Multi-Photon and Entangled-Photon Imaging, Lithography, and Spectroscopy

Photonics Center
Boston University

Malvin Carl Teich

Columbia University
Boston University
University of Central Florida

http://people.bu.edu/teich

International Workshop on

NEW SCIENCE AND TECHNOLOGIES using ENTANGLED PHOTONS (NSTEP)

OSAKA: 8 July 2013

Abstract

Nonlinear optics, which governs the interaction of light with various media, offers a whole raft of useful applications in photonics, including multiphoton microscopy [1], lithography [2], and spectroscopy [3]. It also provides the physicist and engineer with a remarkable range of opportunities for generating light with interesting, novel, and potentially useful properties. As a particular example, entangled-photon beams generated via spontaneous optical parametric down-conversion exhibit quantum-correlation features and coherence properties [4] that are of interest in a number of contexts, including imaging and spectroscopy. Photons are emitted in pairs in an entangled quantum state, forming twin beams [5]. Such light is of interest, for example, in quantum optical coherence tomography [6], a quantum imaging technique that permits an object to be examined in section. This imaging modality is insensitive to the even-order dispersion inherent in the object, thereby potentially increasing the resolution and section depth that can be attained [7]. Equally as important, perhaps, is the recognition that quantum optical coherence tomography serves as a quantum template for constructing classical systems that mimic its salutary properties [8]. We discuss the advantages and disadvantages of a number of techniques in multiphoton and entangled-photon imaging, lithography, and spectroscopy.

[1] M. C. Teich and B. E. A. Saleh, "Mikroskopie s kvantově provázanými fotony (Entangled-Photon Microscopy)," *Ceskoslovenský casopis pro fyziku* **47**, 3-8 (1997).

[2] A. N. Boto, P. Kok, D. S. Abrams, S. L. Braunstein, C. P. Williams, and J. P. Dowling. "Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit," *Phys. Rev. Lett.* 85, 2733 (2000); B. E. A. Saleh, M. C. Teich, and A. V. Sergienko, "Wolf Equations for Two-Photon Light," *Phys. Rev. Lett.* **94**, 223601 (2005).

[3] B. E. A. Saleh, B. M. Jost, H.-B. Fei, and M. C. Teich, "Entangled-Photon Virtual-State Spectroscopy," *Phys. Rev. Lett.* **80**, 3483-3486 (1998).

[4] A. Joobeur, B. E. A. Saleh, T. S. Larchuk, and M. C. Teich, "Coherence Properties of Entangled Light Beams Generated by Parametric Down-Conversion: Theory and Experiment," *Phys. Rev. A* **53**, 4360-4371 (1996).

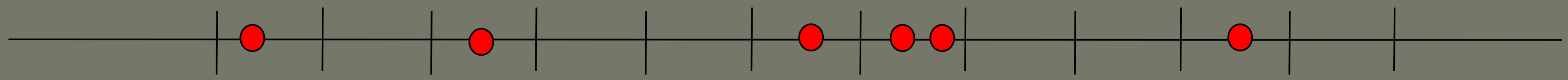
[5] B. E. A. Saleh, A. F. Abouraddy, A. V. Sergienko, and M. C. Teich, "Duality Between Partial Coherence and Partial Entanglement," *Phys. Rev. A* **62**, 043816 (2000).

[6] 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.* **91**, 083601 (2003).

[7] M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, "Dispersion-Cancelled and Dispersion-Sensitive Quantum Optical Coherence Tomography," *Opt. Express* **12**, 1353-1362 (2004); M. B. Nasr, D. P. Goode, N. Nguyen, G. Rong, L. Yang, B. M. Reinhard, B. E. A. Saleh, and M. C. Teich, "Quantum Optical Coherence Tomography of a Biological Sample," *Opt. Commun.* **282**, 1154-1159 (2009).

[8] M. C. Teich, B. E. A. Saleh, F. N. C. Wong, and J. H. Shapiro, "Variations on the Theme of Quantum Optical Coherence Tomography: A Review," *Quant. Inf. Process* **11**, 903-923 (2012) [Special issue on quantum imaging].

Photons Arrive Randomly

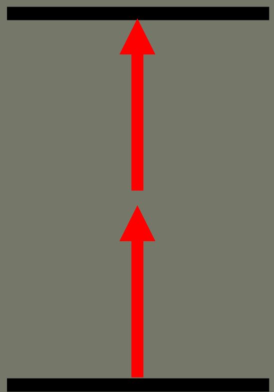


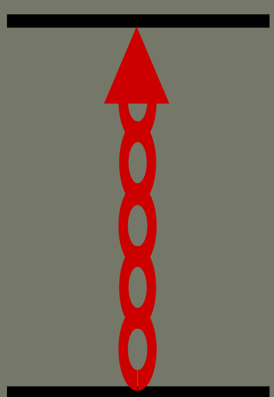
Product of photon-number and phase uncertainties:

$$\Delta n \, \Delta \phi = 1/2$$

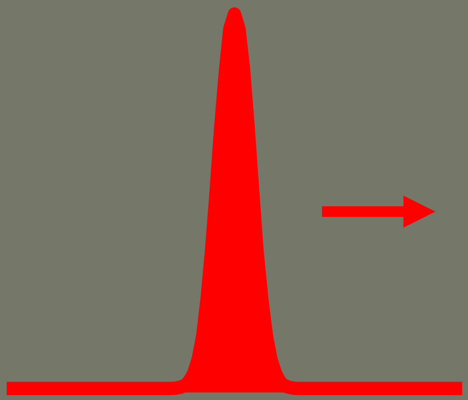
Multiphotonon Excitation vs Entangled-Photon Excitation

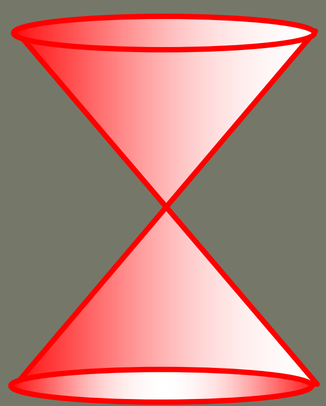
Optics & Photonics News 11, 40 (2000)



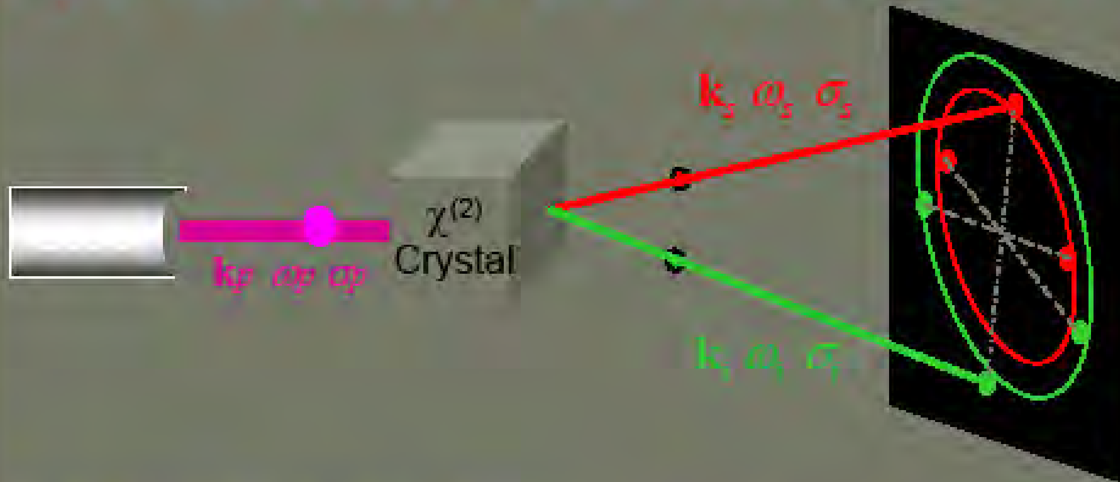


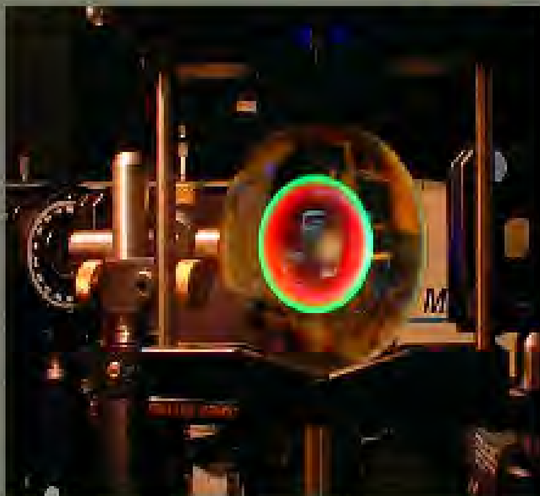
- For classical light, probability of simultaneous absorption of n photons $\propto I^n$
- Multiphoton absorption more likely in regions of high light intensity
- Ultrafast light pulses have high peak intensities, allowing multiphoton excitation at low average power
- Excitation (photoemission, fluorescence,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





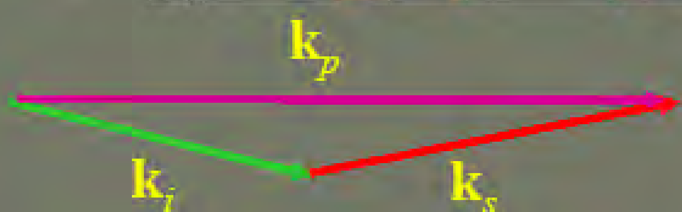
Generation of Entangled Photon Pairs via Spontaneous Parametric Down-Conversion





ENERGY CONSERVATION: $\omega_p = \omega_s + \omega_i$

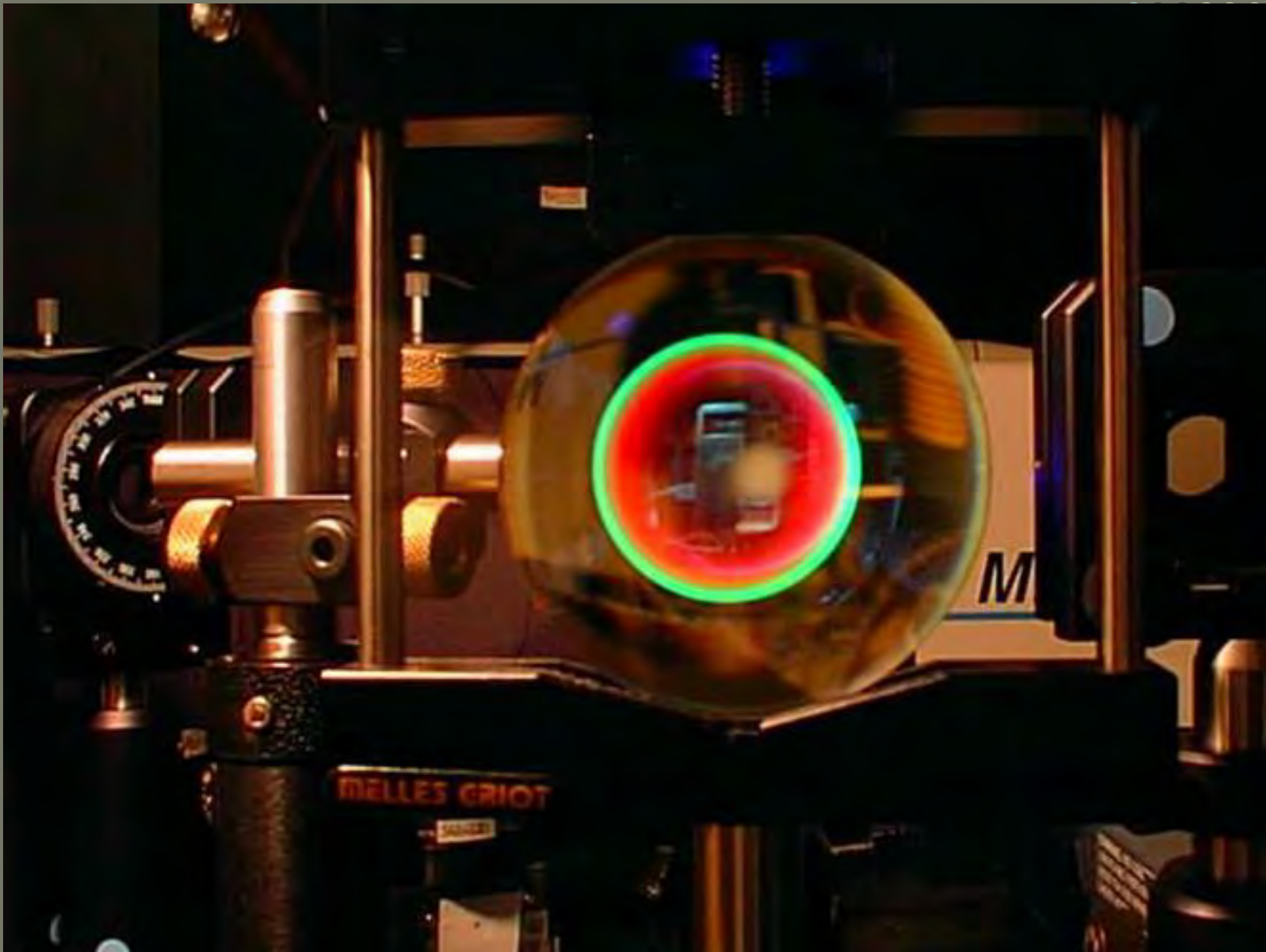
MOMENTUM CONSERVATION: $\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$



