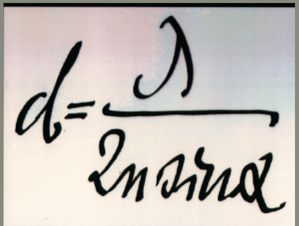
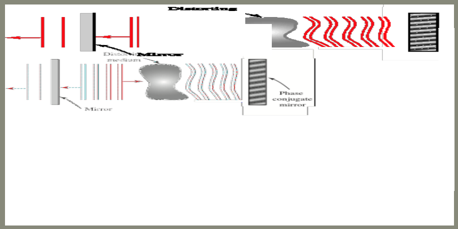
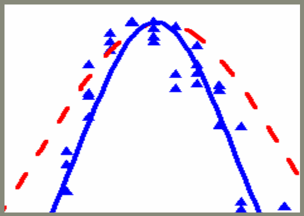
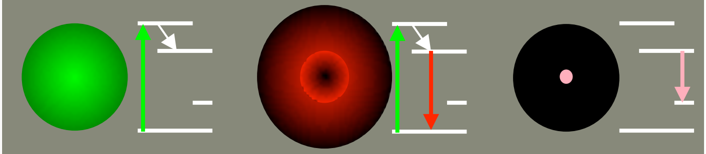
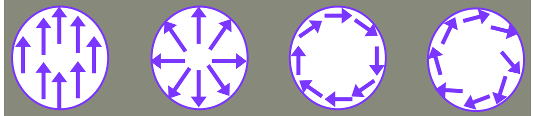
When Can Quantum Imaging Benefit from Entangled Photons?

B. E. A. Saleh, A. V. Sergienko, M. C. Teich
Quantum Imaging Laboratory
Boston University

Quantum-Imaging MURI Annual Review
NWU, 13 November 2009

NONLINEAR AND ENTANGLED-PHOTON IMAGING

Linear Optics	Nonlinear Optics	Quantum Optics
Scalar  $d = \frac{\lambda}{2n\sin\alpha}$	Phase conjugation 	Quadrature-squeezed imaging
Super-resolution 	STED (stimulated emission depletion microscopy) 	Number-squeezed imaging
Vector beam 	Multiphoton imaging	Entangled-photon imaging

Optical Imaging = Extracting the spatial distribution of a remote object (static or dynamic, 2D or 3D, scalar or vector, B/W or color).

EXAMPLES

Multiphoton

- Absorption

T: Göppert-Mayer (1931)
E: Franken *et al*. (1961)

- Photoemission

T: Bloch (1964)
E: Teich & Wolga (1964)

- Microscopy

T: Sheppard & Kompfner (1978)
E: Denk *et al.* (1990)

- Lithography

T:
E: 3D..Maruo & Kawata (1997)

- OCT (Optical Coherence Tomography – Single Photon)

T: Youngquist *et al*. (1987)
E: Huang *et al*. (1991)

Entangled-Photon

- Absorption

T: Fei *et al.* (1997)
E: Dayan *et al.* (2004)

- Photoemission

T: Lissandrin *et al.* (2004)
E:

- Microscopy

T: Teich & Saleh (1997)
E:

- Lithography

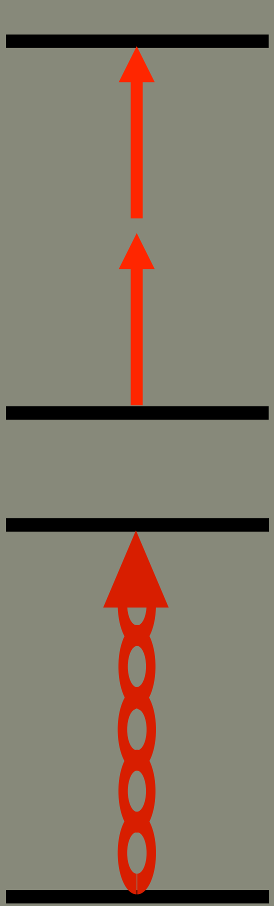
T: Boto *et al.* (2000)
E:

- QOCT (Quantum Optical Coherence Tomography – 2-Photon)

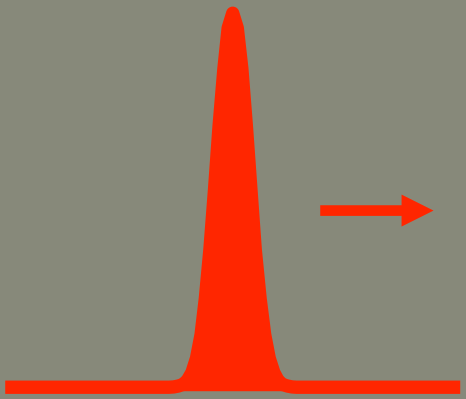
T: Abouraddy *et al.* (2002)
E: Nasr *et al.* (2003)

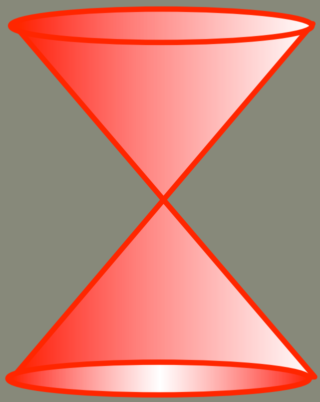
Multiphoton Excitation vs Entangled-Photon Excitation

Optics & Photonics News 11, 40 (2000)

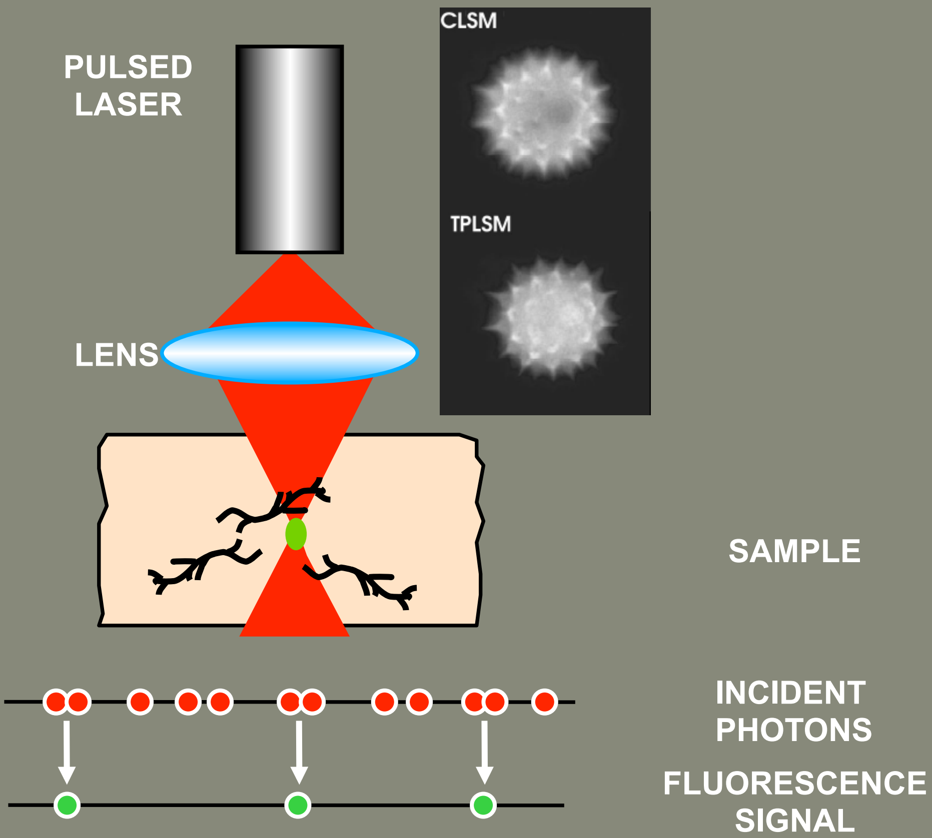


- For classical light, probability of simultaneous absorption of *n* photons $\propto I^n$
- Multiphoton absorption more likely in regions of high light intensity
- Ultrafast light pulses have high peak intensities, allowing multiphoton excitation at low average power
- Excitation (photoemission, fluorescence, lithography, photochemistry), can be localized for *n* photons
- For entangled-*n*-photon light, probability of simultaneous absorption of *n* photons $\propto I$





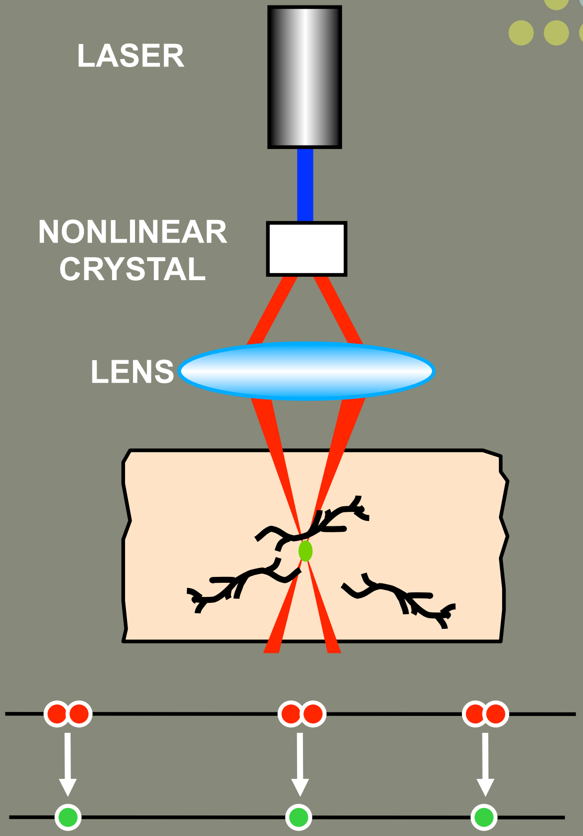
Multiphoton Microscopy



ADVANTANGES: Longer wavelength source penetrates more deeply into tissue. Excitation only occurs only at focal region – eliminates pinhole detectors, increases SNR, and provides optical sectioning capabilities.

DISADVANTAGES: Large photon flux is required. Samples must have broad upper-energy levels. Expensive titanium:sapphire laser system. Sample photodamage.

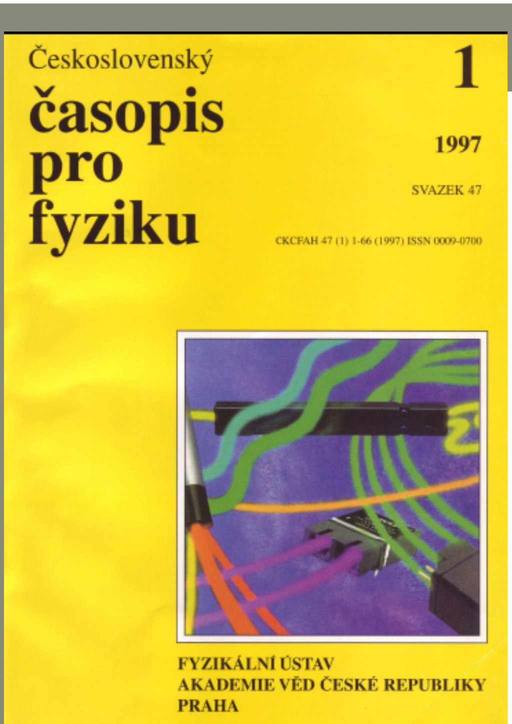
Entangled-Photon Microscopy



ADVANTANGES: Guaranteed photon pairs create comparable depth penetration but at substantially reduced light levels. Samples do not require broad upper-energy levels. Pump laser can be continuous-wave or pulsed.

