverse expertise available at Gordon-CenSSIS. For example, the real biological applications of Q-OCT cannot be pursued without the Center's BioBED expertise and facilities. Once established, Q-OCT could have as wide an array of applications as conventional OCT. This could not be accomplished without access to real samples and biological expertise.

V. Broader Impact

This research deals with a new and powerful modality of subsurface optical sensing and imaging with many potential applications. Advantages include greater axial resolution and higher signal-to-background ratio, immunity to dispersion and hence deeper subsurface penetration, and non-destructive probing of light sensitive materials. Since the quantum information technology is becoming popular, it is important to see its scope extend to the image processing community. It is also essential to educate students about this new paradigm and equip them to deal with its potential applications. Four Ph.D. students have already finished theses in this area and other students are in the pipeline.

VI. Project Budget and Sustainability

The progress made in our efforts under the Gordon-CenSSIS program has helped us obtain additional support from a DOD MURI program for developing photon-counting optical coherence tomography, in both classical and quantum implementations. This offers an additional and synergistic direction for improving the performance of this rather remarkable optical-sectioning technique.

VII. References Cited

[1] Huang, D., Swanson, E.A., Lin, C.P., Schuman, J.S., Stinson, W.G., Chang, W., Hee, M.R., Flotte, T., Gregory, K., Puliafito, C.A., and Fujimoto, J.G., "Optical coherence tomography," *Science,* vol. 254, pp. 1178-1181, 1991.

[2] J. G. Fujimoto, M. E. Brezinski, G. J. Tearney, S. A. Boppart, B. E. Bouma, M. R. Hee, J. F. Southern, and E. A. Swanson, "Optical biopsy and imaging using optical coherence tomography," *Nature Med,* vol.1, pp. 970-972, 1995.

[3] A. F. Fercher, "Optical coherence tomography," *J. Biomed. Opt.,* vol. 1, pp. 157-173, 1996.

[4] J. M. Schmidt, "Optical coherence tomography (OCT): A review", *IEEE J. Select. Topics Quantum Electron*, vol.5, pp 1205-1215, 1999.

[5] M. R. Hee, J. A. Izatt, E. A. Swanson, D. Huang, J. S. Schuman, C. P. Lin, C. A. Puliafito, and J. G. Fujimoto, "Optical Coherence Tomography of the Human Retina", *Archives of Ophthalmology*, vol. 113, pp 325-332, 1995.

[6] M. Brezinski and J. G. Fujimoto, "Optical coherence tomography: High-resolution imaging in nontransparent tissue", *IEEE J. Select. Topics Quantum Electron*, vol. 5, pp 1185-1192, 1999.

[7] J. G. Fujimoto, S. A. Boppart, G. J. Tearney, B. E. Bouma, C. Pitris, and M. E. Brezinski, "High resolution in vivo intra-arterial imaging with optical coherence tomography", *Heart*, vol. 82, pp 128-133, 1999.

[8] J. Welzel, "Optical Coherence Tomography in Clinical Examination of Skin Cancer," *Skin Res. Technol.*, vol. 7, no. 1, 2001.

[9] W. Drexler, U. Morgner, R. K. Ghanta, F. X. Kartner, J. S. Schuman, and J. G. Fujimoto, "Ultrahigh-resolution ophthalmic optical coherence tomography," *Nature Med*, vol. 7, pp 502-507, 2001.

[10] C. K. Hitzenberger, A. Baumgartner, W. Drexler, and A. F. Fercher, "Dispersion effects in partial coherence interferometry: implications for intraocular ranging," *J. Biomed. Opt.*, vol. 4, pp 144-151, 1999.

[11] C. K. Hitzenberger, A. Baumgartner, W. Drexler, and A. F. Fercher, "Dispersion compensation for optical coherence tomography depth-scan signals by a numerical technique", *Opt. Comm.*, vol. 204, pp 67-74, 2002.

[12] E. D. J. Smith, A. V. Zvyagin, and D. D. Sampson, "Real-time dispersion compensation in scanning interferometry", *Opt. Lett.*, vol. 27, pp 1998-2000, 2002.

[13] A. F. Fercher, C. K. Hitzenberger, M. Sticker, R. Zawadzki, B. Karamata, and T. Lasser, "Numerical dispersion compensation for Partial Coherence Interferometry and Optical Coherence Tomography", *Opt. Express*, vol. 9, no. 12, pp 610-615, 2001.

[14] A. F. Fercher, C. K. Hitzenberger, M. Sticker, R. Zawadzki, B. Karamata, and T. Lasser, "Dispersion compensation for optical coherence tomography depth-scan signals by a numerical technique," *Opt. Comm.*, vol. 204, no. 1-6, pp 67-74, 2002.

[15] D. Branning, A. L. Migdall, and A. V. Sergienko, "Simultaneous Measurement of group and phase delay between two photons," *Phys. Rev.* A, vol. 62, pp 063808, 2000.