PHOTONS ARE EMITTED IN PAIRS (TWINS):	**IDEAL**	**REAL**
•Each at a random time, but times are correlated :	$t_s - t_i = \tau = \text{const}$	$\Delta\tau \equiv \tau_e$
•Each is broadband, but frequencies are anti-correlated :	$\omega_s + \omega_i = \omega_p = \text{const}$	$\Delta\omega_p$
•Each is multidirectional, but directions are anti-correlated :	$\mathbf{k}_s + \mathbf{k}_i = \mathbf{k}_p = \text{const}$	$\Delta\mathbf{k} \equiv A_e$

•Each with random polarization, but polarizations are orthogonal : (Type-II SPDC)

After Joobeur, Saleh, and Teich, "Spatiotemporal Coherence Properties of Entangled Light Beams Generated by Parametric Down-Conversion," *Phys. Rev. A* **50**, 3349 (1994)


MELLES GRIOT

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: 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)

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: 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)

Second-Harmonic Generation (SHG)

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan

Frequency-Doubled Ruby Laser 347.1 nm

Ruby Laser 694.3 nm

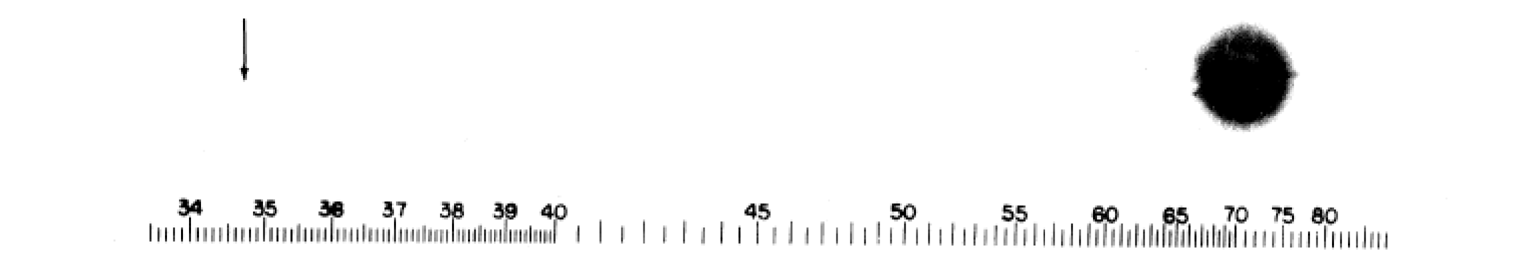


FIG. 1. A direct reproduction of the first plate in which there was an indication of second harmonic. The wavelength scale is in units of 100 A. The arrow at 3472 A indicates the small but dense image produced by the second harmonic. The image of the primary beam at 6943 A is very large due to halation.

Enhancement of SHG via Thermal Light or Speckle

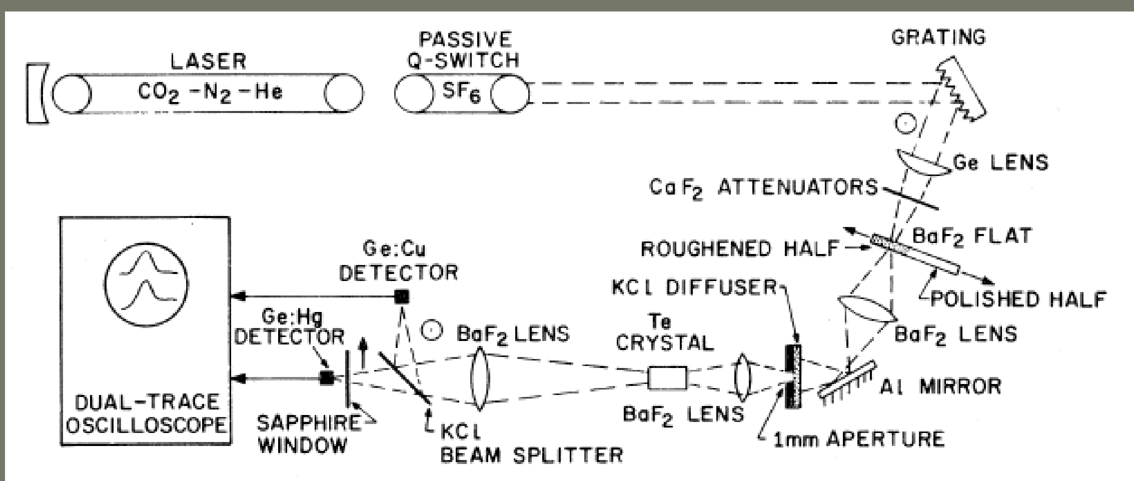
Volume 2, number 5 OPTICS COMMUNICATIONS October 1970

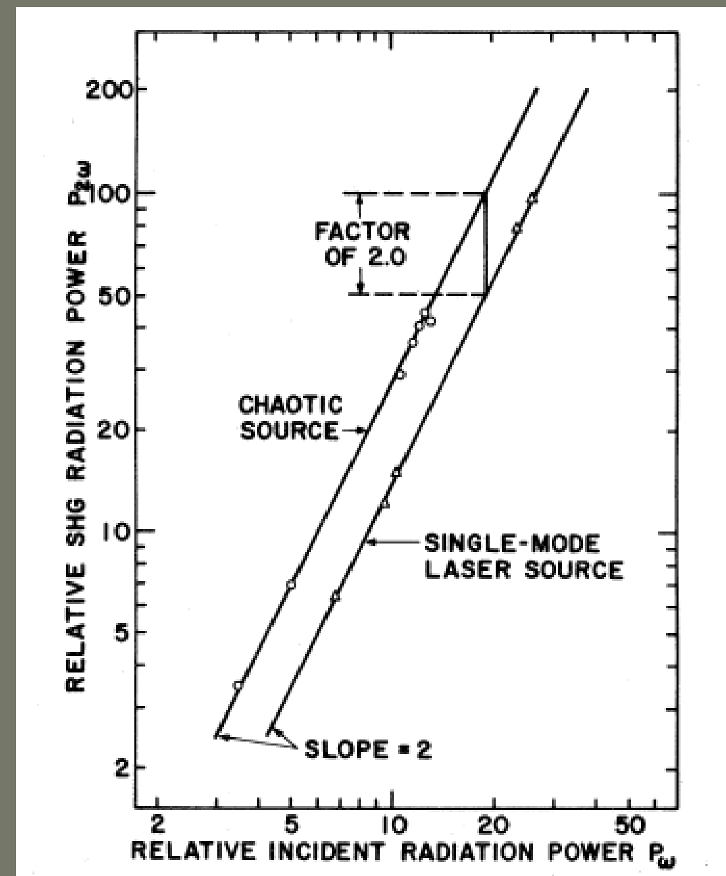
PHOTON-CORRELATION ENHANCEMENT OF SHG AT 10.6 μm