DISADVANTAGES: Overall photon flux is low. Entangled-photon absorption cross-section and entanglement area are not well established.

After Teich and Saleh, "Mikroskopie s kvantově provázanými fotony (Entangled-Photon Microscopy)," *Československý časopis pro fyziku* **47**, 3 (1997)
U.S. Patent 5,796,477 (issued 18 August 1998)



Československý

časopis pro fyziku

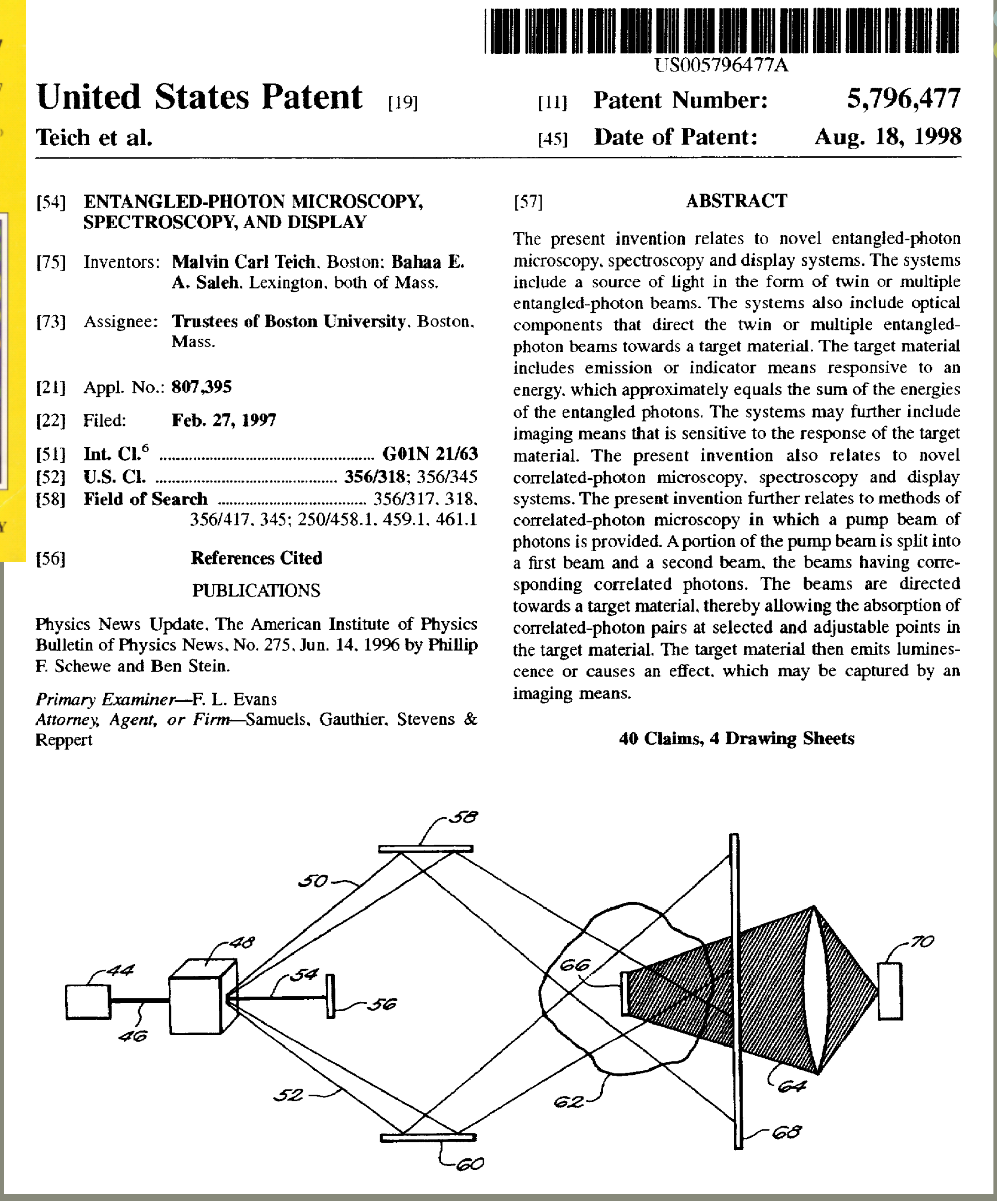
1

1997

SVAZEK 47

CKCFAH 47 (1) 1-66 (1997) ISSN 0009-0700

FYZIKÁLNÍ ÚSTAV
AKADEMIE VĚD ČESKÉ REPUBLIKY
PRAHA



US005796477A

United States Patent [19]

Teich et al.

[11] **Patent Number: 5,796,477**

[45] **Date of Patent: Aug. 18, 1998**

[54] **ENTANGLED-PHOTON MICROSCOPY, SPECTROSCOPY, AND DISPLAY**

[75] Inventors: **Malvin Carl Teich**, Boston; **Bahaa E. A. Saleh**, Lexington, both of Mass.

[73] Assignee: **Trustees of Boston University**, Boston, Mass.

[21] Appl. No.: **807,395**

[22] Filed: **Feb. 27, 1997**

[51] **Int. Cl.**^{6} **G01N 21/63**

[52] **U.S. Cl.** **356/318**; 356/345

[58] **Field of Search** 356/317, 318, 356/417, 345; 250/458.1, 459.1, 461.1

[56] **References Cited**

PUBLICATIONS

Physics News Update, The American Institute of Physics Bulletin of Physics News, No. 275, Jun. 14, 1996 by Phillip F. Schewe and Ben Stein.

Primary Examiner—F. L. Evans
Attorney, Agent, or Firm—Samuels, Gauthier, Stevens & Reppert

[57] **ABSTRACT**

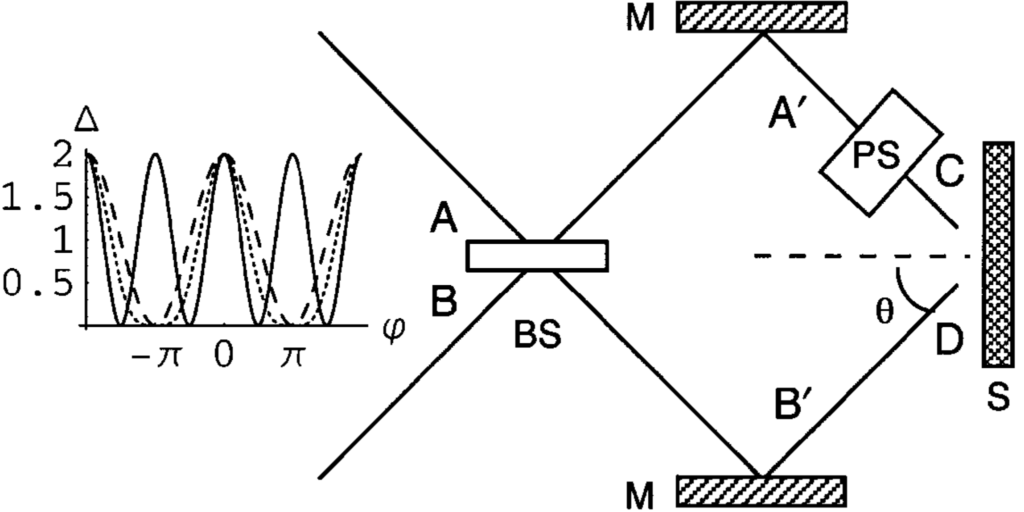
The present invention relates to novel entangled-photon microscopy, spectroscopy and display systems. The systems include a source of light in the form of twin or multiple entangled-photon beams. The systems also include optical components that direct the twin or multiple entangled-photon beams towards a target material. The target material includes emission or indicator means responsive to an energy, which approximately equals the sum of the energies of the entangled photons. The systems may further include imaging means that is sensitive to the response of the target material. The present invention also relates to novel correlated-photon microscopy, spectroscopy and display systems. The present invention further relates to methods of correlated-photon microscopy in which a pump beam of photons is provided. A portion of the pump beam is split into a first beam and a second beam, the beams having corresponding correlated photons. The beams are directed towards a target material, thereby allowing the absorption of correlated-photon pairs at selected and adjustable points in the target material. The target material then emits luminescence or causes an effect, which may be captured by an imaging means.

40 Claims, 4 Drawing Sheets

EXAMPLES

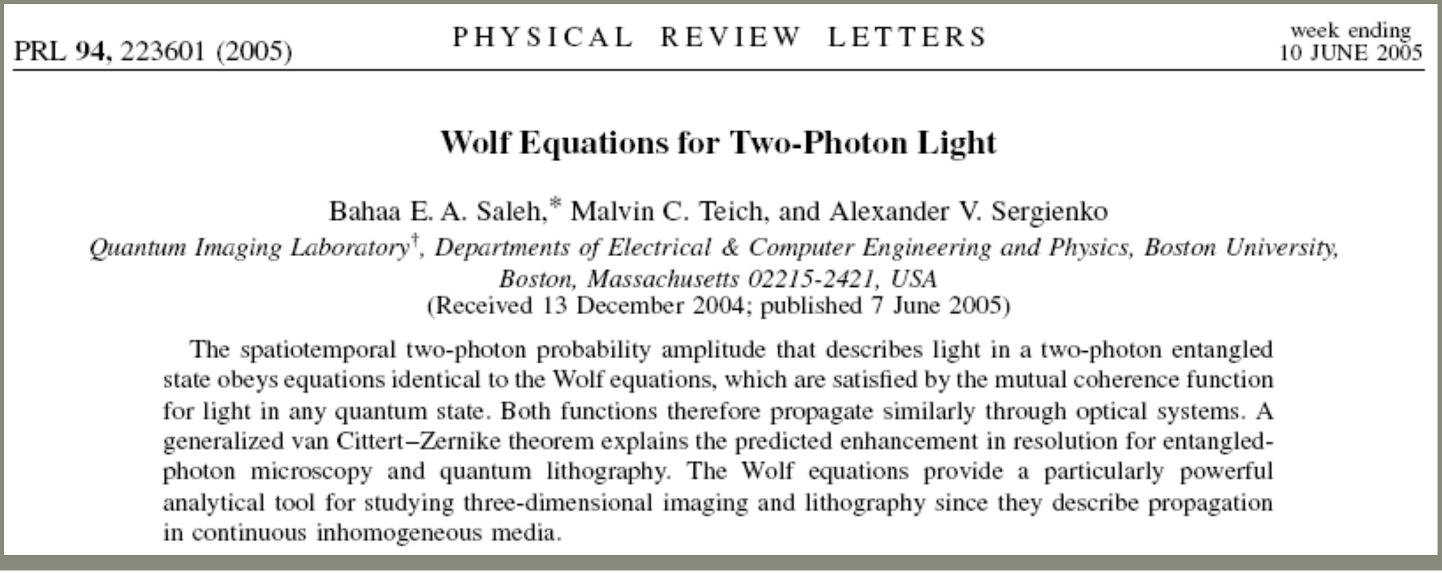
Multiphoton	Entangled-Photon
◆ Absorption	◆ Absorption
T: Göppert-Mayer (1931)	T: Fei *et al.* (1997)
E: Franken *et al.* (1961)	E: Dayan *et al.* (2004)
◆ Photoemission	◆ Photoemission
T: Bloch (1964)	T: Lissandrin *et al.* (2004)
E: Teich & Wolga (1964)	E:
◆ Microscopy	◆ Microscopy
T: Sheppard & Kompfner (1978)	T: Teich & Saleh (1997)
E: Denk *et al.* (1990)	E:
◆ Lithography	◆ Lithography
T:	T: Boto *et al.* (2000)
E: 3D..Maruo & Kawata (1997)	E:
◆ OCT (Optical Coherence Tomography – Single Photon)	◆ QOCT (Quantum Optical Coherence Tomography – 2-Photon)
T: Youngquist *et al.* (1987)	T: Abouraddy *et al.* (2002)
E: Huang *et al.* (1991)	E: Nasr *et al.* (2003)