[16] M. Hayat, S. Abdullah, A. Joobeur, and B. Saleh, "Maximum likelihood image estimation using photon-correlated beams," *IEEE Transactions on Image Processing*, vol.11, pp 838-846, Aug. 2002.

[17] A. F. Abouraddy, K. C. Toussaint, Jr., A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, "Ellipsometric Measurements using Photon Pairs Generated by Spontaneous Parametric Down-Conversion," *Opt. Lett.*, vol. 26, pp 1717-1719, Nov. 2001.

[18] A. F. Abouraddy, B. E. A. Saleh, A. V. Sergienko, M. C. Teich "Role of Entanglement in Two-Photon Imaging" *Physical Review Letters*, vol. 87, pp 123602, Sept. 2001.

[19] A. F. Abouraddy, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, "Quantum Holography", *Optics Express*, vol. 9, no. 10, pp. 498-505, Nov. 2001.

[20] A. F. Abouraddy, M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, "Quantum-optical coherence tomography with dispersion cancellation," *Phys. Rev*. A, vol. 65, pp 053817, 2002.

[21] A. F. Abouraddy, M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, "Quantum-optical coherence tomography with dispersion cancellation," *Phys. Rev*. A, vol. 65, pp 053817, 2002.

[22] M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, "Demonstration of Dispersion-Cancelled Quantum-Optical Coherence Tomography," *Phys. Rev. Lett*., vol. 91, pp. 083601, Aug. 2003.

[23] M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich "Dispersion-Cancelled and Dispersion-Sensitive Quantum Optical Coherence Tomography," *Optics Express*, vol.12, pp 1353-1362, April 2004.

[24] M. C. Booth, G. Di Giuseppe, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, "Polarization-Sensitive Quantum-Optical Coherence Tomography," *Physical Review A*, vol. 69, pp 043815, Apr. 2004.

[25] S. Carrasco, J. P. Torres, and L. Torner, A. Sergienko, B. E. A. Saleh, and M. C. Teich "Enhancing the axial resolution of quantum optical coherence tomography by aperiodic quasi-phase-matching", *Optics Letters*, vol. 29, p. 2429, October 2004.

[26] K. C. Toussaint, Jr., G. Di Giuseppe, K. J. Bycenski, A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, "Quantum Ellipsometry Using Correlated-Photon Beams", *Physical Review* A, vol. 70, 023801, August 2004.

[27] S. Carrasco, J. P. Torres, and L. Torner, A. V. Sergienko, B. E. A. Saleh, and M. C. Teich "Spatial to spectral mapping in spontaneous parametric downconversion," *Physical Review* A, 043817, October 2004.

[28] F. Abouraddy, P. R. Stone, A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, "Entangled-Photon Imaging of a Pure Phase Object", *Phys. Rev. Lett.*, vol. 93, pp.213903, November 2004.

[29] M. B. Nasr, G. Di Giuseppe, B. E. A. Saleh, A. V. Sergienko, "Generation of high-flux ultra-broadband light by bandwidth amplification in spontaneous parametric downconversion," *Optics Communications*, vol. 246, pp. 521, Feb. 2005.

[30] B. E. A. Saleh, M. C. Teich, and A. V. Sergienko, "Noise in photon-correlation imaging with thermal and entangled photons," *SPIE Conference on Fluctuations and Noise in Photonics and Quantum Optics III*, Austin, Texas, May 2005.

[31] Carrasco, S., Nasr, M. B., Sergienko, A. V., Saleh, B. E. A., Teich, M. C., Torres, J. P. and Torner, L., "Broadband light generation by noncollinear Parametric Down-Conversion," *Opt. Lett.,* vol. 31, pp. 253-255, January 2006.

[32] Carrasco, S., Sergienko, A. V., Saleh, B. E. A., Teich, M. C., Torres, J. P., and Torner, L., "Spectral Engineering of Entangled Two-Photon States," *Phys. Rev.* A, vol. 73, pp. 063802, June 2006.

[33] Booth, M. C., Saleh, B. E. A., Sergienko, A. V., and Teich, M. C., "Temperature and Wavelength Dependence of Fermi-Tail Photoemission and Two-Photon Photoemission from Multialkali Semiconductors," *J. Applied Physics*, vol. 100, pp. 023521, July 2006.

[34] Guillet de Chatellus, H., Sergienko, A. V., Saleh, B. E. A., Teich, M. C., and Di Giuseppe, G., "Non-collinear and Non-Degenerate Polarization-Entangled Photon Generation via Concurrent Type-I Parametric Downconversion in PPLN," *Opt. Express,* vol. 14, pp. 10060-10072, October 2006.