M. C. TEICH *
Department of Electrical Engineering, Columbia University, New York, New York 10027, *USA*

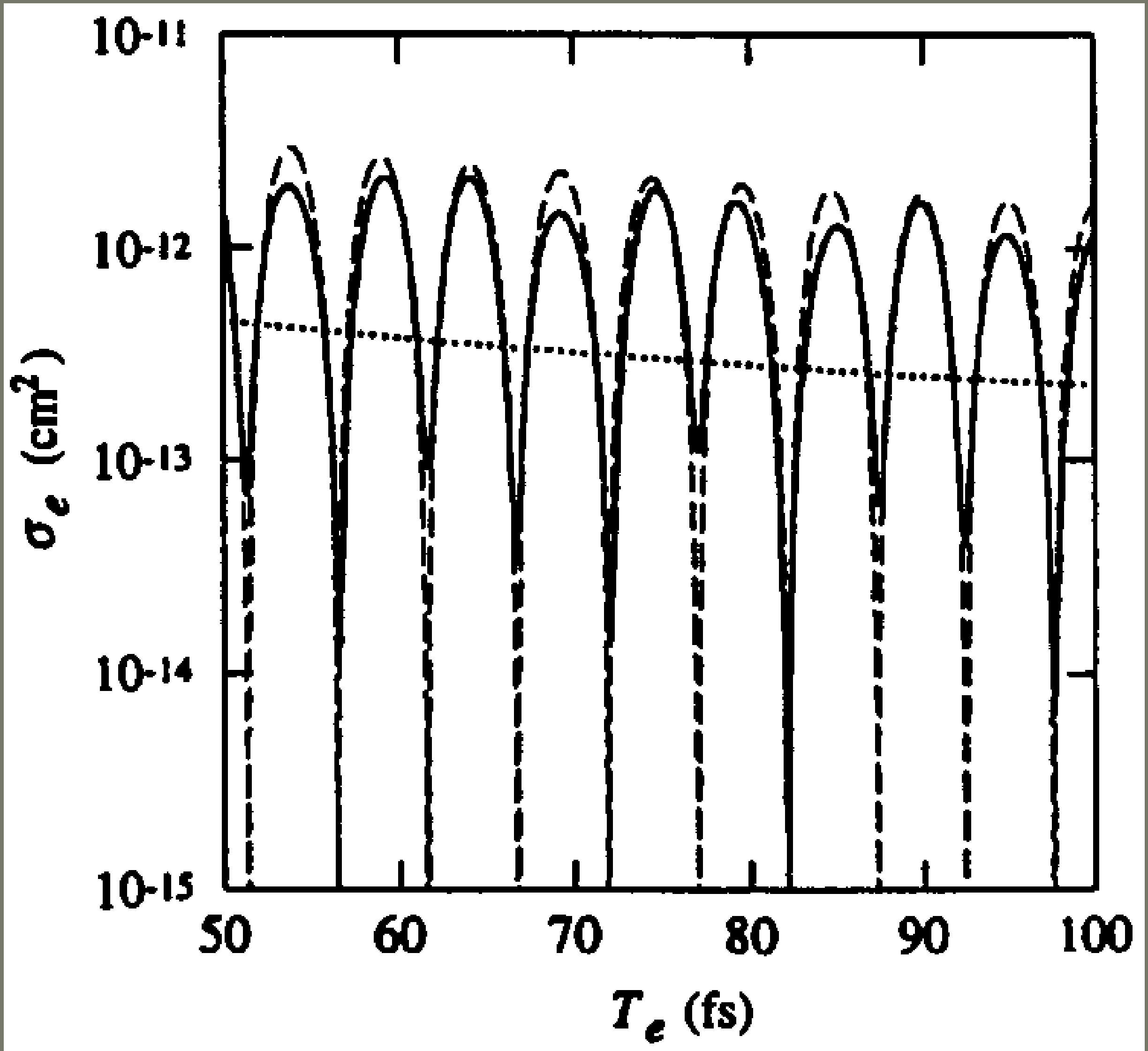
and

R. L. ABRAMS and W. B. GANDRUD
Bell Telephone Laboratories, Incorporated, Whippany, New Jersey 07981, *USA*



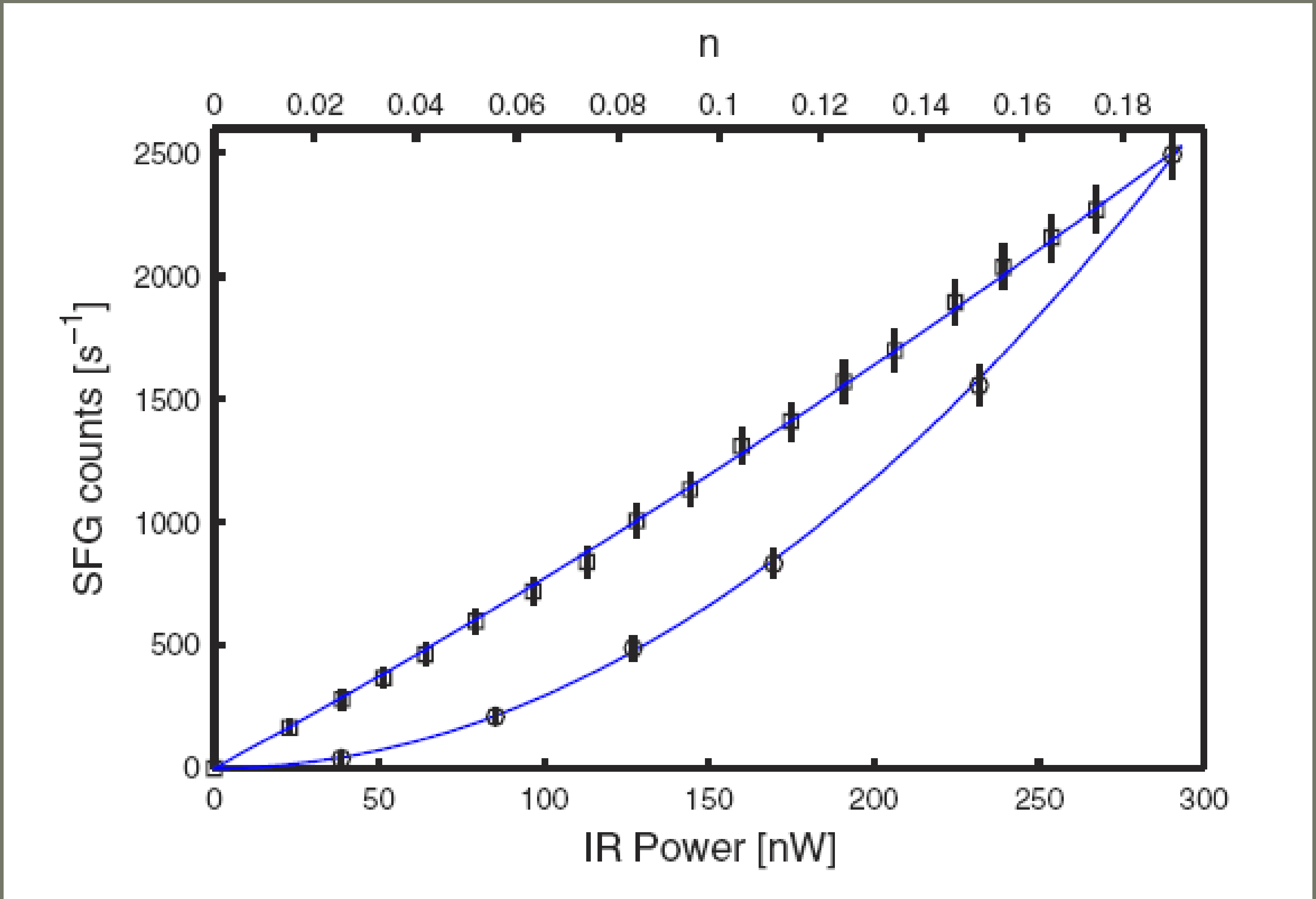


Entangled-Photon Absorption (Theory)



After Fei, Jost, Popescu, Saleh, and Teich, "Entanglement-Induced Two-Photon Transparency," *Phys. Rev. Lett.* **78**, 1679 (1997)

Entangled-Photon SFG (Experiment)



After Dayan, Pe’er, Friesem, and Silberberg, “Nonlinear Interactions with an Ultrahigh Flux of Broadband Entangled Photons,” *Phys. Rev. Lett.* **94**, 043602 (2005)

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: 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)

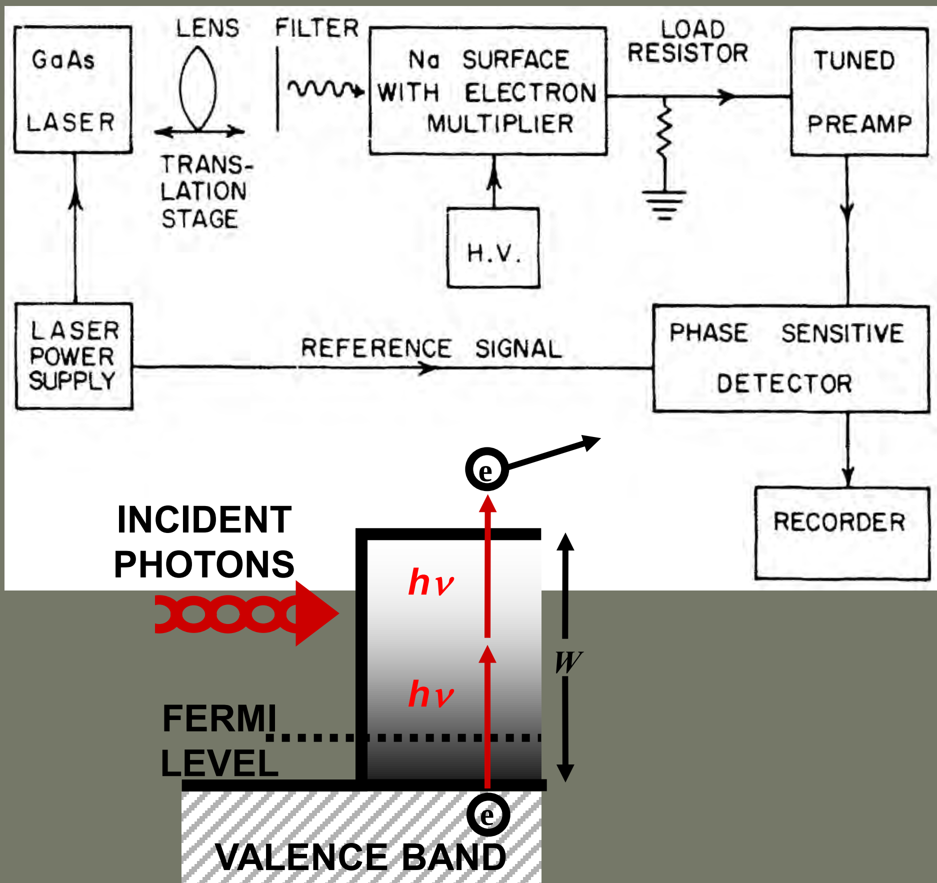
E:

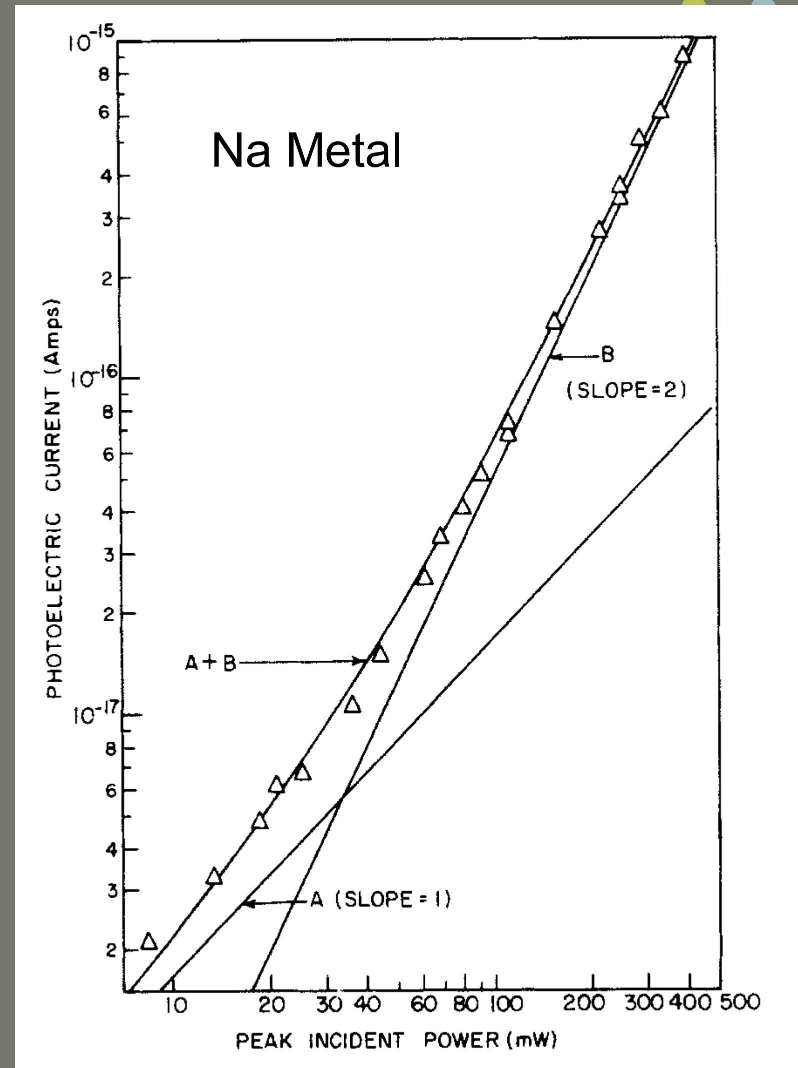
- **QOCT** (Quantum Optical Coherence Tomography – 2-Photon)

T: Abouraddy *et al*. (2002)

E: Nasr *et al*. (2003)

Two-Photon Photoemission





$$E_{max} = h\nu - W \quad \text{(Einstein)}$$
$$E_{max} = 2h\nu - W \quad \text{(2QPE)}$$

After Teich, Schröer, and Wolga, "Double-Quantum Photoelectric Emission from Sodium Metal," *Phys. Rev. Lett.* **13**, 611 (1964)

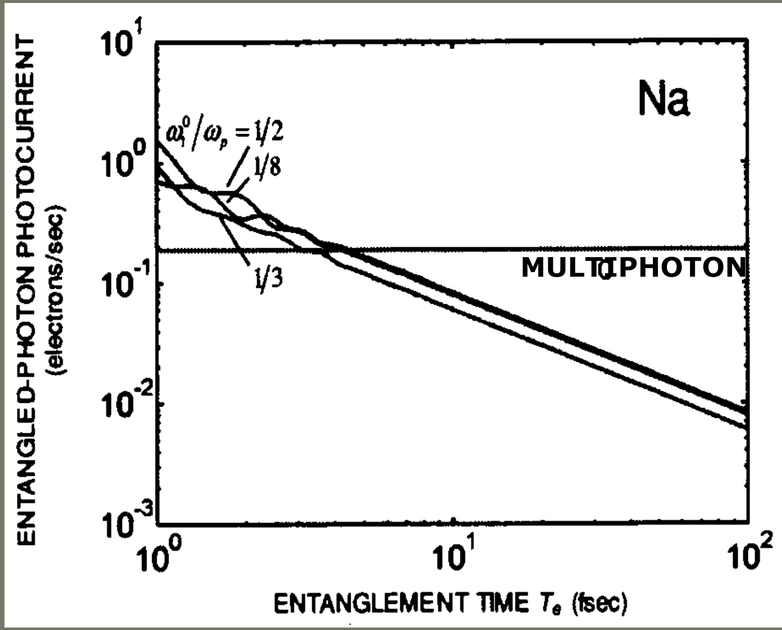
Two-Photon Photoemission Dependence on State of Light Four-Photon Hanbury-Brown–Twiss

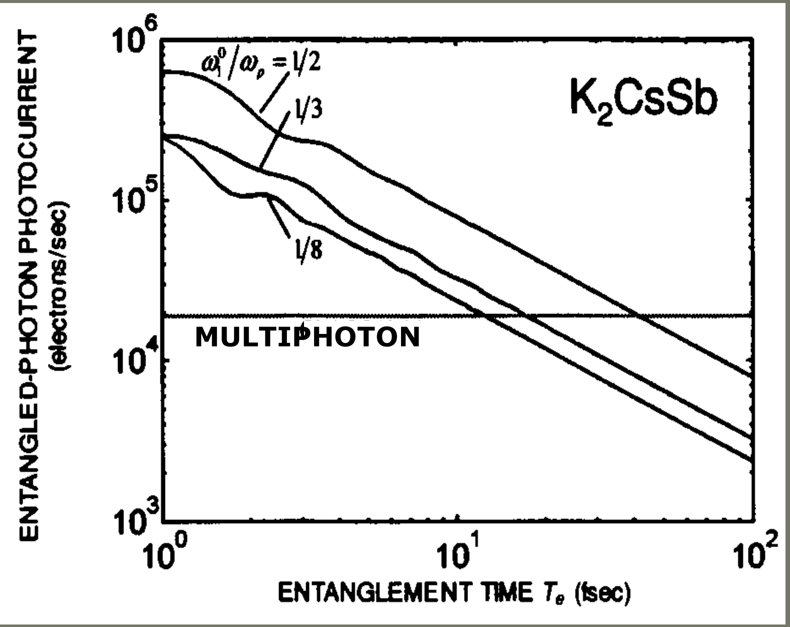
This communication discusses the dependence of the two-quantum photoeffect, and of certain other nonlinear processes, upon the higher order correlation functions[3] of the radiation field. As a special case of the results described, it is shown that the absolute magnitude of the effect induced in a two-quantum detector[4] by a thermal source is expected to be twice as large as that induced by a single-mode ideal laser source[5] of the same intensity.[6] Physically, the effect occurs because of correlations in the photon arrival times at the absorbing atom, and is closely related to the Hanbury Brown–Twiss effect. In the following treatment, it is assumed that all sources possess precise first-order coherence.