Entangled-Photon Lithography (Theory)



After Boto, Kok, Abrams, Braunstein, Williams, and Dowling, “Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit,” *Phys. Rev. Lett.* 85, 2733 (2000)

Origin of factor of 2 resolution enhancement and validity for arbitrary masks:



PRL **94,** 223601 (2005) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2005

Wolf Equations for Two-Photon Light

Bahaa E. A. Saleh,* Malvin C. Teich, and Alexander V. Sergienko
Quantum Imaging Laboratory†, *Departments of Electrical & Computer Engineering and Physics, Boston University, Boston, Massachusetts 02215-2421, USA*

(Received 13 December 2004; published 7 June 2005)

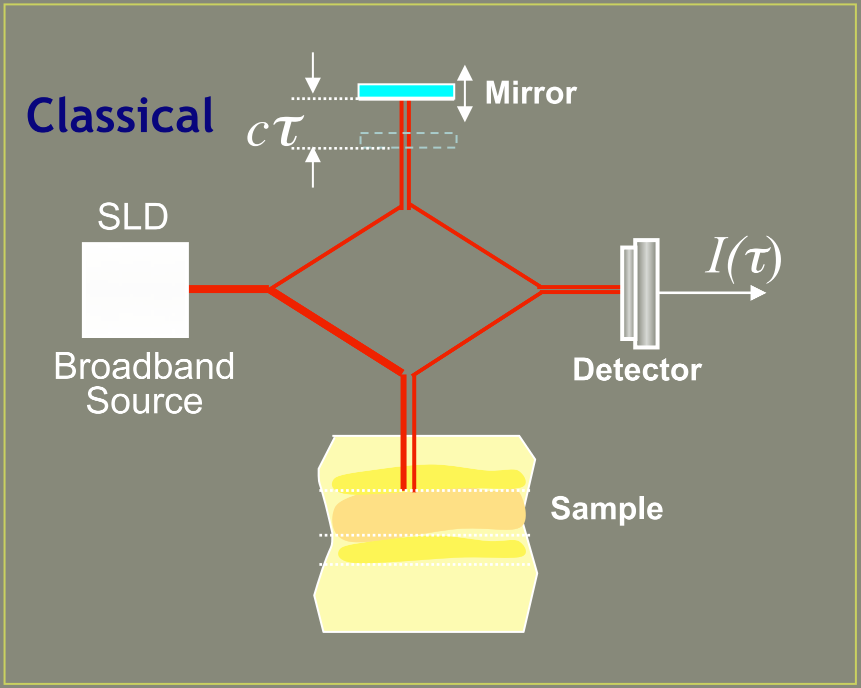
The spatiotemporal two-photon probability amplitude that describes light in a two-photon entangled state obeys equations identical to the Wolf equations, which are satisfied by the mutual coherence function for light in any quantum state. Both functions therefore propagate similarly through optical systems. A generalized van Cittert–Zernike theorem explains the predicted enhancement in resolution for entangled-photon microscopy and quantum lithography. The Wolf equations provide a particularly powerful analytical tool for studying three-dimensional imaging and lithography since they describe propagation in continuous inhomogeneous media.

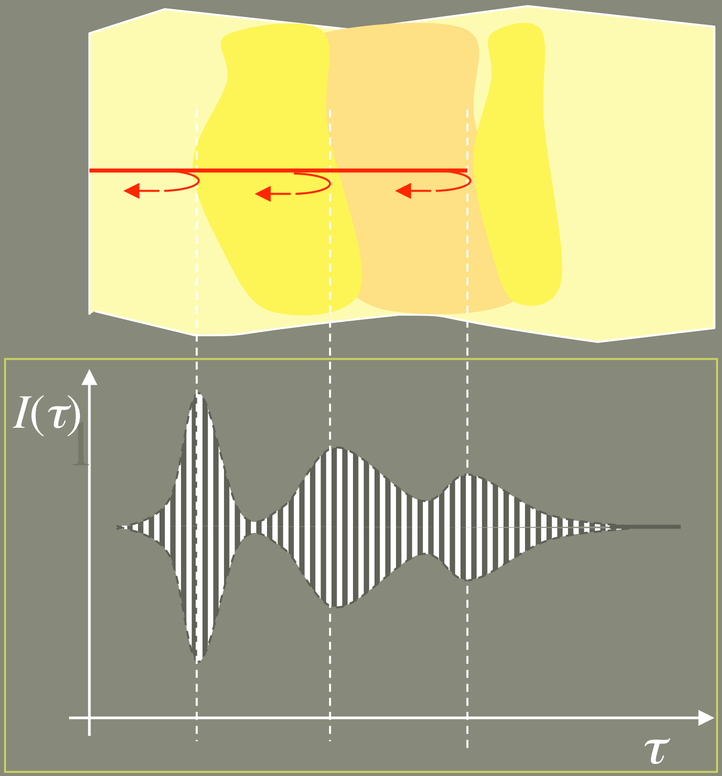
EXAMPLES

Multiphoton	Entangled-Photon
◆ **Absorption**	◆ **Absorption**
T: Göppert-Mayer (1931)	T: Fei *et al.* (1997)
E: Franken *et al*. (1961)	E: Dayan *et al.* (2004)
◆ **Photoemission**	◆ **Photoemission**
T: Bloch (1964)	T: Lissandrin *et al.* (2004)
E: Teich & Wolga (1964)	E:
◆ **Microscopy**	◆ **Microscopy**
T: Sheppard & Kompfner (1978)	T: Teich & Saleh (1997)
E: Denk *et al.* (1990)	E:
◆ **Lithography**	◆ **Lithography**
T:	T: Boto *et al.* (2000)
E: 3D..Maruo & Kawata (1997)	E:
◆ **OCT** (Optical Coherence Tomography – Single Photon)	◆ **QOCT** (Quantum Optical Coherence Tomography – 2-Photon)
T: Youngquist *et al*. (1987)	T: Abouraddy *et al.* (2002)
E: Huang *et al*. (1991)	E: Nasr *et al.* (2003)

Classical Optical Coherence Tomography (OCT)

OCT = Interferometric reflectometry using a broadband source of light (short coherence length)





Axial resolution is often of the order of a few μm

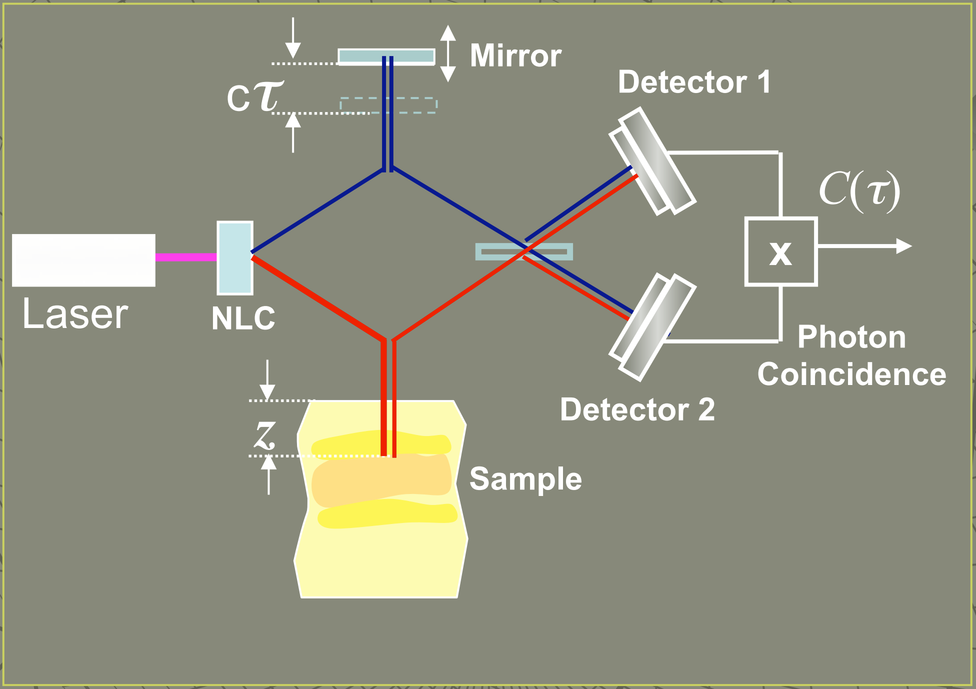
Submicron resolution is possible with fs lasers and supercontinuum light

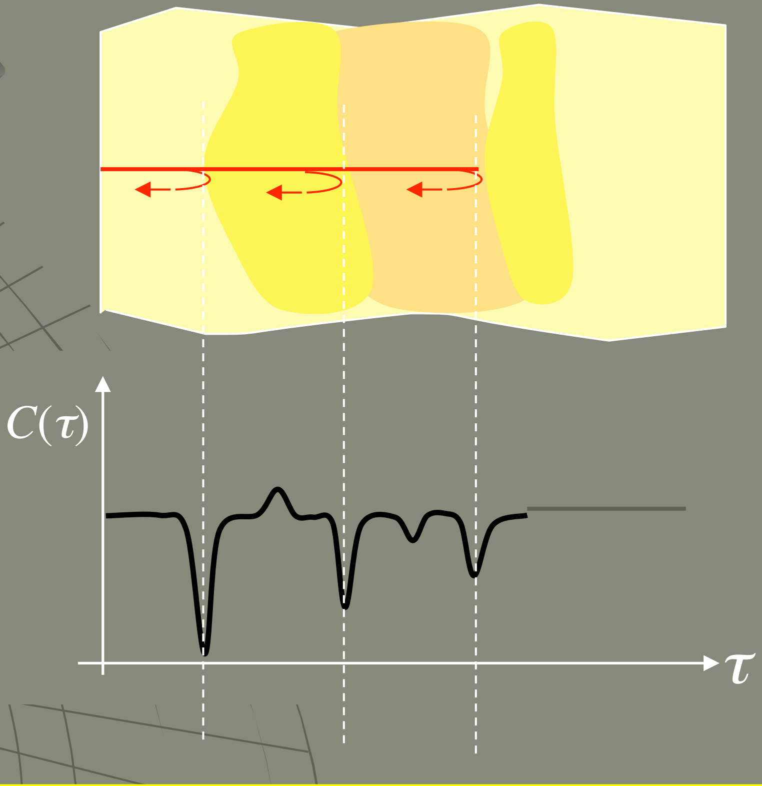
In a dispersive medium, the resolution deteriorates to tens of μm

See Youngquist, Carr, and Davies, “Optical coherence-domain reflectometry: A new optical evaluation technique,” Opt. Lett. **12**, 158–160 (1987).