VIII. <u>Documentation</u>

A. Publications Acknowledging NSF Support

Journal Papers

J1. Abouraddy, A.F., Yarnall, T., Saleh, B. E. A. and Teich, M. C., "Violation of Bell's Inequality with Continuous Spatial Variables," *Phys. Rev. A,* vol. 75, article 052114, May 2007.

J2. Yarnall, T., Abouraddy, A. F., Saleh, B. E. A. and Teich, M. C., "Experimental Violation of Bell's Inequality in Spatial-Parity Space," *Phys. Rev. Lett.*, vol. 99, article 170408, Oct. 2007.

J3. Yarnall, T., Abouraddy, A. F., Saleh, B. E. A. and Teich, M. C., "Synthesis and Analysis of Entangled Photonic Qubits in Spatial-Parity Space," *Phys. Rev. Lett.*, vol. 99, article 250502, Dec. 2007.

Conference Papers

C1. Bonato, C., Sergienko, A. V., Saleh, B. E. A. and Teich, M. C., "Two-Photon Spectral Coherency Matrix and Multi-Parameter Optical Entanglement," *Quantum Electronics and Laser Science Conference*, Baltimore MD, pp. 1, May 2007.

C2. Abouraddy, A. F., Yarnall, T., Saleh, B. E. A. and Teich, M. C., "Violation of Bell's Inequality with continuous spatial variables," *Quantum Electronics and Laser Science Conference*, Baltimore MD, pp. 1-2, May 2007.

C3. A.Sergienko, C. Bonato, B. E. A. Saleh, and M. C. Teich, "Two-Photon Spectral Coherency Matrix and Multi-Parameter Optical Entanglement," European Conference on Lasers and Electro-Optics and the International Quantum Electronics Conference (CLEOE-IQEC), Munich (Germany), p. 1, Jun. 2007.

C4. Abouraddy, A. F., Yarnall, T., Saleh, B. E. A. and Teich, M. C., "Violation of Bell's Inequality in Spatial Parity Space," *International Conference on Quantum Information (ICQI)*, Rochester NY, paper JWC34, Jun. 2007.

C5. Yarnall, T., Abouraddy, A. F., Saleh, B. E. A. and Teich, M. C., "Generation and Analysis of Entangled Two-Photon States in Spatial-Parity Space," *International Conference on Quantum Information (ICQI)*, Rochester NY, paper JWC31, Jun. 2007.

C6. Nasr, M. B., Sergienko, A. V., Saleh, B. E. A., Teich, M. C., Hum, D. and Fejer, M. M., "Generation of Ultra-Broadband Spontaneous Parametric Down Conversion from Chirped Periodically Poled Stoichiometric Lithium Tantalate," *International Conference on Quantum Information (ICQI)*, Rochester NY, paper IThH5, Jun. 2007.

C7. Sergienko, A. V., Jaspan, M., Minaeva, O., Saleh, B. E. A. and Teich, M. C., "Engineering Robust Optical Entanglement for Quantum Communication," *International Conference on Quantum Information (ICQI)*, Rochester NY, paper IFC1, Jun. 2007.

C8. Saleh, B. E. A., "Entangled Qubits in Photonic Spatial-Parity Space," *Royal Society Conference on Photons, Atoms, and Qubits (PAQ07)*, London UK, Sep. 2007.

C9. Saleh, M. F., Dal Negro, L. and Saleh, B. E. A., "Optical Switching by Parametric Amplification in Nonlinear Photonic Crystal Microcavities," *Frontiers in Optics*, San Jose CA, paper FMD5, Sep. 2007.

B. Workshops and Seminars

1. Teich, M. C., "Multi-Photon and Entangled-Photon Imaging and Lithography," General Physics Seminar, Invited Lecture, Louisiana State University, Baton Rouge, Louisiana, February 2007.
2. Teich, M. C., "Quantum Optical Coherence Tomography," Photonics Center Faculty Forum, Boston University, Boston, Massachusetts, April 2007.
3. Teich, M. C., "Multi-Photon and Entangled-Photon Imaging and Lithography," Department of Electrical & Computer Engineering Colloquium, University of New Mexico, and IEEE LEOS Albuquerque Chapter Lecture, Albuquerque, New Mexico, May 2007.
4. Teich, M. C., "Multi-Photon and Entangled-Photon Imaging and Lithography," Invited Colloquium, The Institute of Photonic Sciences (ICFO), Castelldefels (Barcelona), Spain, July 2007.
5. Saleh, B. E. A., "Classical and Quantum Optical Coherence Imaging and Tomography," CREOL, University of Central Florida, August 28, 2007.
6. Saleh, B. E. A., "Entangled Qubits in Photonic Spatial Parity Space: Recent Measurement of Bell's Inequality Violation," Imperial College, September 7, 2007.
7. Saleh, B. E. A., "Quantum Optical Coherence Tomography with Temporally Compressed Biphotons," Imperial College, September 10, 2007.