In the same way, the correlation in photon arrival times will be reflected in any process consisting of the annihilation of two or more photons. For example, consider a Hanbury Brown–Twiss experiment using two double-quantum detectors rather than the conventional single-quantum detectors. Assuming that the electronic resolving time is less than the coherence time of the radiation, the excess coincidence counting rate for such an experiment is calculated to be $\{[g_4/(g_2)^2]-1\}$ (for a thermal source, this quantity is equal to 5). This is in analogy with the case for the ordinary Hanbury Brown–Twiss experiment where the excess coincidence counting rate is given by g_2-1 (which is equal to unity for a thermal source). In the experiment using double-quantum detectors, the excess coincidence rate reflects the fourth-order coherence properties of the field. This experiment would, however, be difficult to perform with currently available two-photon detectors.

After Teich and Wolga, "Multiple-Photon Processes and Higher Order Correlation Functions," *Phys. Rev. Lett.* **16**, 625 (1966)

Entangled-Photon Photoemission (Theory)





After Lissandrin, Saleh, Sergienko, and Teich, "Quantum Theory of Entangled-Photon Photoemission," *Phys. Rev. B* **69**, 165317 (2004)

NONLINEAR AND ENTANGLED-PHOTON IMAGING

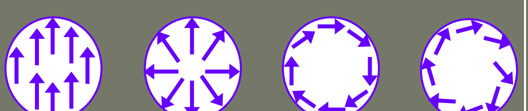
Linear Optics

- Scalar

$$d = \frac{\lambda}{2n\sin\alpha}$$

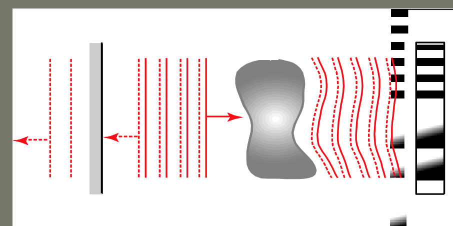
- Super-resolution

- Vector beam

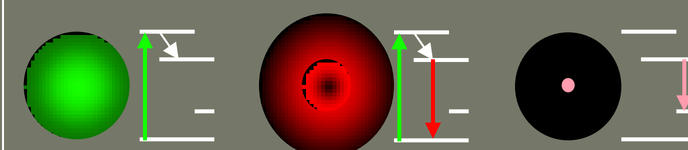


Nonlinear Optics

- Phase conjugation



- STED (stimulated emission depletion microscopy)



- Multiphoton imaging

Quantum Optics

- Quadrature-squeezed imaging
- Number-squeezed 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).

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

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: 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:

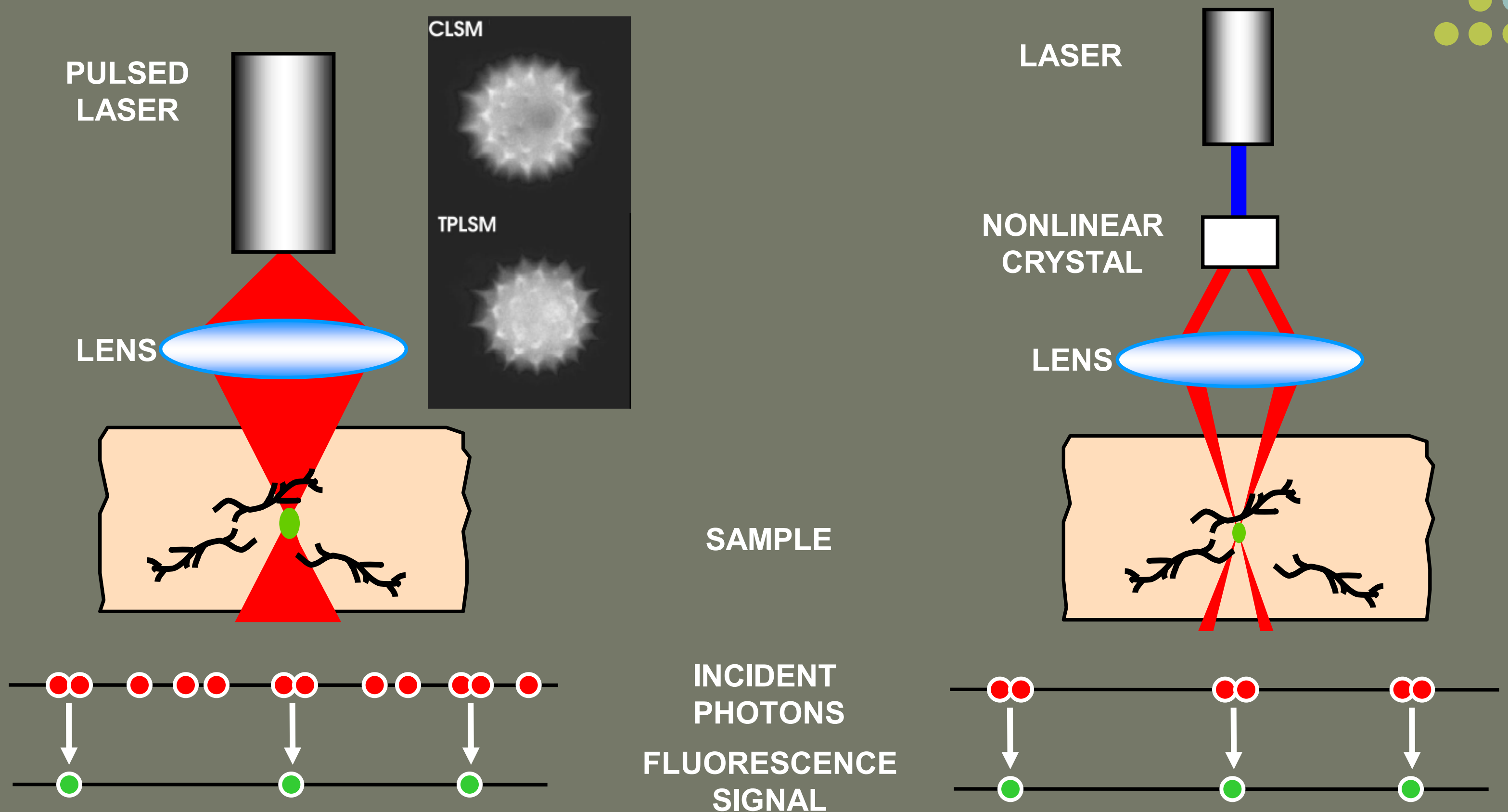
- QOCT (Quantum Optical Coherence Tomography – 2-Photon)

T: Abouraddy *et al*. (2002)

E: Nasr *et al*. (2003)

Multiphoton Microscopy

Entangled-Photon 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.

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)

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

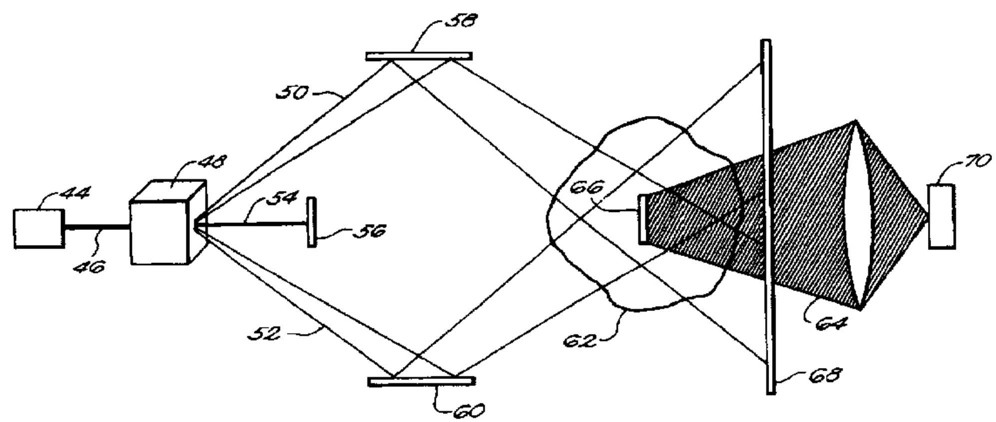
Physics News Update, The American Institute of Physics Bulletin of Physics News, No. 275, Jun. 14, 1996 by Phillip F. Schewe and Ben Stein.

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

- **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)

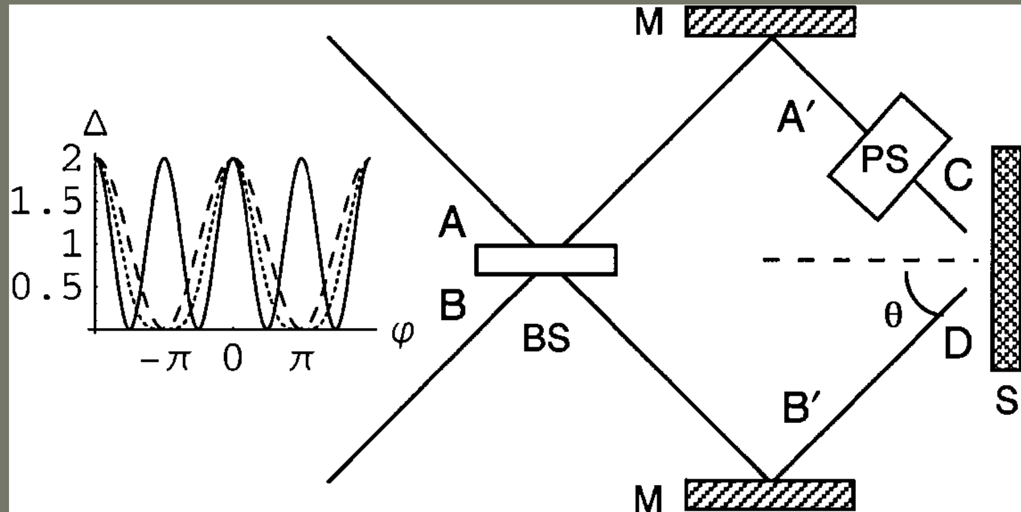
E:

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

T: Abouraddy *et al*. (2002)

E: Nasr *et al*. (2003)

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

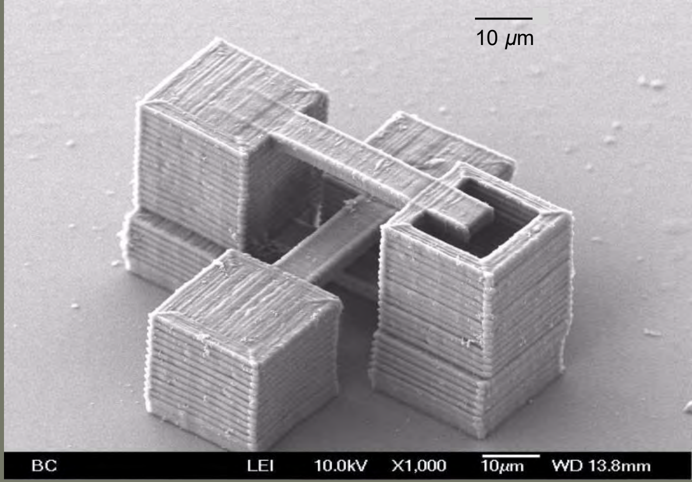
Wolf Equations for Two-Photon Light

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.

3D Lithography

Example: Radical Multiphoton
Absorption Polymerization



- Multiphoton absorption by a photo-initiator in a viscous liquid pre-polymer resin generates radicals. (A co-initiator may be required as well.)
- Photoexcitation of the photo-initiator begins a chain reaction that hardens the resin locally.
- Theoretical resolution available via multiphoton absorption (MPA) inversely proportional to the numerical aperture.
- Chemical nonlinearity (quenching of radicals by oxygen or recombination) can lead to a substantial increase in resolution via thresholding.