Quantum Optical Coherence Tomography (QOCT)

= OCT based on quantum interferometry of spectrally-entangled photons generated by downconverted light from a nonlinear crystal



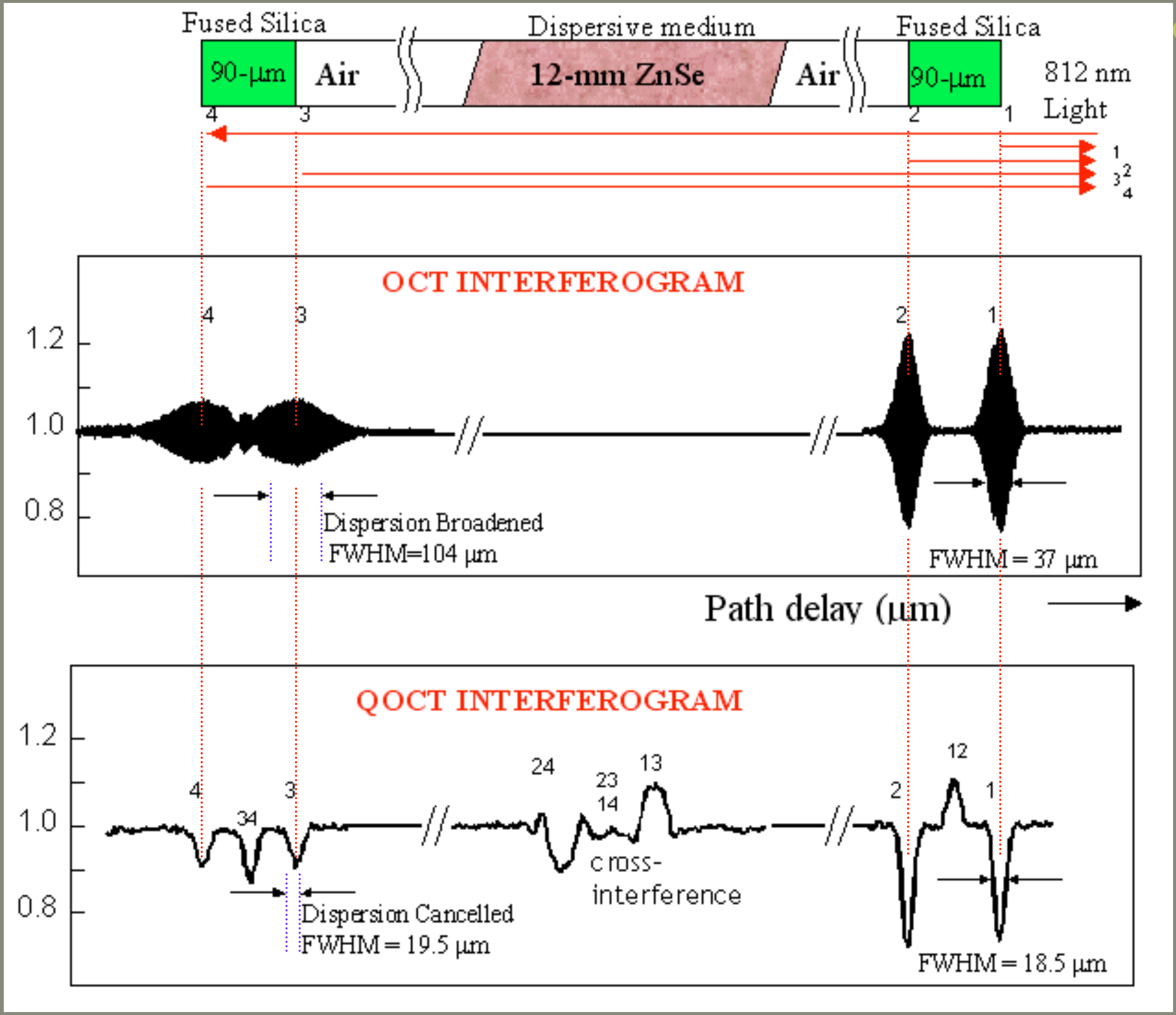


Advantages of QOCT:

- ☐ **Factor of 2 improvement in axial resolution for same spectral width**
- ☐ **Insensitivity to group-velocity dispersion w. concomitant improvement in axial resolution**

After Abouraddy, Nasr, Saleh, Sergienko, and Teich, “Quantum-Optical Coherence Tomography with Dispersion Cancellation,” *Phys. Rev. A* **65**, 053817 (2002)

Dispersion-Free QOCT (Experiment)

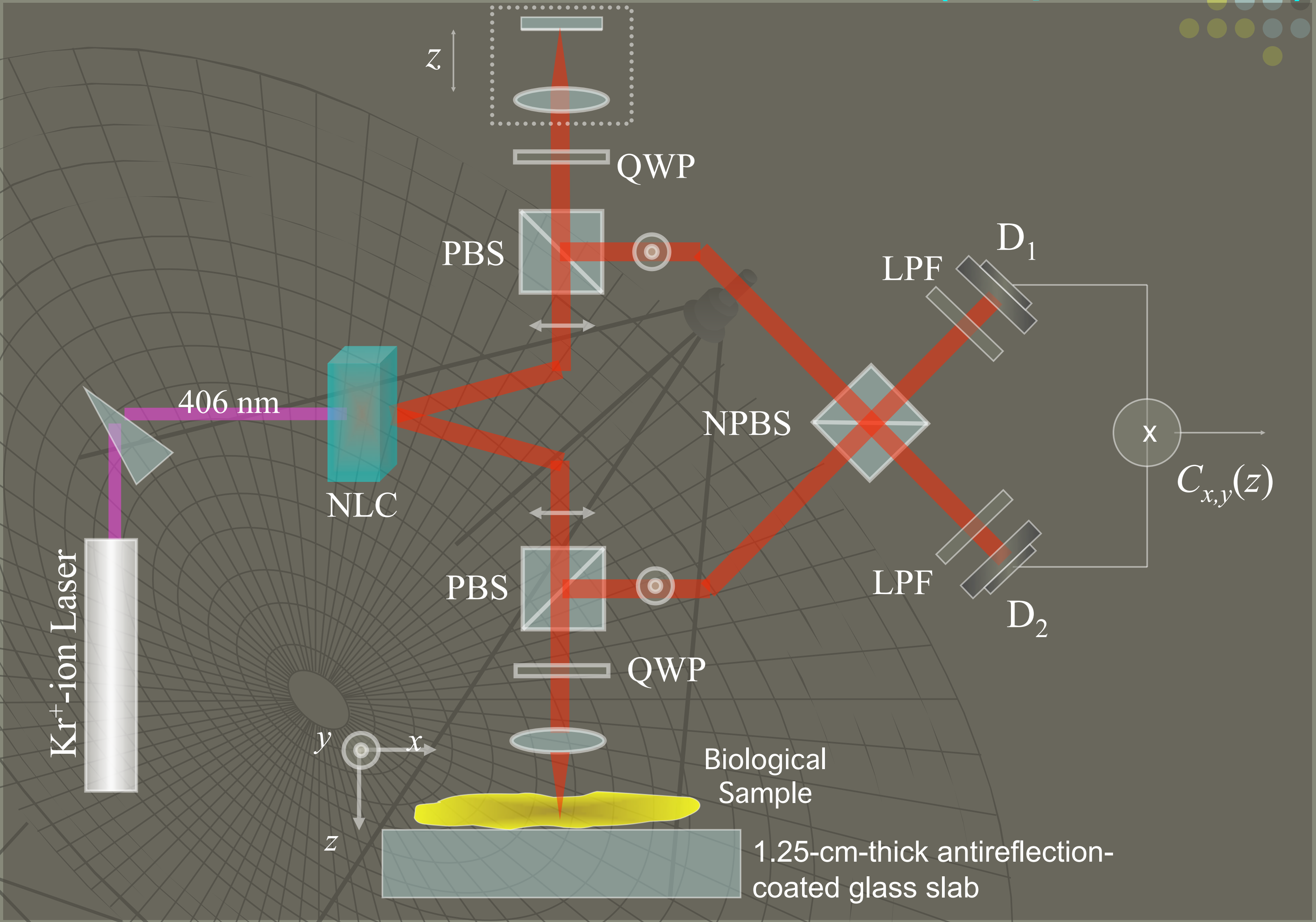


After Nasr, Saleh, Sergienko, and Teich, “Dispersion-Cancelled and Dispersion-Sensitive Quantum Optical Coherence Tomography,” *Opt. Express* **12**, 1353 (2004)

OCT vs. QOCT

- QOCT offers improved axial resolution in comparison with conventional OCT for sources of same spectral bandwidth
- Source bandwidth for QOCT governed by process of entangled-photon generation (e.g., crystal width); can be tuned
- Self-interference at each boundary immune to even-order group-velocity dispersion introduced by layers above
- Inter-boundary interference sensitive to dispersion of inter-boundary layers; dispersion parameters can thus be estimated

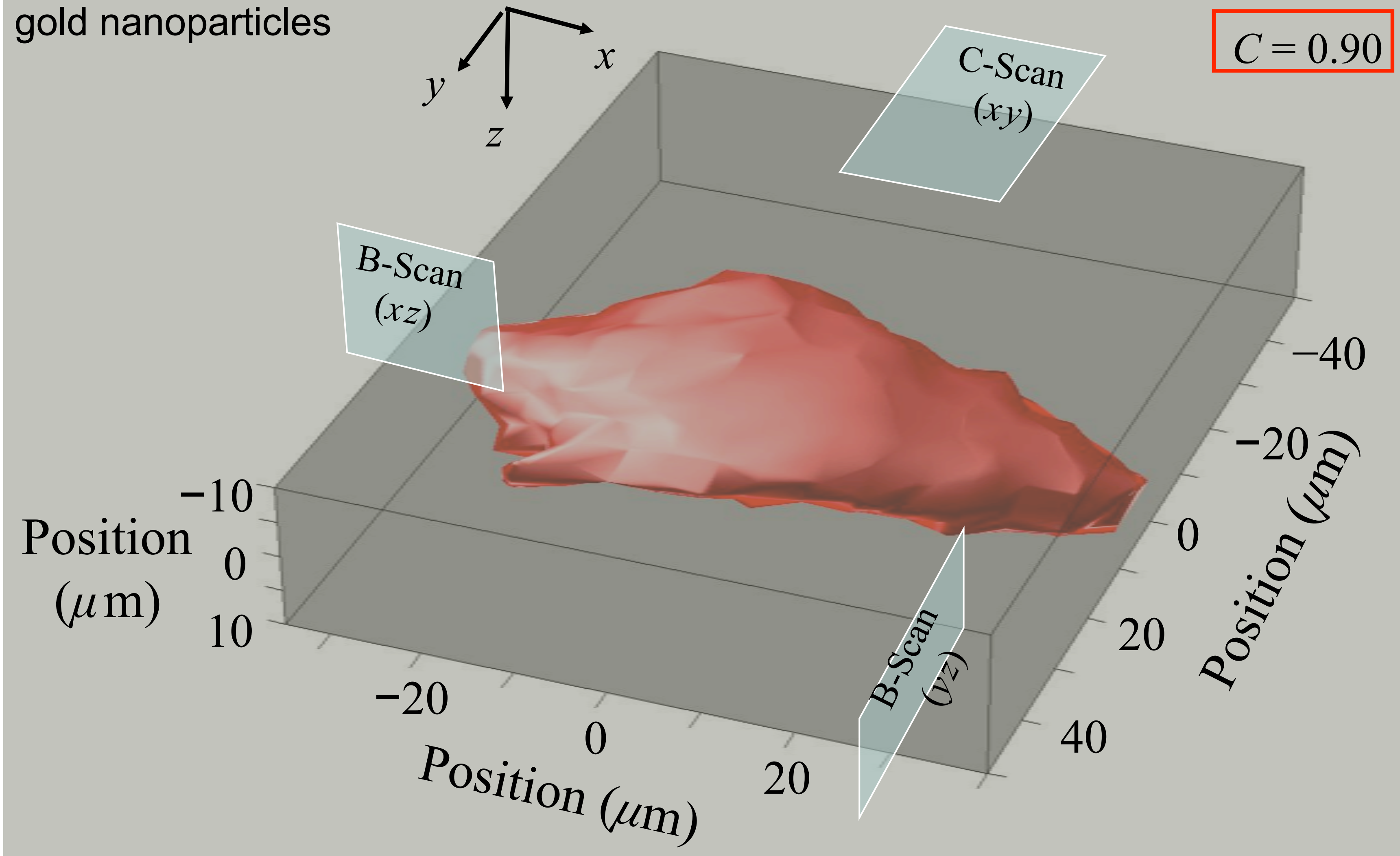
QOCT of Onion-Skin Cells in 3D (Experiment)



After Nasr, Goode, Nguyen, Rong, Yang, Reinhard, Saleh, and Teich, "Quantum Optical Coherence Tomography of a Biological Sample," *Opt. Commun.* **282**, 1154 (2009).