After Baldacchini, LaFratta, Farrer, Teich, Saleh, Naughton, and Fourkas, "Acrylic-Based Resin with Favorable Properties for Three-Dimensional Two-Photon Polymerization," *J. Appl. Phys.* **95**, 6072 (2004)

J|A|C|S
COMMUNICATIONS

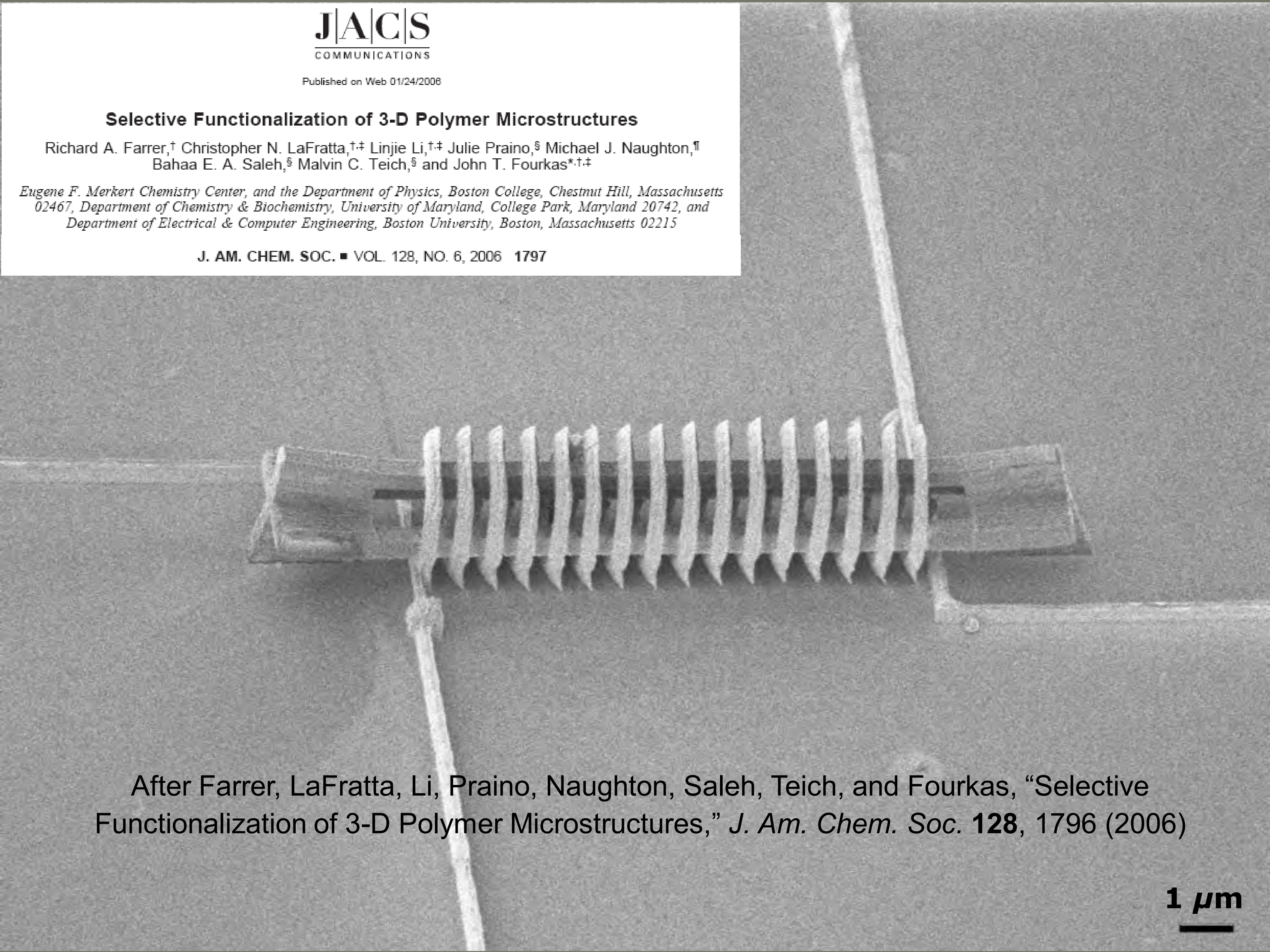
Published on Web 01/24/2006

Selective Functionalization of 3-D Polymer Microstructures

Richard A. Farrer,[†] Christopher N. LaFratta,[†,‡] Linjie Li,[†,‡] Julie Praino,[§] Michael J. Naughton,[¶] Bahaa E. A. Saleh,[§] Malvin C. Teich,[§] and John T. Fourkas*[,†,‡]

Eugene F. Merkert Chemistry Center, and the Department of Physics, Boston College, Chestnut Hill, Massachusetts 02467, Department of Chemistry & Biochemistry, University of Maryland, College Park, Maryland 20742, and Department of Electrical & Computer Engineering, Boston University, Boston, Massachusetts 02215

J. AM. CHEM. SOC. ■ VOL. 128, NO. 6, 2006 1797



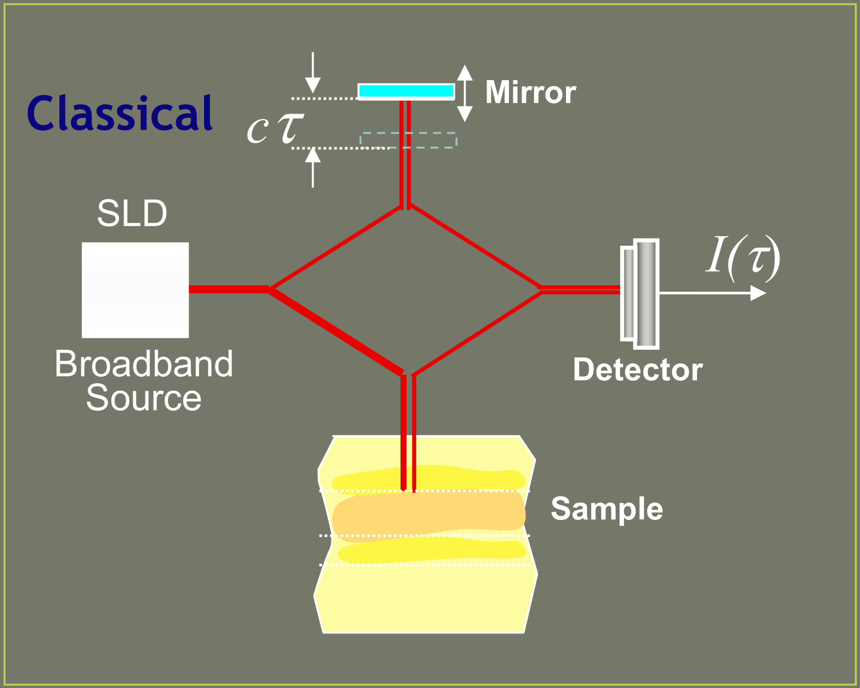
After Farrer, LaFratta, Li, Praino, Naughton, Saleh, Teich, and Fourkas, "Selective Functionalization of 3-D Polymer Microstructures," *J. Am. Chem. Soc.* **128**, 1796 (2006)

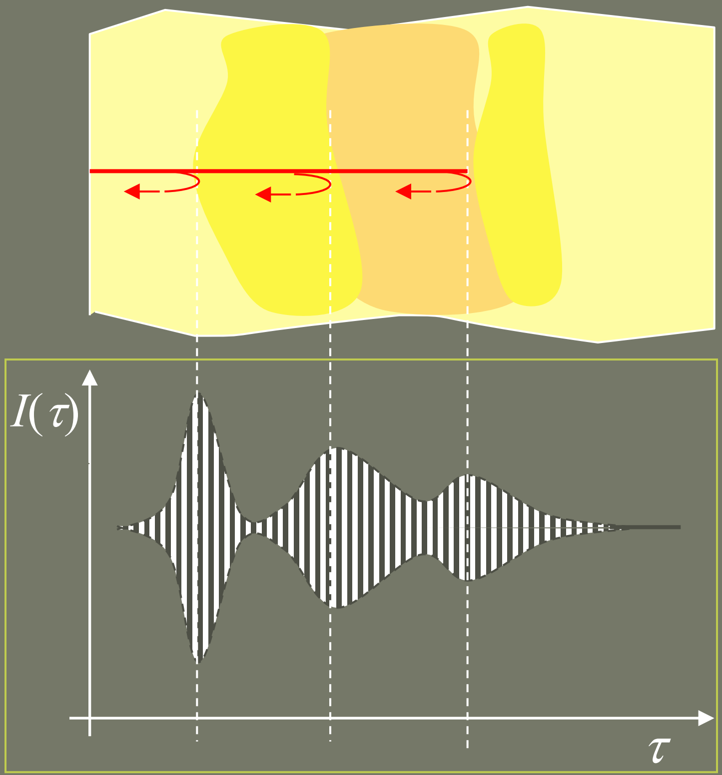
EXAMPLES

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: ancient	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)



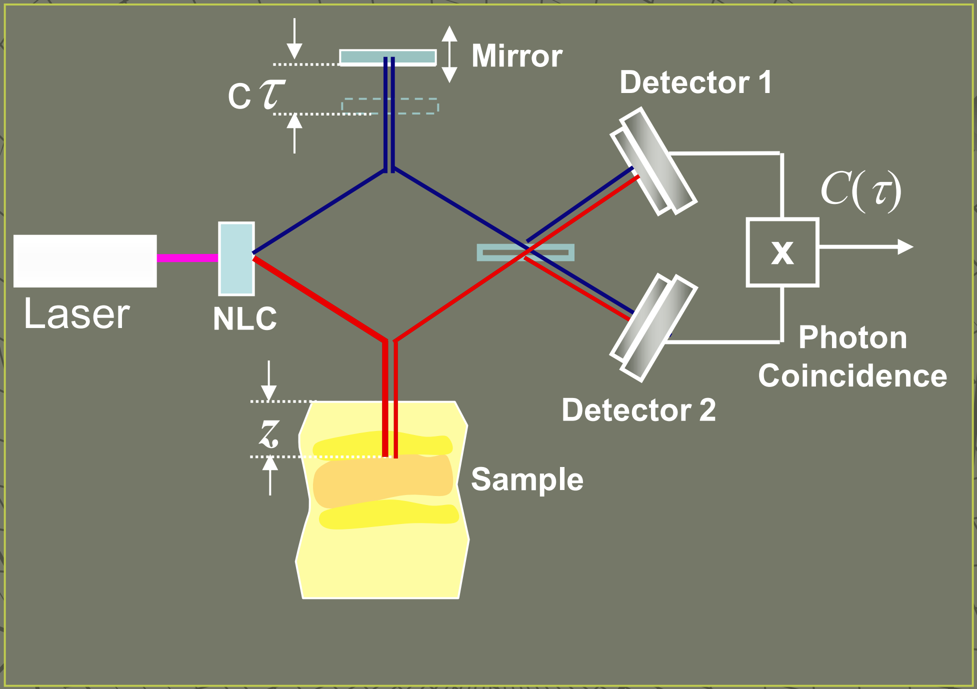


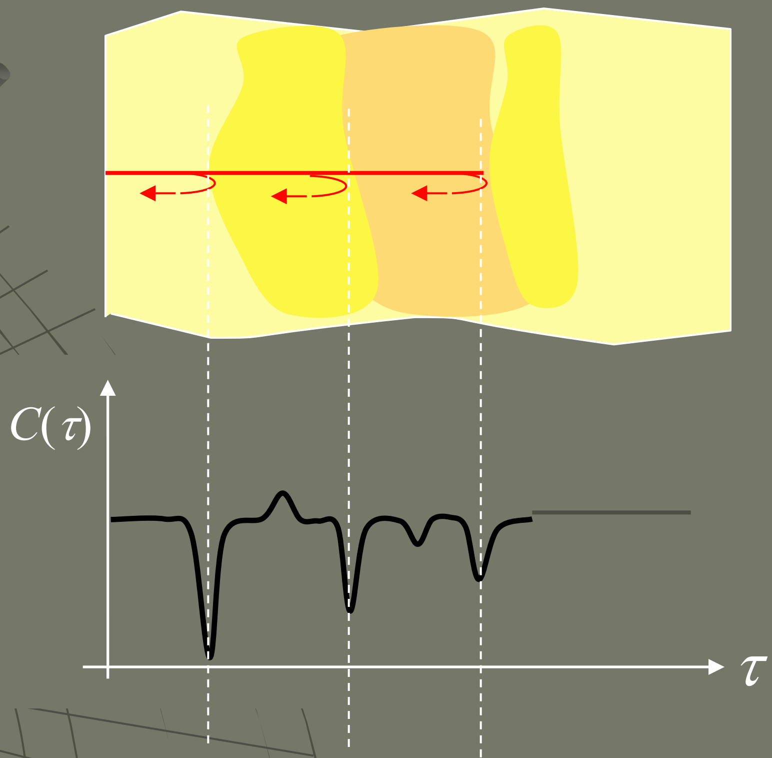
- Axial resolution is often of the order of a few μm
- Submicron resolution is possible with fs lasers and supercontinuum light
- In a dispersive medium, the resolution deteriorates to tens of μm

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





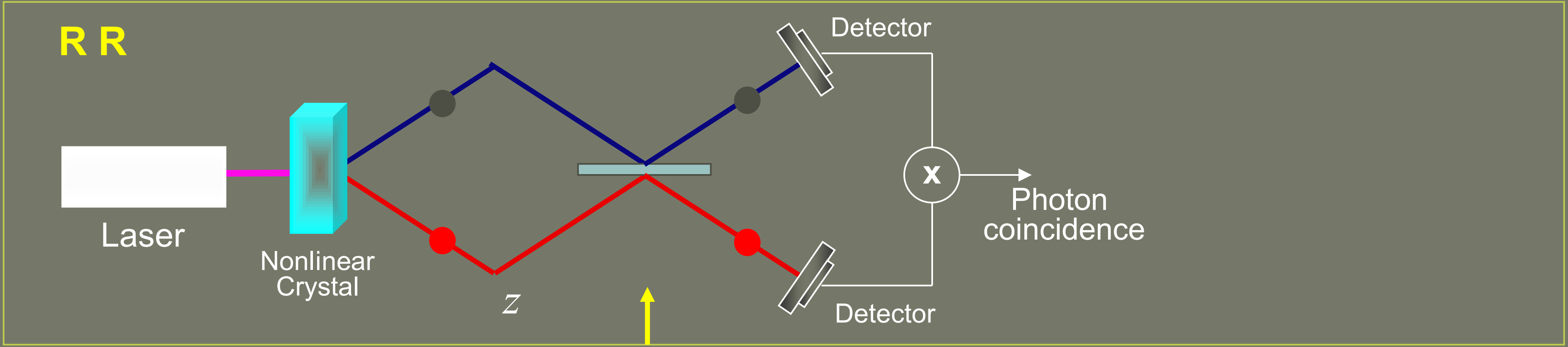
Advantages of QOCT:

- **Factor of roughly 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)

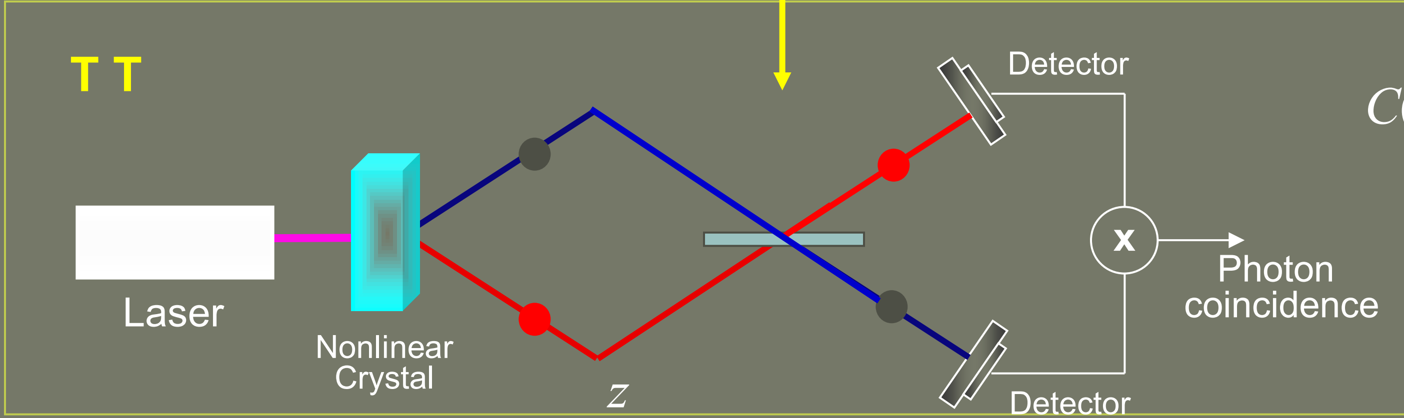
Indistinguishability Yields Interference

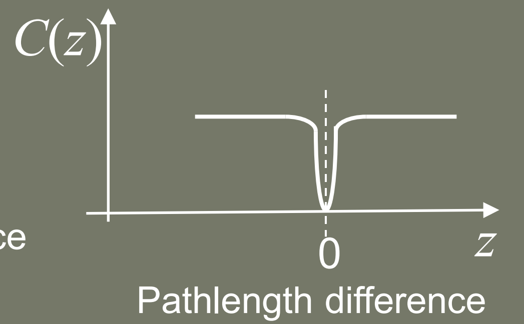
There are four possible photon paths at the beamsplitter: RT, TR, RR, and TT. For indistinguishable photons, the RR and TT alternatives cancel by virtue of the π phase shift at the beamsplitter. The remaining RT and TR alternatives yield both photons exiting the same port of the beamsplitter (they appear to stick together) so that the probability of photon coincidence is zero.



CANCELS

RESULTING IN:



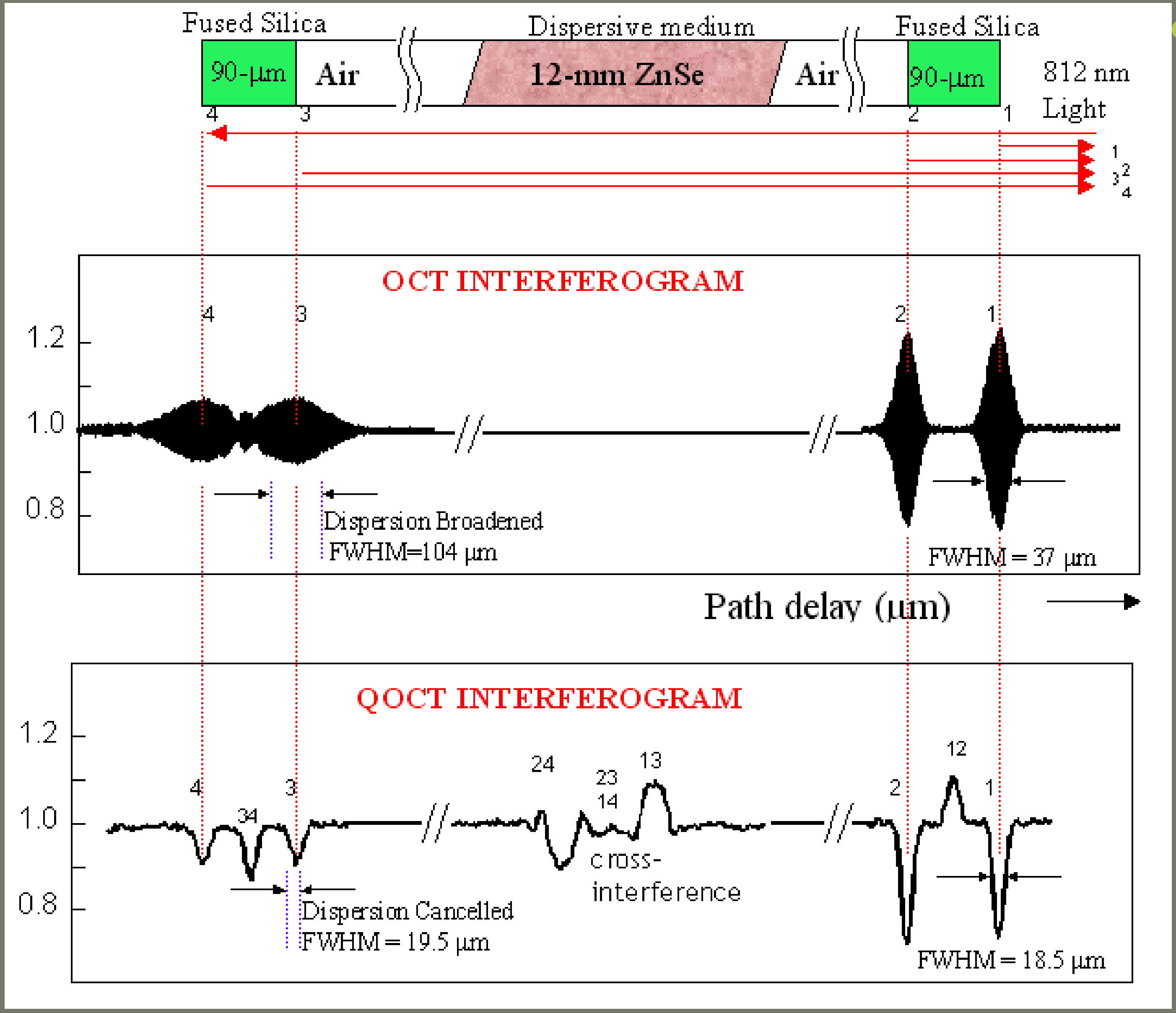


Note that coincidence detection achieves high visibility despite unbalanced loss

C. K. Hong, Z. Y. Ou, and L. Mandel, *Phys. Rev. Lett.* **59**, 2044 (1987)

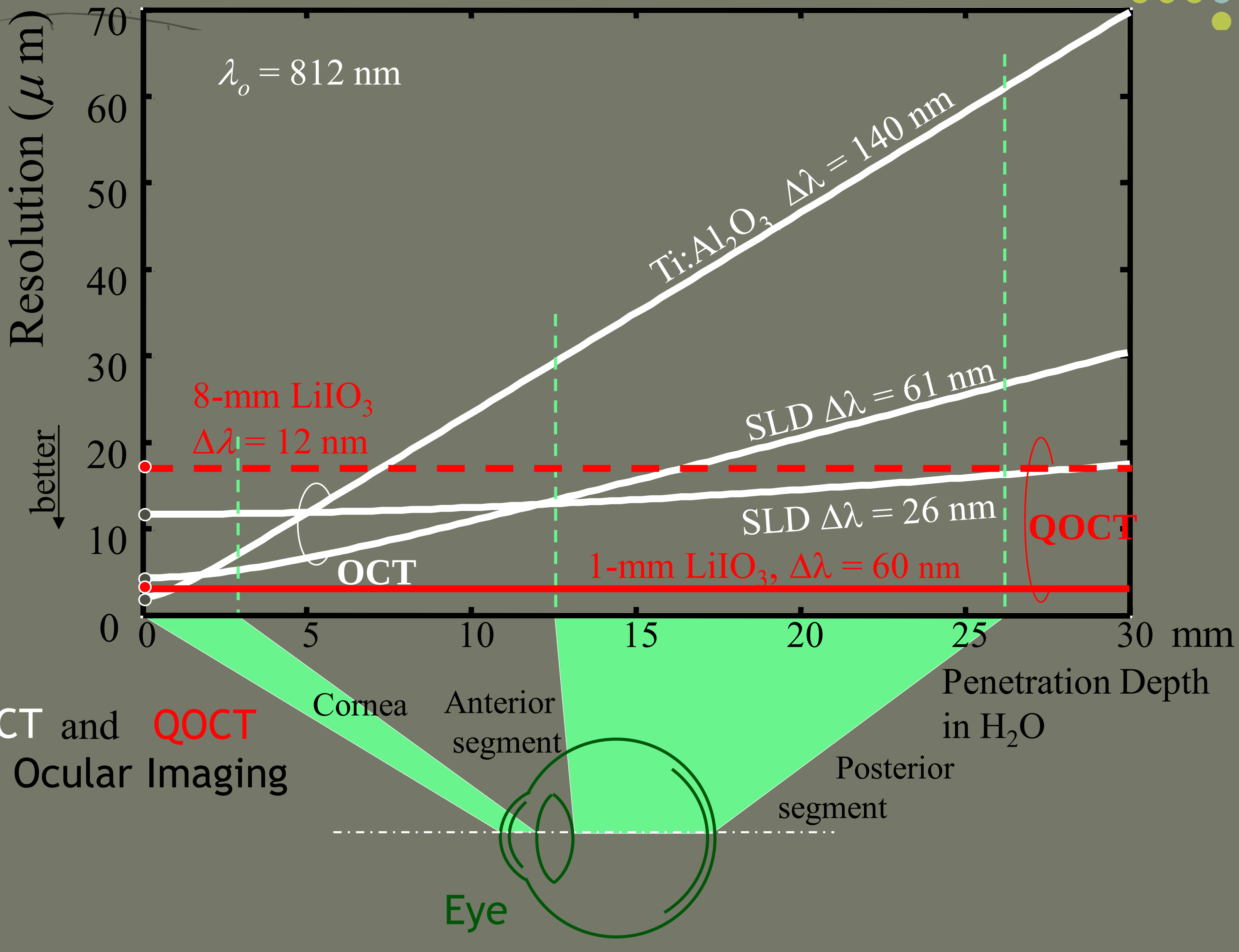
PhUL version: A. F. Abouraddy, T. M. Yarnall, and G. Di Giuseppe, *Phys. Rev. A* **87**, 062106 (2013)

Dispersion-Free QOCT (Experiment)