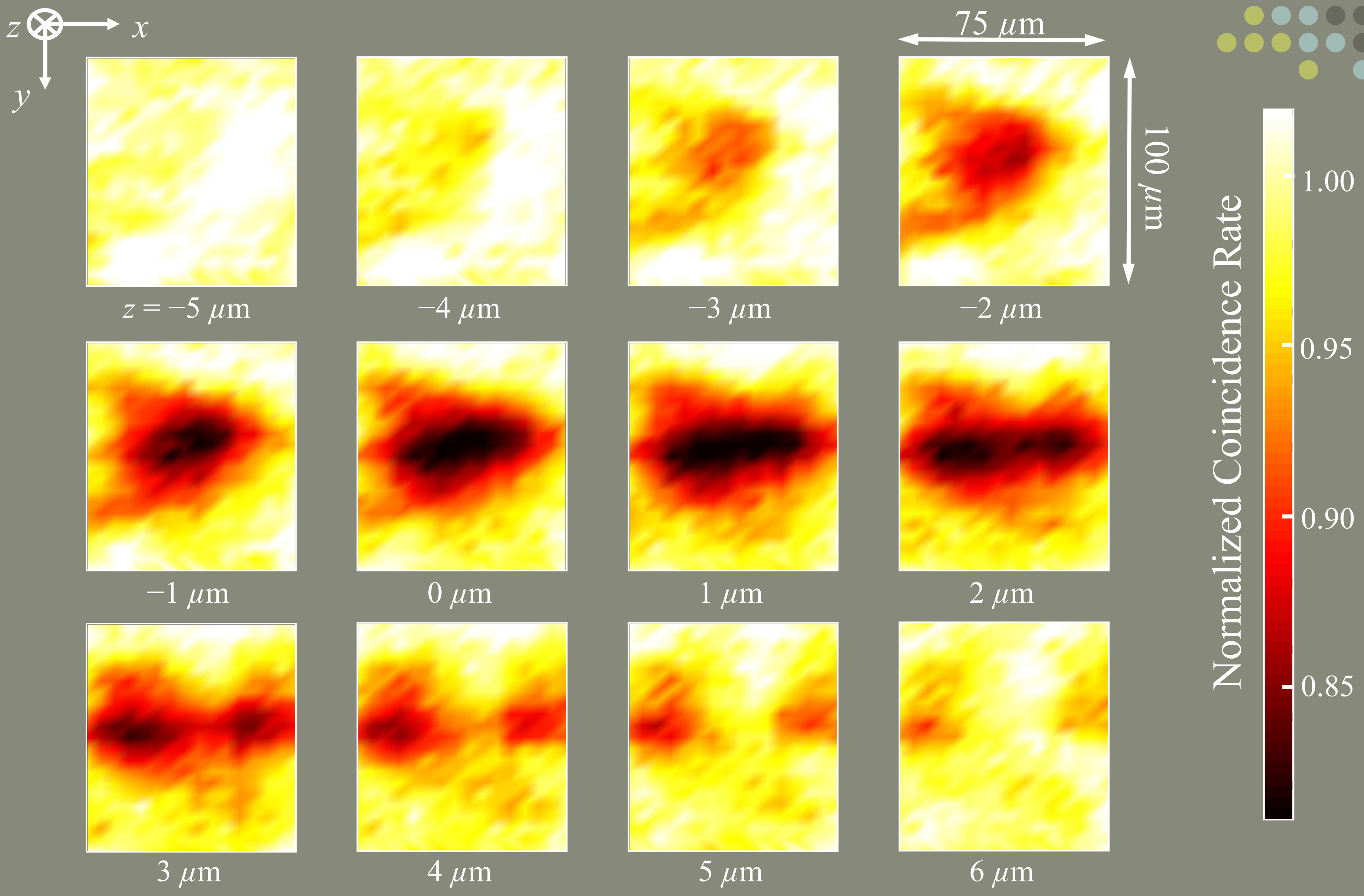
3D Contours of Constant Coincidence Rate

Sample coated with BSA-functionalized gold nanoparticles



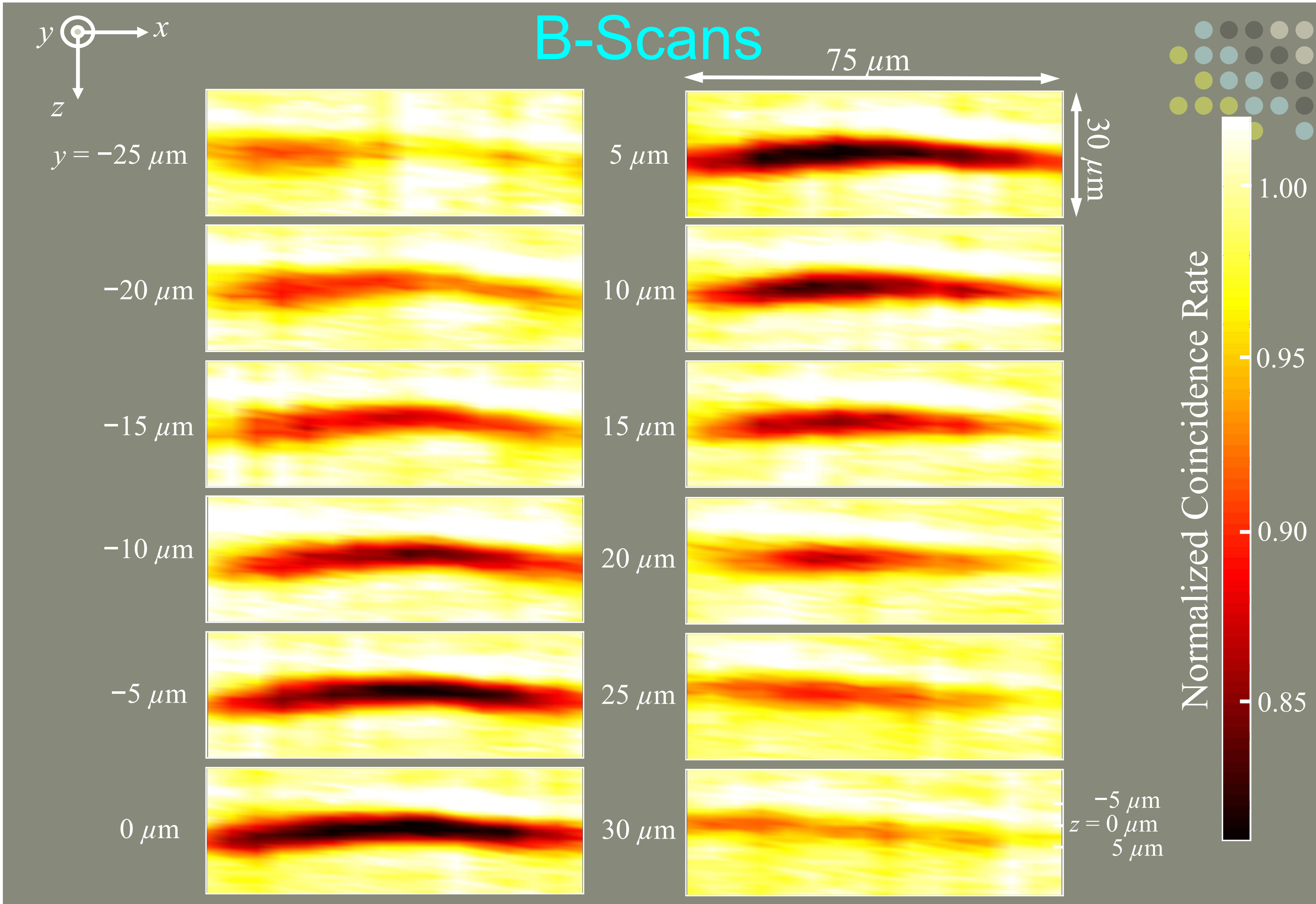
After Nasr, Goode, Nguyen, Rong, Yang, Reinhard, Saleh, and Teich, “Quantum Optical Coherence Tomography of a Biological Sample,” *Opt. Commun.* **282**, 1154 (2009).

C-Scans



After Nasr, Goode, Nguyen, Rong, Yang, Reinhard, Saleh, and Teich, "Quantum Optical Coherence Tomography of a Biological Sample," *Opt. Commun.* **282**, 1154 (2009).

B-Scans



After Nasr, Goode, Nguyen, Rong, Yang, Reinhard, Saleh, and Teich, “Quantum Optical Coherence Tomography of a Biological Sample,” *Opt. Commun.* **282**, 1154 (2009).

Applications of OCT and QOCT

- Transparent tissue such as eye: retinal nerve fiber layer, retinal thickness, contour changes in the optic disk; subcutaneous blood vessels

- Turbid media: vascular wall, plaque

- Polarization-OCT: tissues with collagen or elastin fibers: muscle, tendons; normal and thermally damaged soft tissues

Recent Improvements Enabling Biological QOCT

- Compact optical configuration
- Use of lenses to enhance spatial resolution
- Use of PBS/QWPs to increase photon flux (factor of 4)
- Enhanced sample preparation using gold nanoparticles and BSA

Continuing Challenges for QOCT

- Limited photon flux: improvement via decreased entanglement time
- Limited axial resolution: improvement via increased source bandwidth

Biological QOCT: Summary

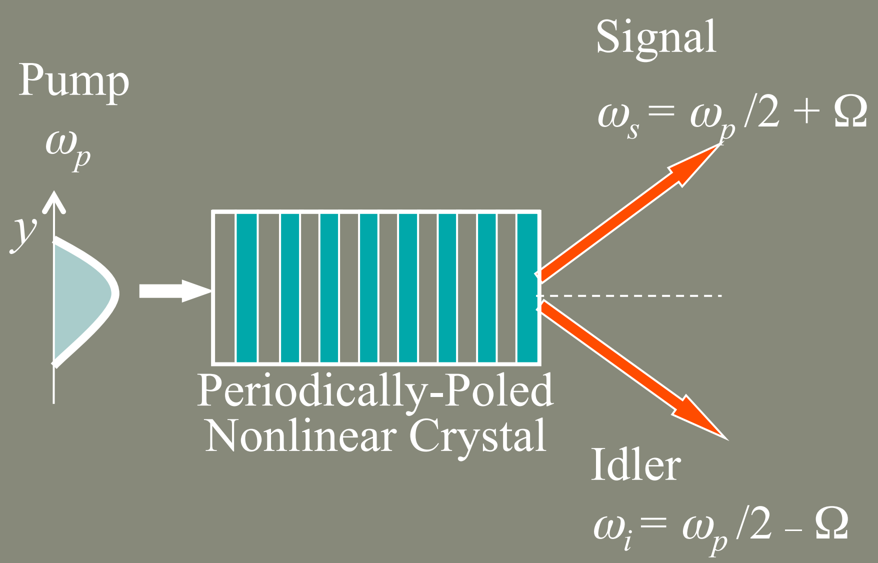
- First demonstration of the interaction of a quantum-entangled entity and a biological system (nonplanar, scattering, diffusive medium) — entanglement survived the interaction to create an image
- Demonstration of the viability of quantum 3D imaging of a biological sample
- Gold nanoparticles were used to enhance the sample reflectance — a new paradigm for quantum imaging
- Axial resolution (7.5 μm) can be improved to 1μm. Transverse resolution (12 μm) can be improved
- Scan time remains too long (but pump power was only 2 mW, corresponding to 0.5 pW of downconverted photons or 10^6 photon pairs/sec)

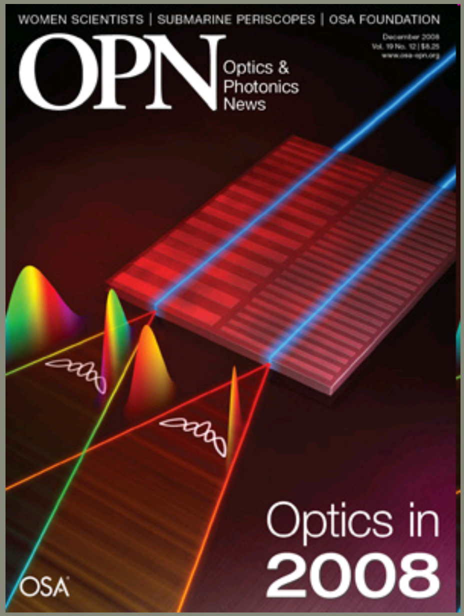
Further Advances

- Quasi-phase matched (QPM) downconversion (increased photon flux)
- Chirped quasi-phase-matched downconversion (increased flux bandwidth)
- QOCT resolution enhancement via chirped-QPM downconversion
- QOCT resolution enhancement via superconducting single-photon detectors
- Photon-counting OCT (biological) at $\lambda = 1$ μm using chirped-QPM SPDC
- Inspired quantum-mimetic implementations of QOCT
- Entangled-photon generation via guided-wave parametric downconversion
- Use of ultrafast compression techniques for generic quantum imaging
- Odd-order dispersion cancellation and aberration cancellation

Quasi-Phase-Matched (QPM) Downconversion

Chirped Quasi-Phase-Matched (QPM) Downconversion




WOMEN SCIENTISTS | SUBMARINE PERISCOPES | OSA FOUNDATION

OPN Optics & Photonics News

Optics in 2008

OSA

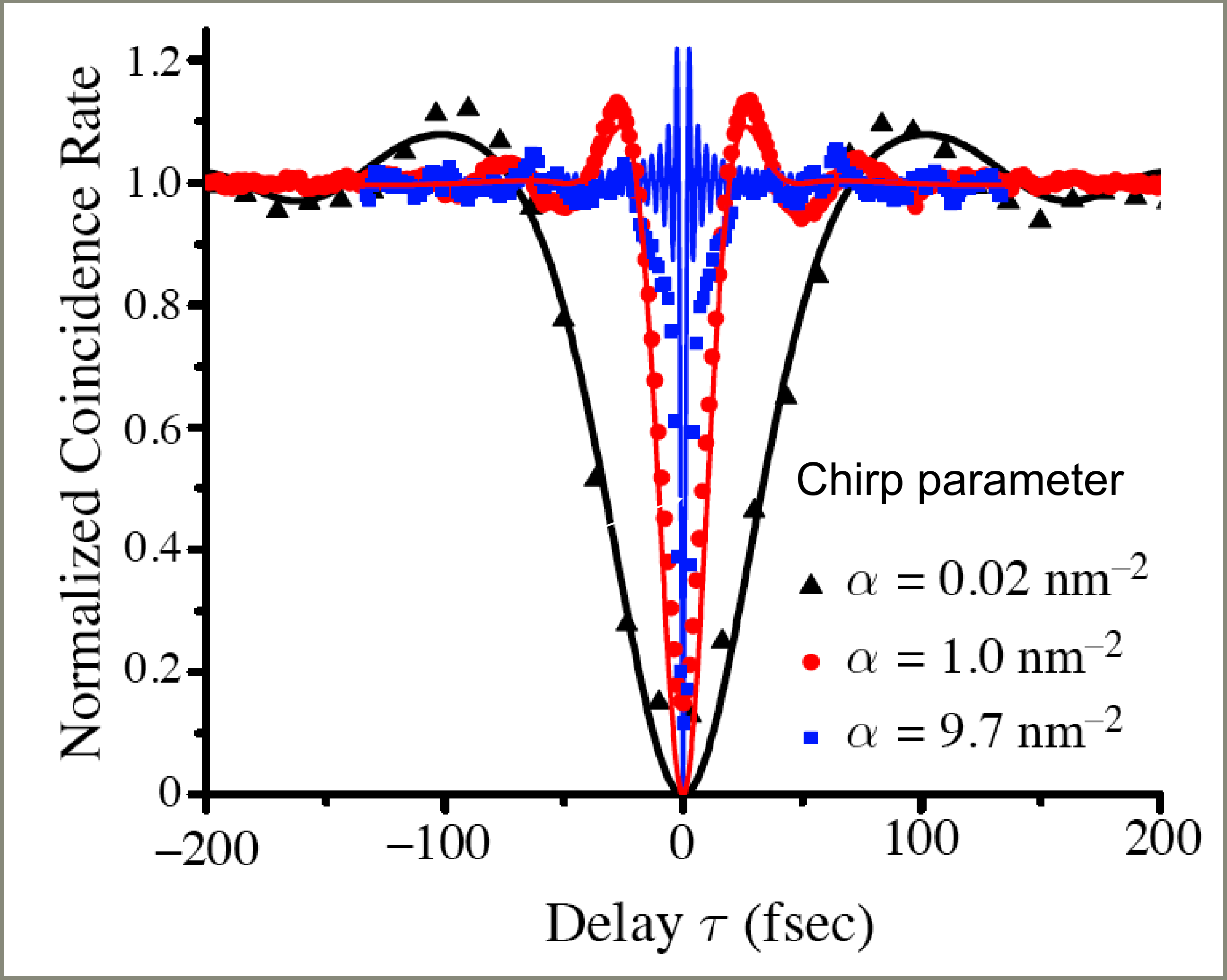
Increased Photon Flux

Increased Spectral Bandwidth

QOCT with Chirped-QPM Downconversion Enhances Resolution

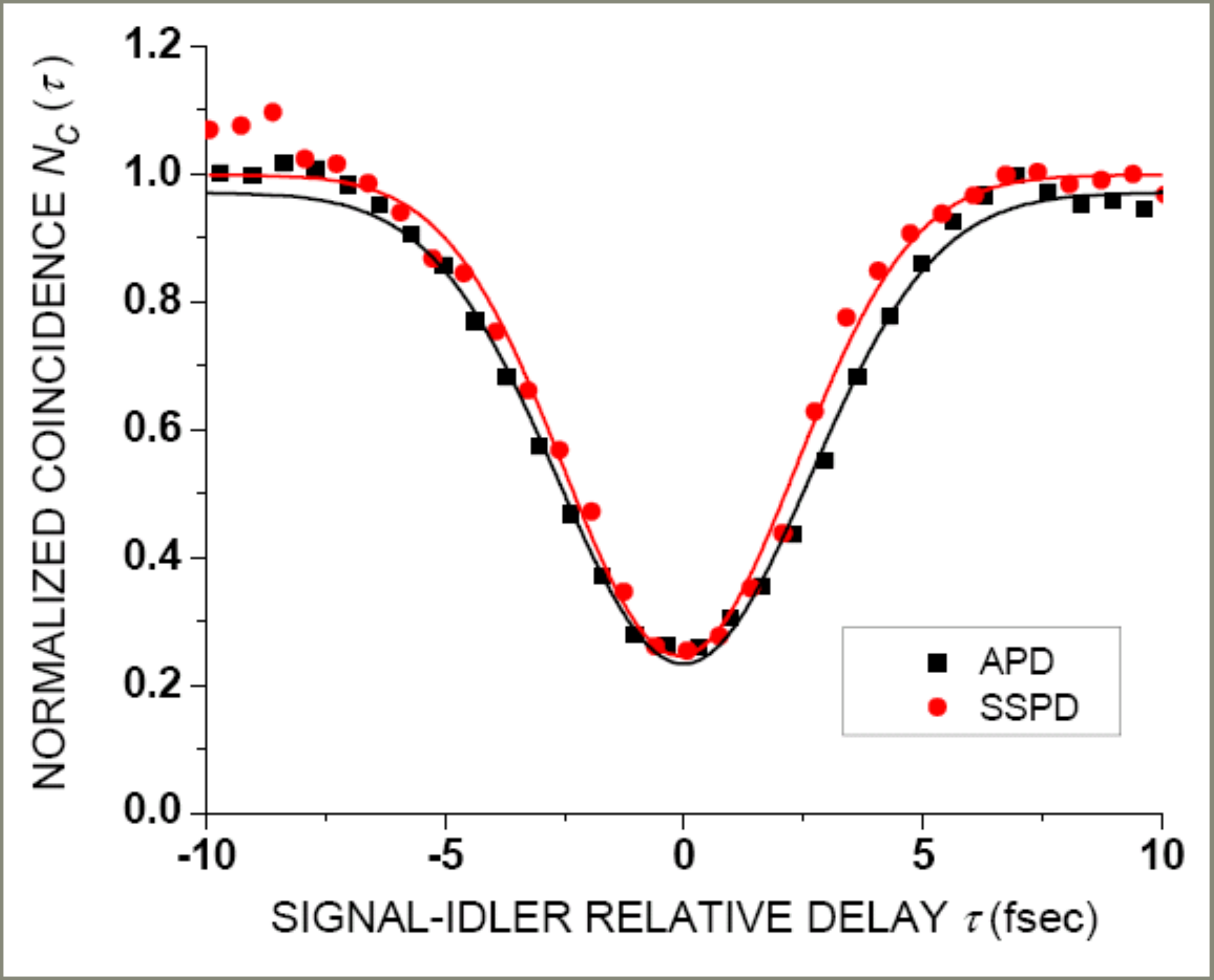
After Carrasco, Torres, Torner, Sergienko, Saleh, and Teich, “Enhancing the Axial Resolution of Quantum Optical Coherence Tomography by Chirped Quasi-Phase-Matching,” *Opt. Lett.* **29**, 2429 (2004)