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

Dispersion in OCT and QOCT

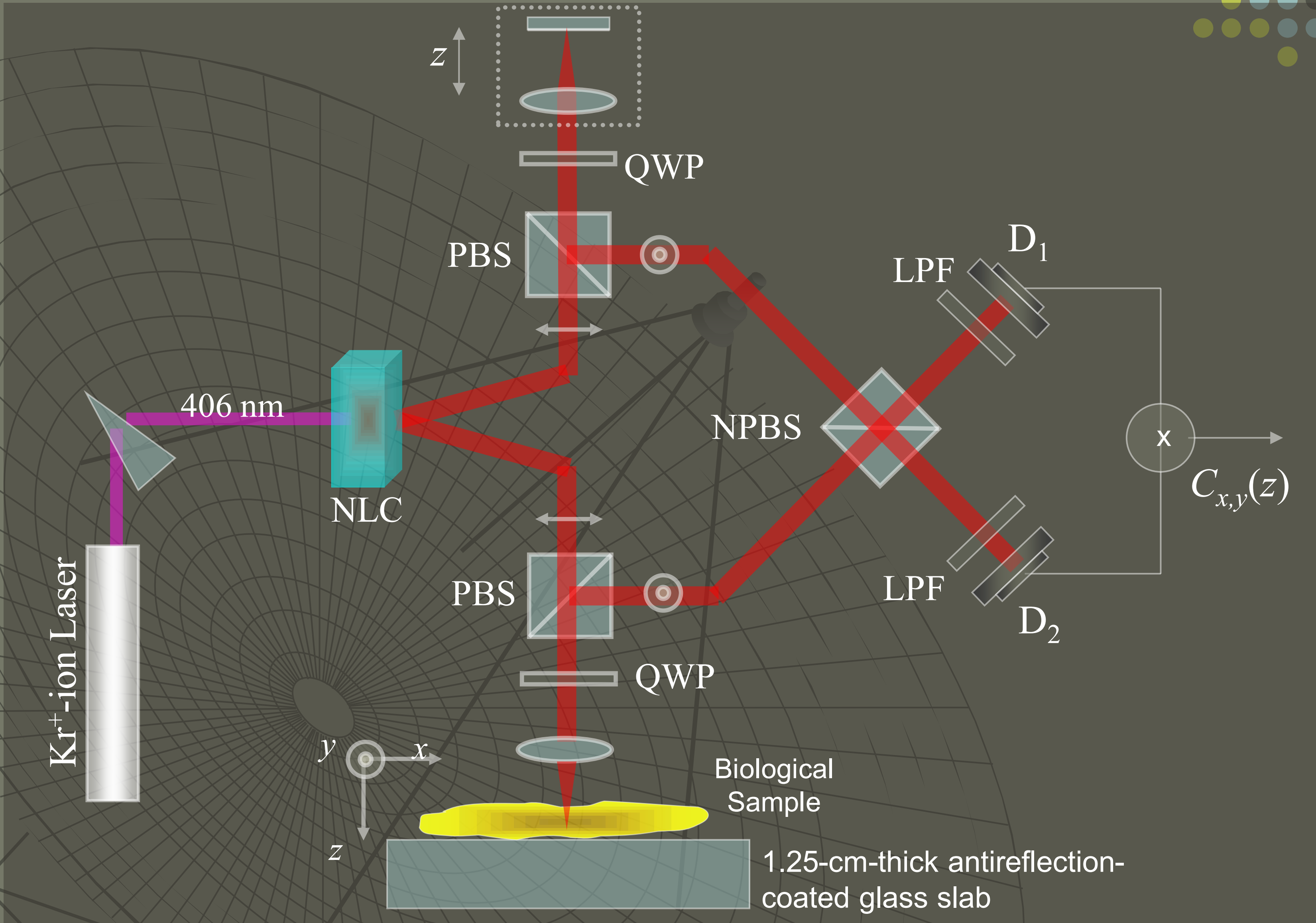


OCT and QOCT
in Ocular Imaging

QOCT vs. OCT

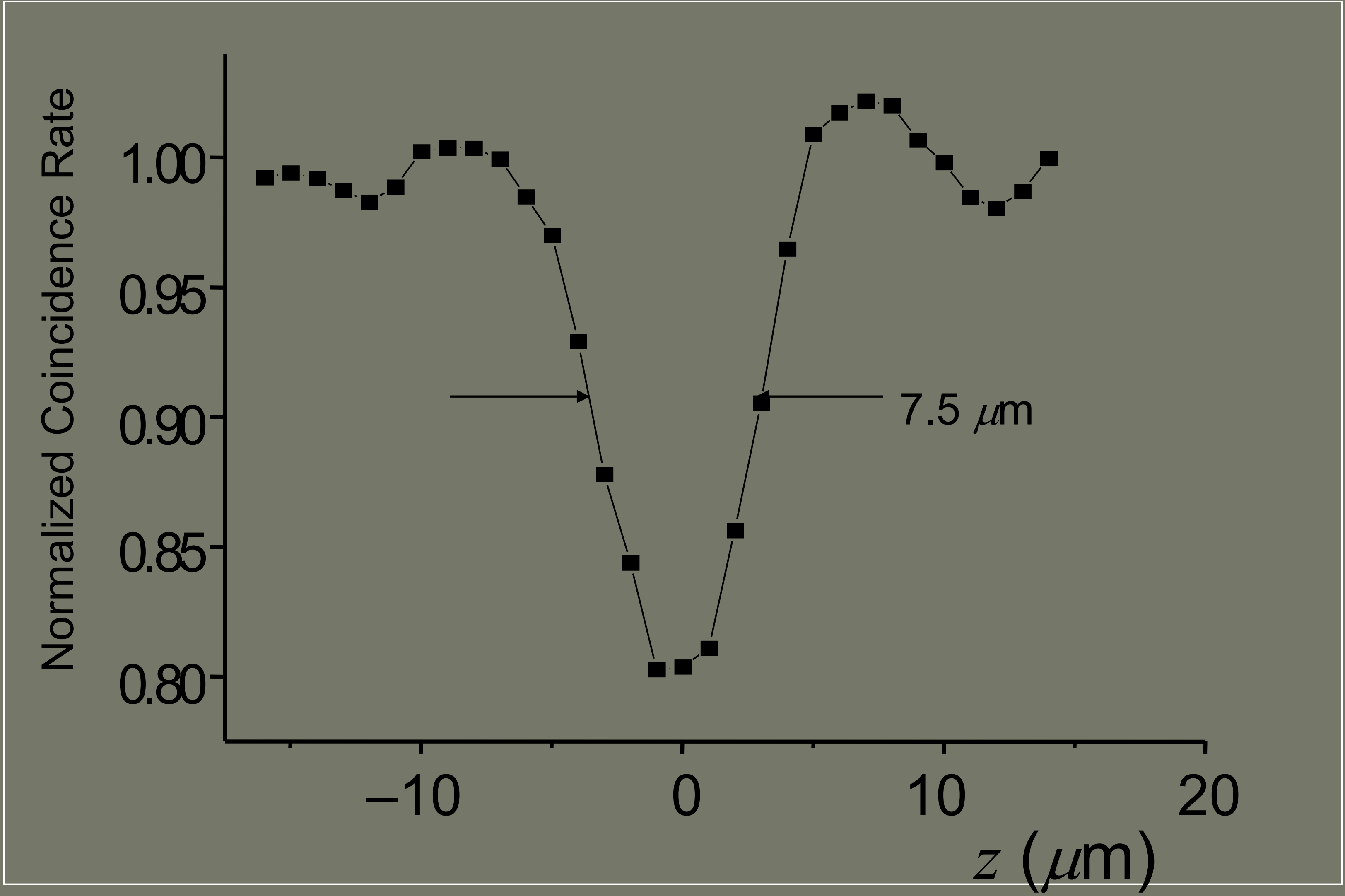
- Q-OCT offers improved axial resolution in comparison with conventional OCT for sources of same spectral bandwidth; the advantage, roughly a factor of 2, depends on the joint spectrum of the source
- The source bandwidth for Q-OCT, which is governed by the process of entangled-photon generation can be tuned
- Self-interference at each boundary is immune to group-velocity dispersion introduced by layers above it
- Inter-boundary interference is sensitive to dispersion of inter-boundary layers; dispersion parameters can thus be estimated
- Many challenges face QOCT, however, including limited photon flux and increased complexity of the optical configuration

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)

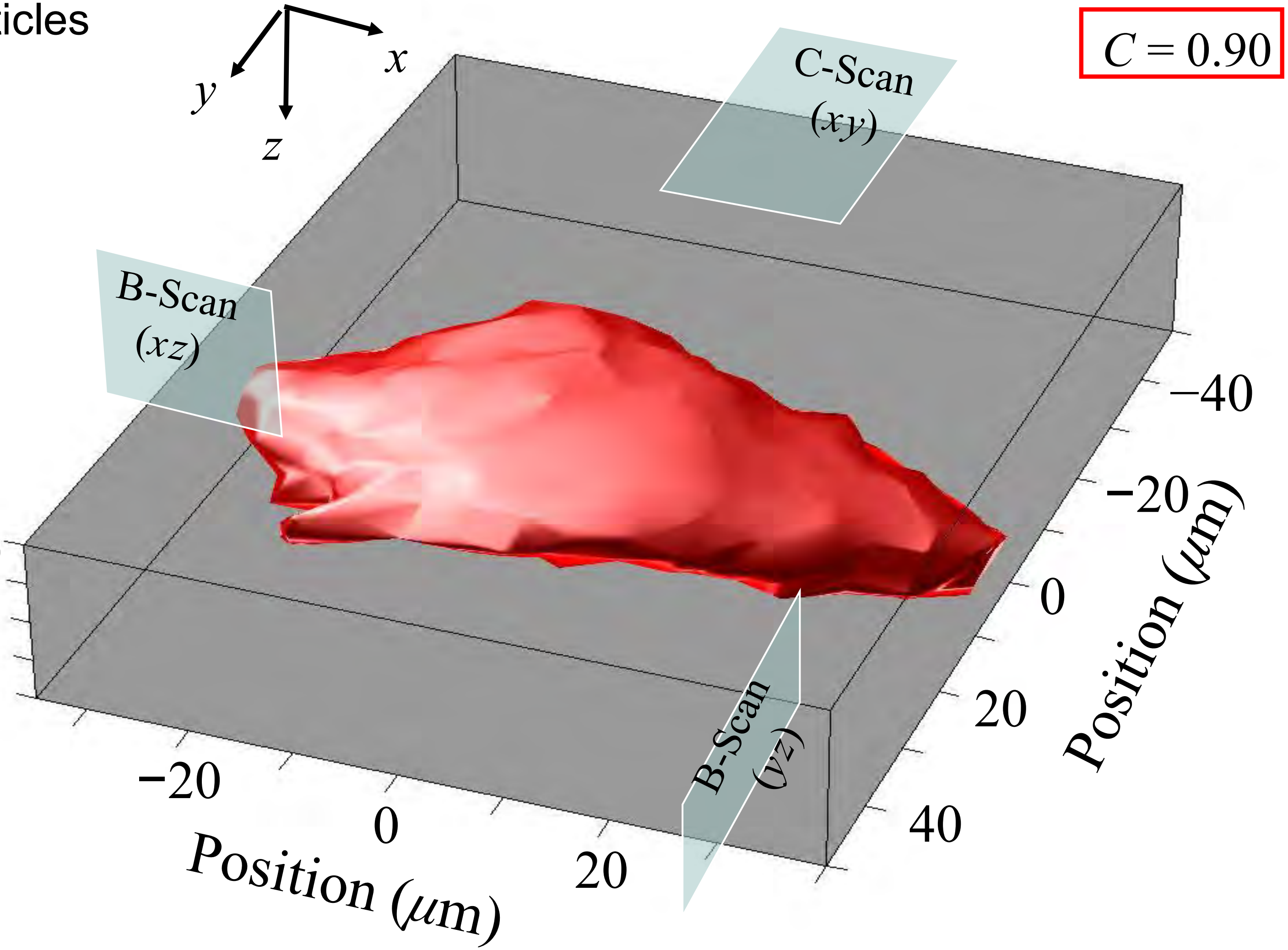
A-Scan



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

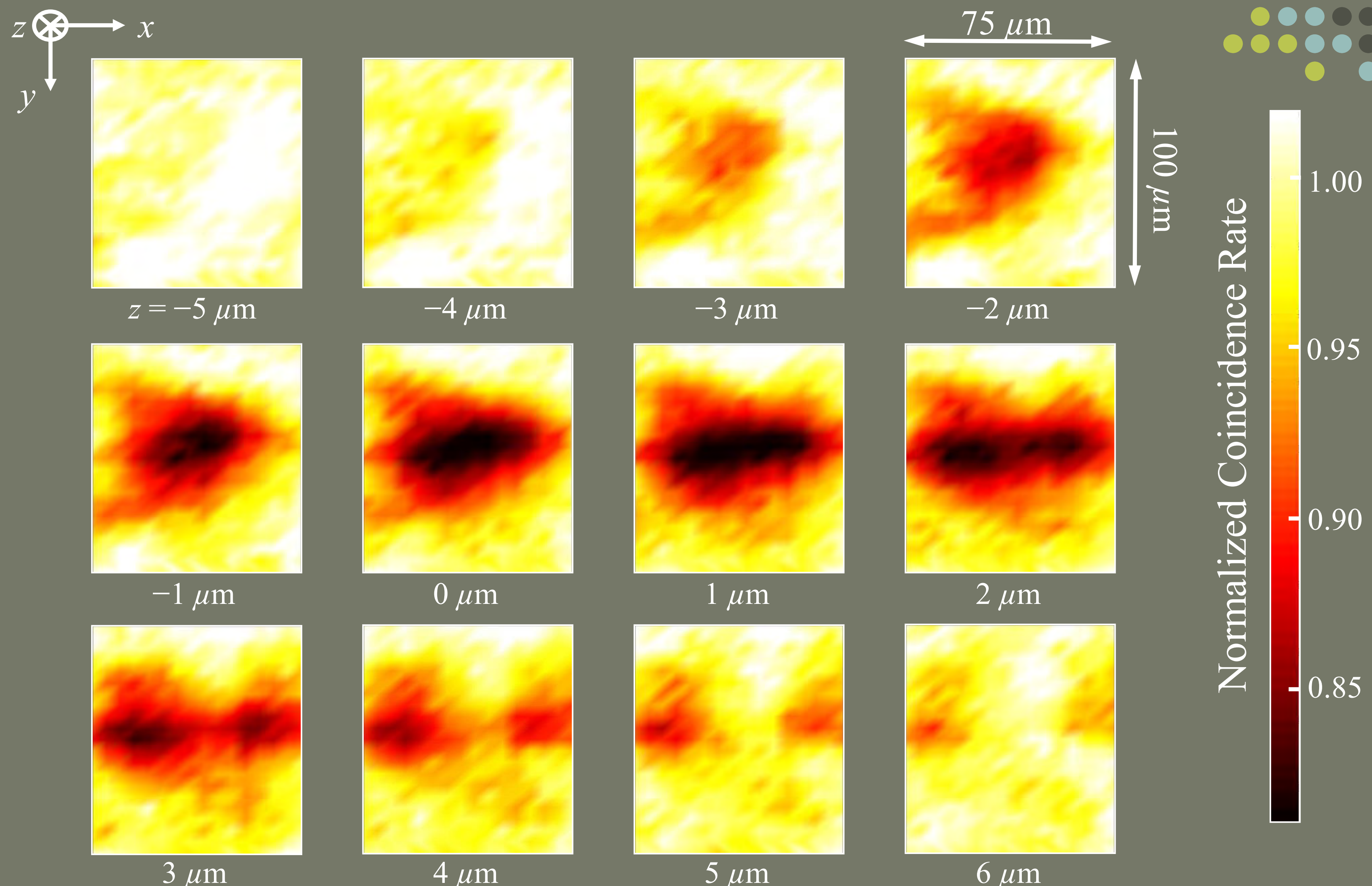
3D Contours of Constant Coincidence Rate