Enhancement of QOCT Resolution via Chirped QPM: 19 *μm* to 1 *μm*



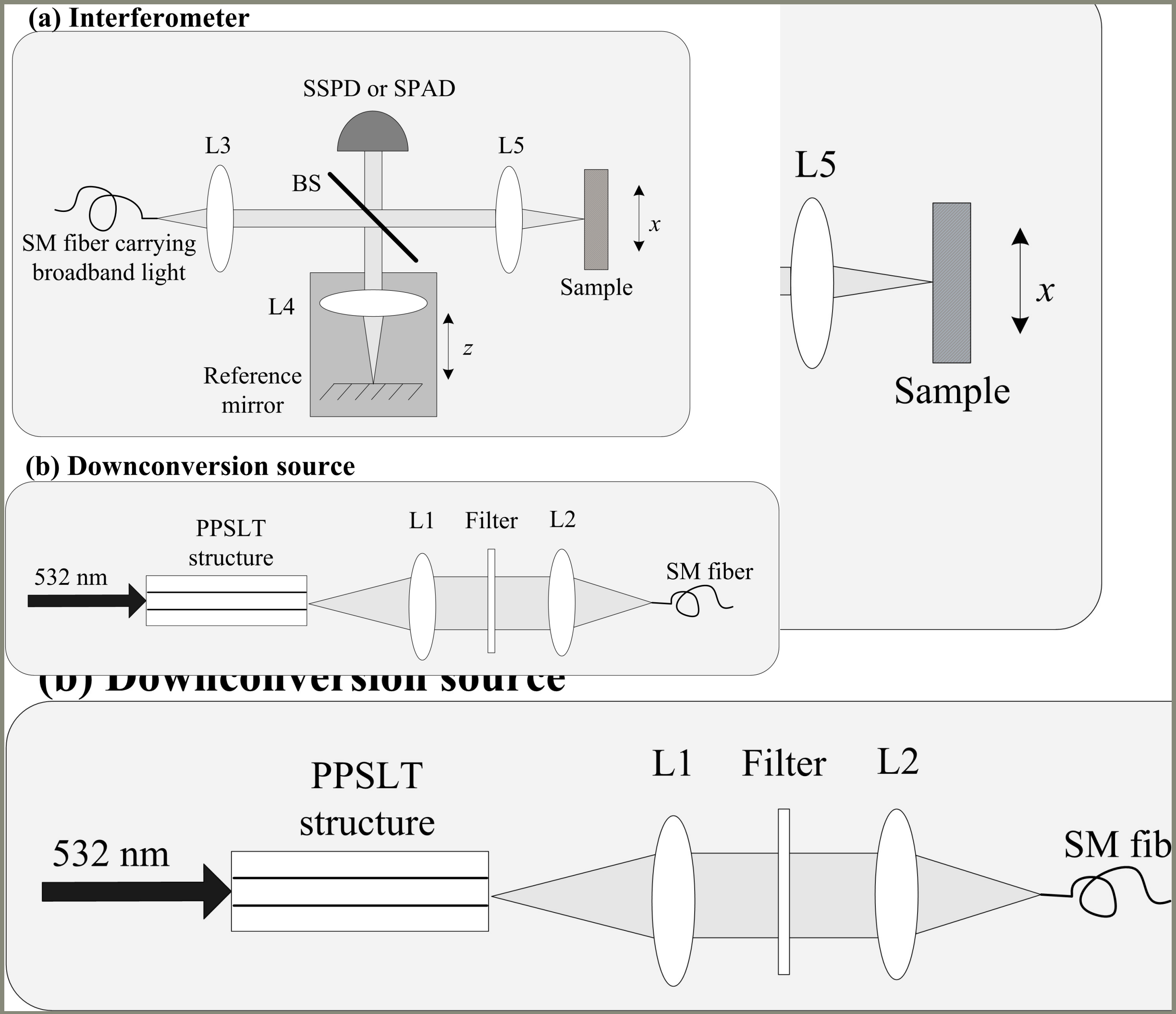
After Nasr, Carrasco, Saleh, Sergienko, Teich, Torres, Torner, Hum, and Fejer, “Ultrabroadband Biphotons Generated via Chirped Quasi-Phase-Matched Optical Parametric Down-Conversion,” *Phys. Rev. Lett.* **100**, 183601 (2008)

Further enhancement of QOCT Resolution via Increase in Detector Bandwidth



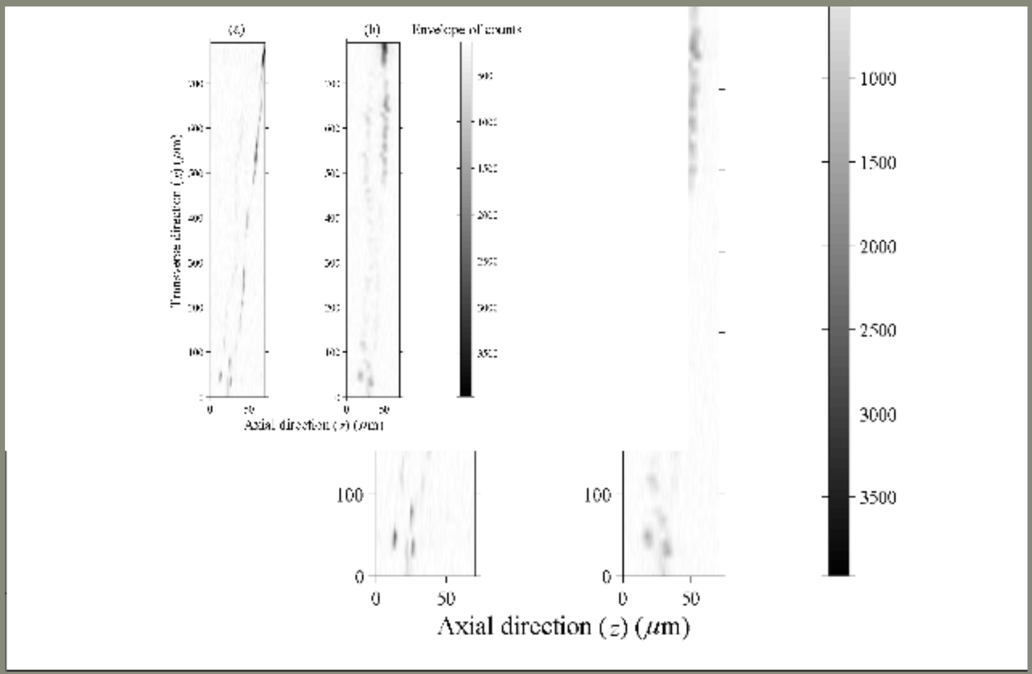
After Nasr, Minaeva, Goltsman, Sergienko, Saleh, and Teich, "Submicron Axial Resolution in an Ultrabroadband Two-Photon Interferometer Using Superconducting Single-Photon Detectors," *Opt. Express* **16**, 15104 (2008)

Photon-Counting OCT of a Biological Sample Using Chirped-QPM and an SSPD



After Mohan, Minaeva, Goltsman, M. Saleh, Nasr, Sergienko, B. Saleh, and Teich "Ultrabroadband Coherence-Domain Imaging Using Parametric Downconversion and Superconducting Single-Photon Detectors at 1064 nm," *Applied Optics* **48**, 4009-4017 (2009)

Photon-Counting OCT of a Biological Sample Using Chirped-QPM and an SSPD

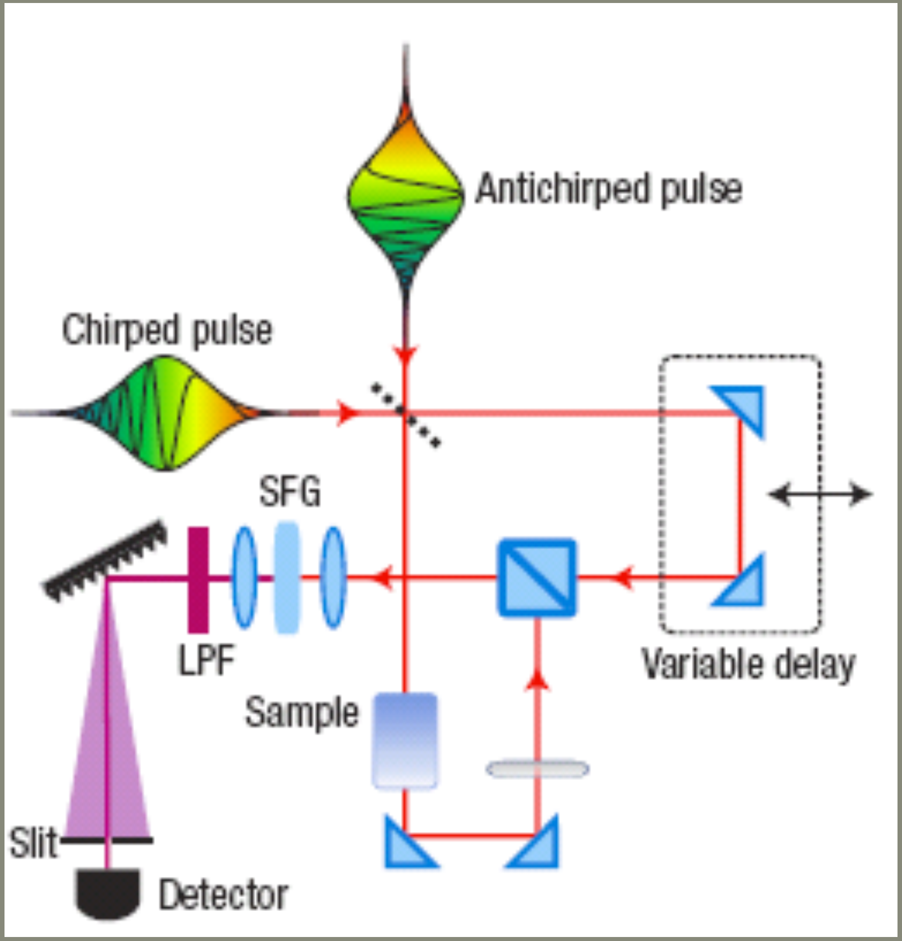


After Mohan, Minaeva, Goltsman, M. Saleh, Nasr, Sergienko, B. Saleh, and Teich "Ultrabroadband Coherence-Domain Imaging Using Parametric Downconversion and Superconducting Single-Photon Detectors at 1064 nm," *Applied Optics* **48**, 4009-4017 (2009)

Quantum-Mimetics

B. I. Erkmen and J. H. Shapiro, “Phase-Conjugate Optical Coherence Tomography,” *Phys. Rev. A* **74**, 041601 (2006).

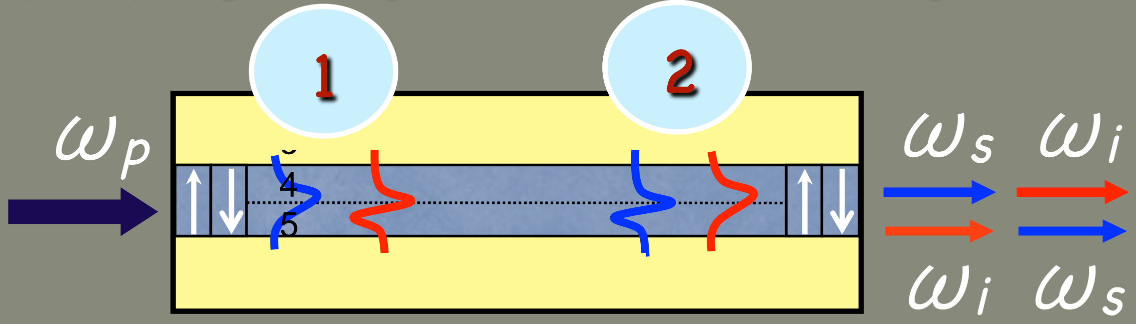
Chirped-Pulse Interferometry Using SFG (Time-Reversed HOM)



R. Kaltenbaek, J. Lavoie, D. N. Biggerstaff, and K. J. Resch, “Quantum-Inspired Interferometry with Chirped Laser Pulses,” *Nature Physics* **4**, 864-868 (2008).

Modal, Spectral, and Polarization Entanglement in Guided-Wave Parametric Downconversion

Co-propagating SPDC in waveguides



Direction ⟶ Waveguide modes

Phase mis-matching

$$\Delta\beta_1 = \beta_p^{(m_p)} - \beta_s^{(0)} - \beta_i^{(1)}$$

$$\Delta\beta_2 = \beta_p^{(m_p)} - \beta_s^{(1)} - \beta_i^{(0)}$$

Modal Entanglement

In general,

$$\Delta\beta_1 \neq \Delta\beta_2$$

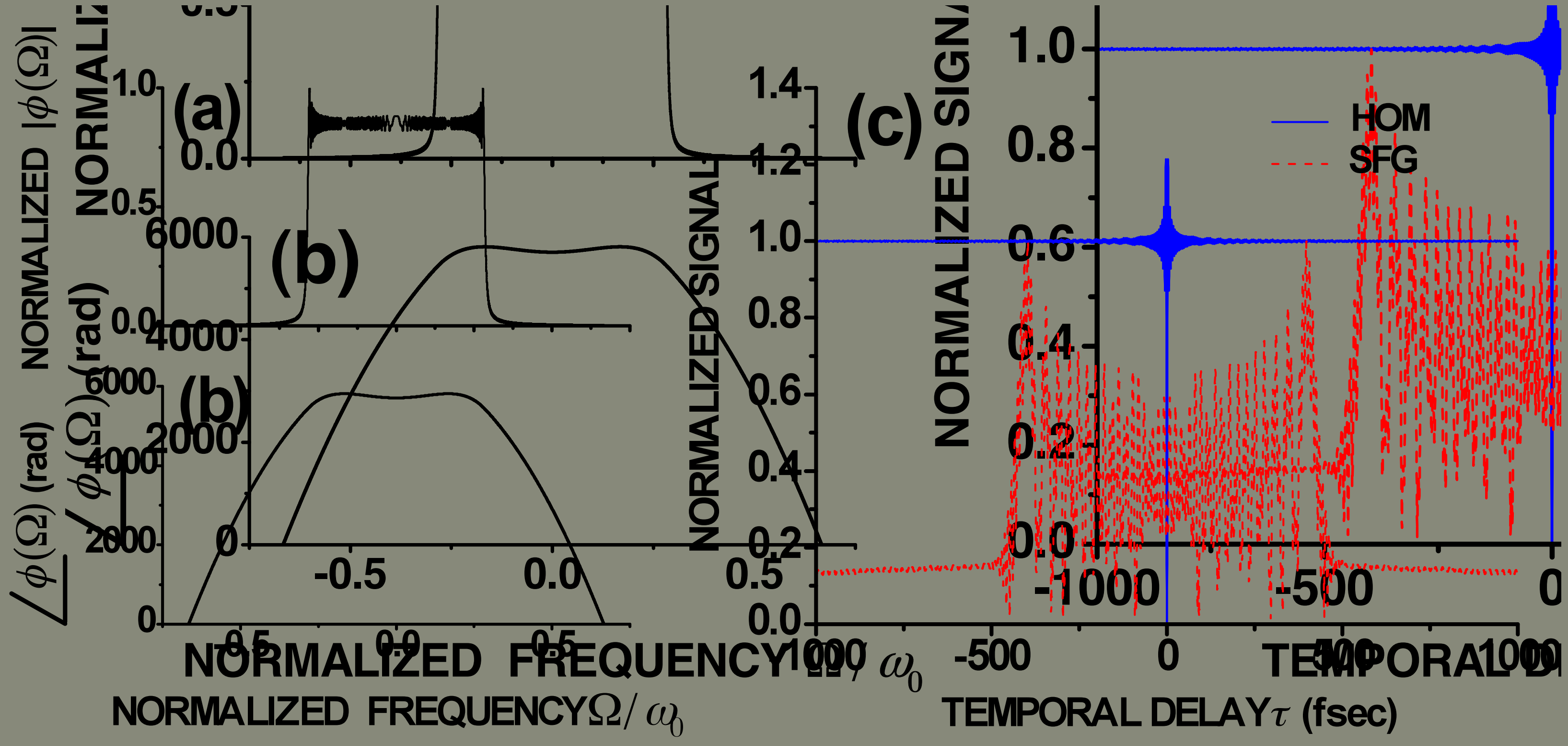
By controlling waveguide dimensions

$$\Delta\beta_1 = \Delta\beta_2 \longrightarrow \Lambda_1 = \Lambda_2$$

Single poling period

After Saleh, Saleh, and Teich, "Modal, Spectral, and Polarization Entanglement in Guided-Wave Parametric Down-Conversion," *Phys. Rev. A* **79**, 053842 (2009)

Biphoton Compression Might Make Entangled-Photon Photoemission, Microscopy, and Lithography Work



After Nasr, Carrasco, Saleh, Sergienko, Teich, Torres, Torner, Hum, and Fejer, “Ultrabroadband Biphotons Generated via Chirped Quasi-Phase-Matched Optical Parametric Down-Conversion,” *Phys. Rev. Lett.* **100**, 183601 (2008)

BOSTON UNIVERSITY
Statement of Work
May 1, 2008 – April 30, 2010

1. QUANTUM-OPTICAL COHERENCE TOMOGRAPHY (QOCT) USING PARAMETRIC DOWNCONVERSION IN CHIRPED NONLINEAR CRYSTALS

Nasr, Goode, Nguyen, Rong, Yang, Reinhard, Saleh, and Teich, “Quantum Optical Coherence Tomography of a Biological Sample,” *Opt. Commun.* **282**, 1154 (2009)

2. THERMAL VS. TWO-PHOTON IMAGING

Saleh and Teich, “Noise in Classical and Quantum Photon-Correlation Imaging,” in *Advances in Information Optics and Photonics*, Vol. PM183, edited by A. T. Friberg and R. Dändliker (SPIE Press, Bellingham, WA, 2008), ch. 21, pp. 423-435

3. ENTANGLED-PHOTONIC QUBITS IN SPATIAL-PARITY SPACE FOR DIGITAL QUANTUM IMAGING

Yarnall, Abouraddy, Saleh, and Teich, “Spatial Coherence Effects in Second- and Fourth-Order Temporal Interference,” *Opt. Express* 16, 7634-7640 (2008)

Chapter 21

Noise in Classical and Quantum Photon-Correlation Imaging

Bahaa E. A. Saleh and Malvin Carl Teich

Photonics Center and Department of Electrical and Computer Engineering, Boston University, Boston, MA, USA

In *Advances in Information Optics & Photonics*, Vol. PM183, edited by A. Friberg and R. Dändliker (SPIE Press, Bellingham, WA, 2008), Chapter 21, pp. 423-435

REDUX: When Can Quantum Imaging Benefit from Entangled Photons?

Multiphoton

- Absorption

T: Göppert-Mayer (1931)
E: Franken *et al*. (1961)

- Photoemission

T: Bloch (1964)
E: Teich & Wolga (1964)

- Microscopy

T: Sheppard & Kompfner (1978)
E: Denk *et al.* (1990)

- Lithography

T: ancient
E: 3D..Maruo & Kawata (1997)

- OCT (Optical Coherence Tomography – Single Photon)

T: Youngquist *et al*. (1987)
E: Huang *et al*. (1991)

Entangled-Photon

- Absorption

T: Fei *et al.* (1997)
E: Dayan *et al.* (2004)

- Photoemission

T: Lissandrin *et al.* (2004)
E:

- Microscopy

T: Teich & Saleh (1997)
E:

- Lithography

T: Boto *et al.* (2000)
E:

- QOCT (Quantum Optical Coherence Tomography – 2-Photon)

T: Abouraddy *et al.* (2002)
E: Nasr *et al.* (2003)

[***Other applications: digital quantum imaging, distributed imaging and holography, quantum metrology and ellipsometry, quantum information and communications***]

ACKNOWLEDGMENTS

Boston University:

- Ayman Abouraddy
- Mark Booth
- Francesco Lissandrin
- Nishant Mohan
- Olga Minaeva
- Julie Praino
- Mohammed Saleh
- David Simon
- Jason Stewart
- Andrew Whiting
- Tim Yarnall

- Giovanni Di Giuseppe
- Martin Jaspan
- Boshra Nasr

University of Maryland-College Park:

- John Fourkas
- Rick Farrer
- Chris LaFratta

Institut de Ciències Fotòniques:

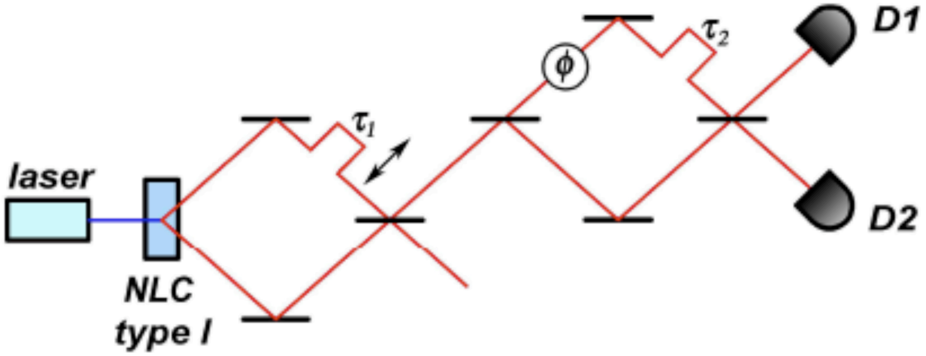
- Silvia Carrasco
- Juan Torres
- Lluis Torner

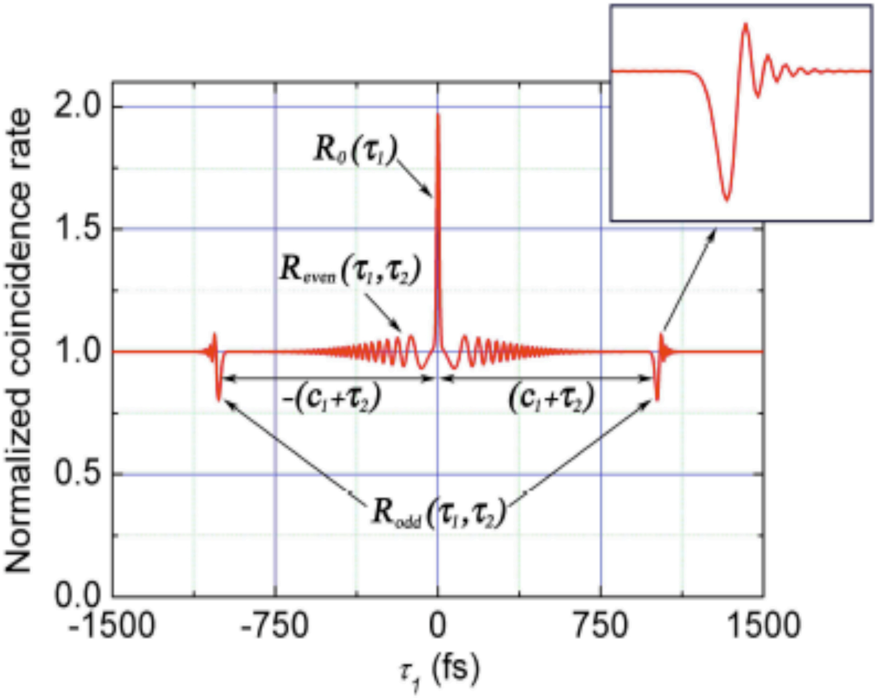
Stanford University:

- David Hum
- Martin Fejer

SASHA:
Dispersion and Aberration Cancellation

Odd-Order and Even-Order Dispersion Cancellation





Simultaneous odd- and even-order dispersion cancellation in quantum interferometry

Olga Minaeva,[1,2] Cristian Bonato,[1,3] Bahaa E.A. Saleh,[1] David S. Simon,[1] and Alexander V. Sergienko[1,4]