Sample coated with BSA-functionalized gold nanoparticles



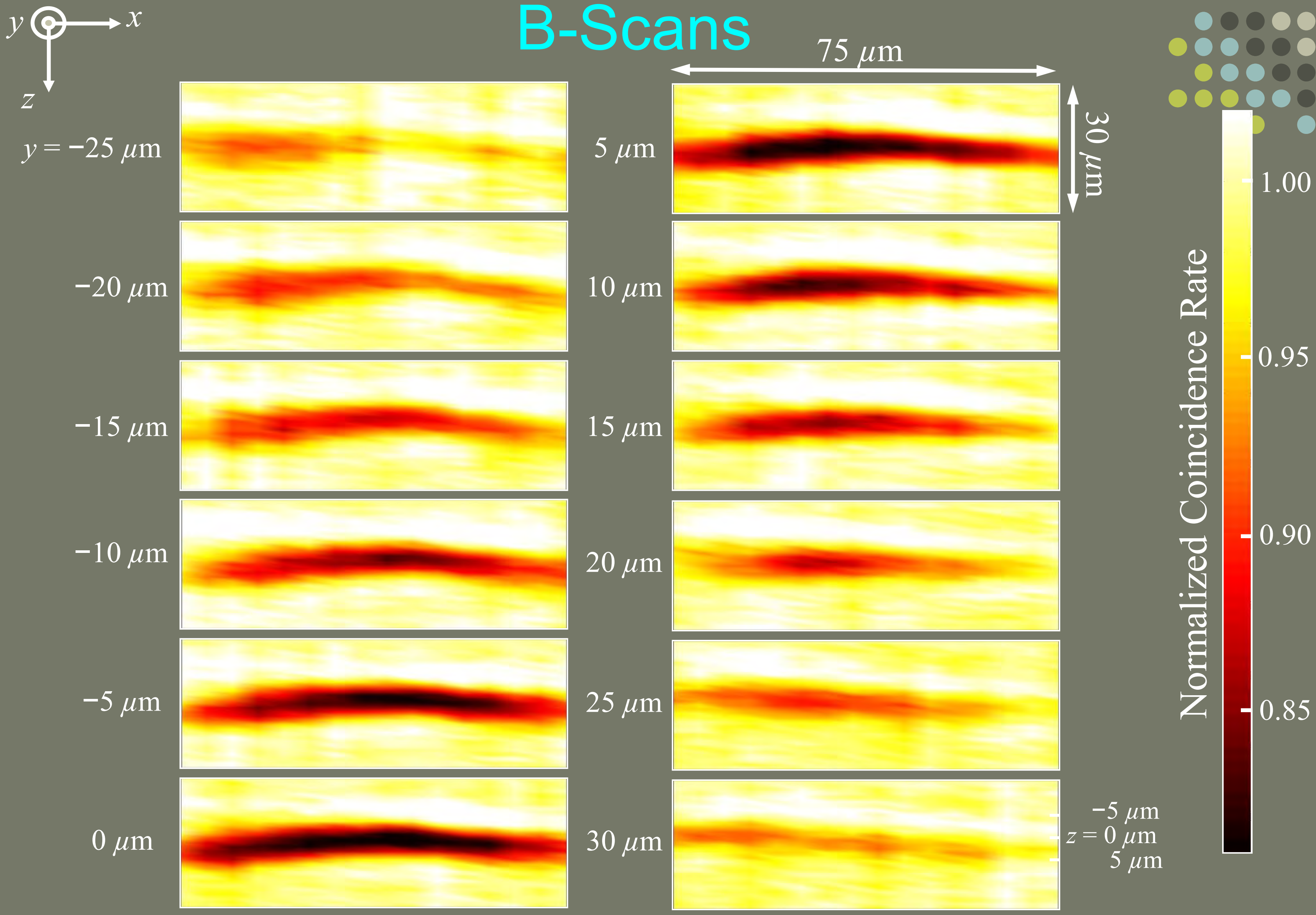
After Nasr, Goode, Nguyen, Rong, Yang, Reinhard, Saleh, and Teich, “Quantum Optical Coherence Tomography of a Biological Sample,” *Opt. Commun.* **282**, 1154 (2009)

C-Scans



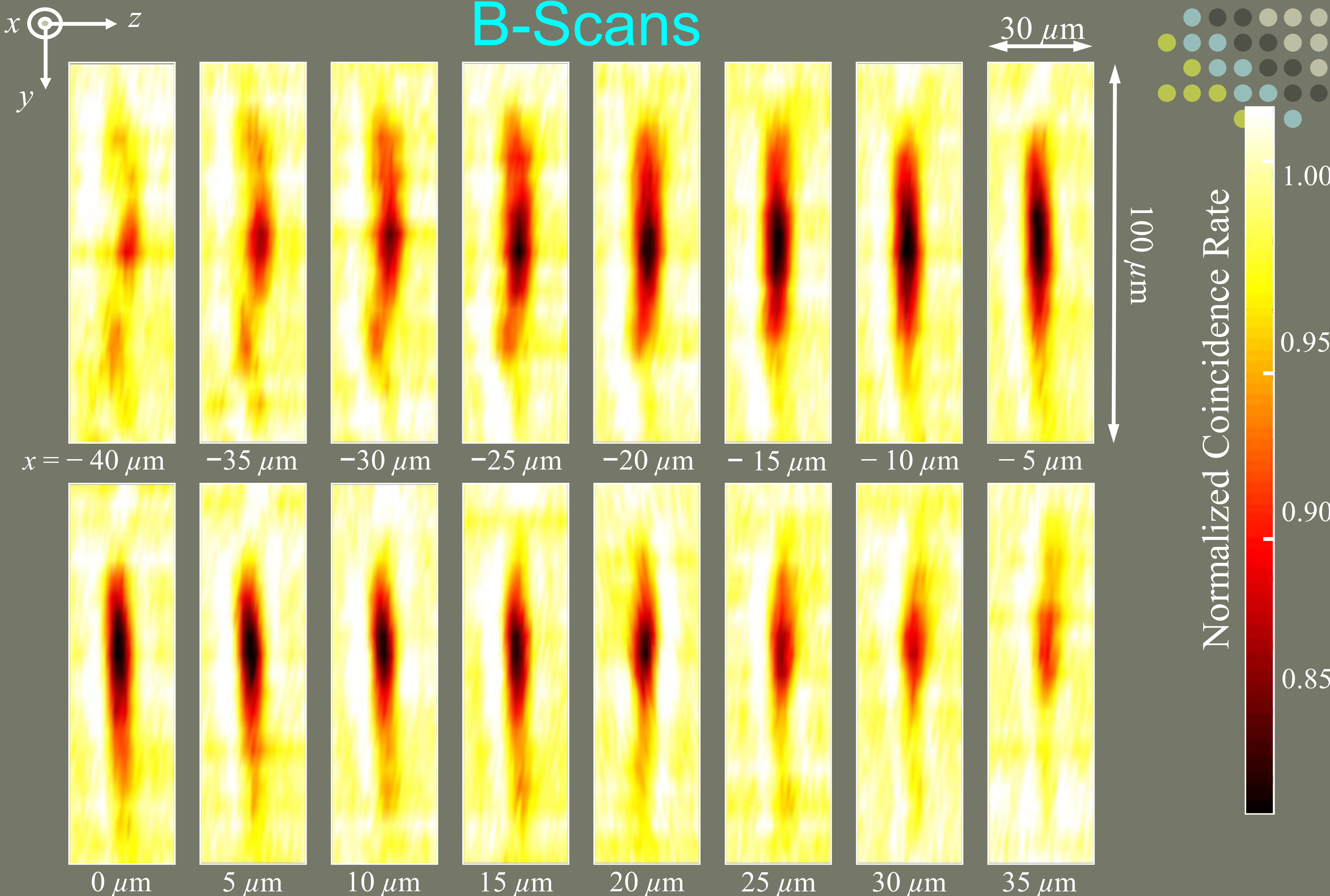
After Nasr, Goode, Nguyen, Rong, Yang, Reinhard, Saleh, and Teich, "Quantum Optical Coherence Tomography of a Biological Sample," *Opt. Commun.* **282**, 1154 (2009)

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)

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: eye--retinal nerve fiber layer, retinal thickness, contour changes in the optic disk; subcutaneous blood vessels
- Turbid media: vascular wall, placques
- Polarization versions: tissues with collagen or elastin fibers: muscle, tendons; normal and thermally damaged soft tissues

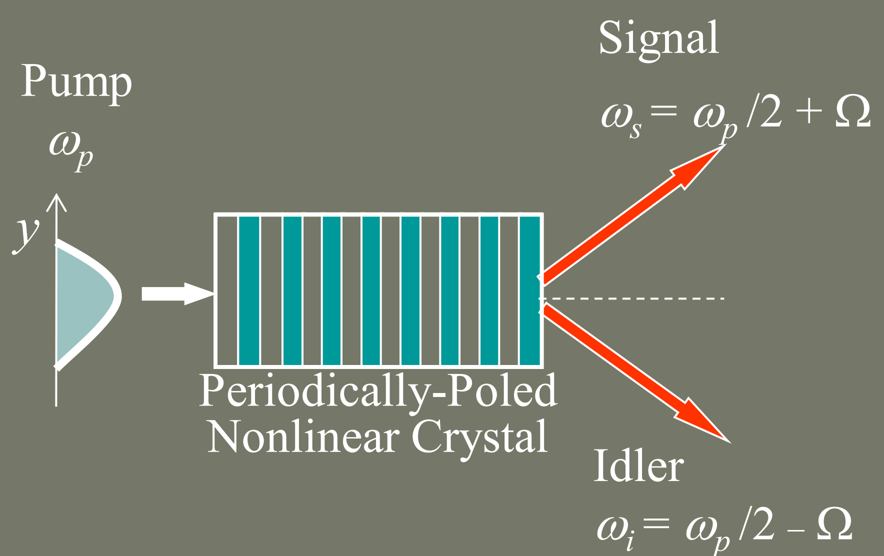
Continuing Challenges for QOCT

- Limited photon flux (improvement via decreased entanglement time)
- Limited axial resolution (improvement via increased source bandwidth)
- Increased complexity and cost of optical arrangement

Further Advances (following slides)

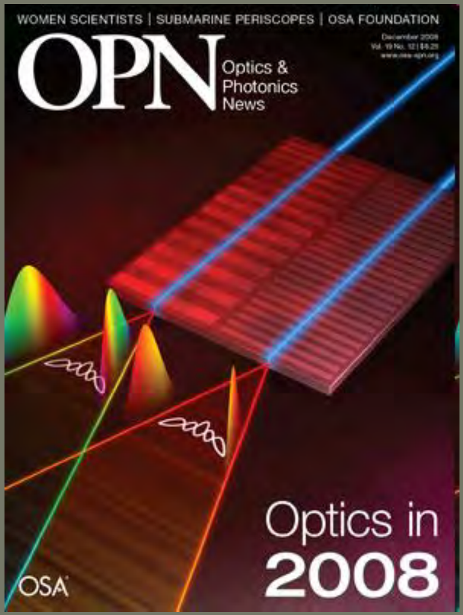
- Quasi-phase matched (QPM) downconversion (increased photon flux)
- Chirped quasi-phase-matched downconversion (increased bandwidth)
- QOCT resolution enhancement via chirped-QPM downconversion
- QOCT resolution enhancement via superconducting single-photon detectors
- Photon-counting OCT (biological)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

Quasi-Phase-Matched (QPM) Downconversion



Increased Photon Flux

Chirped Quasi-Phase-Matched (QPM) Downconversion

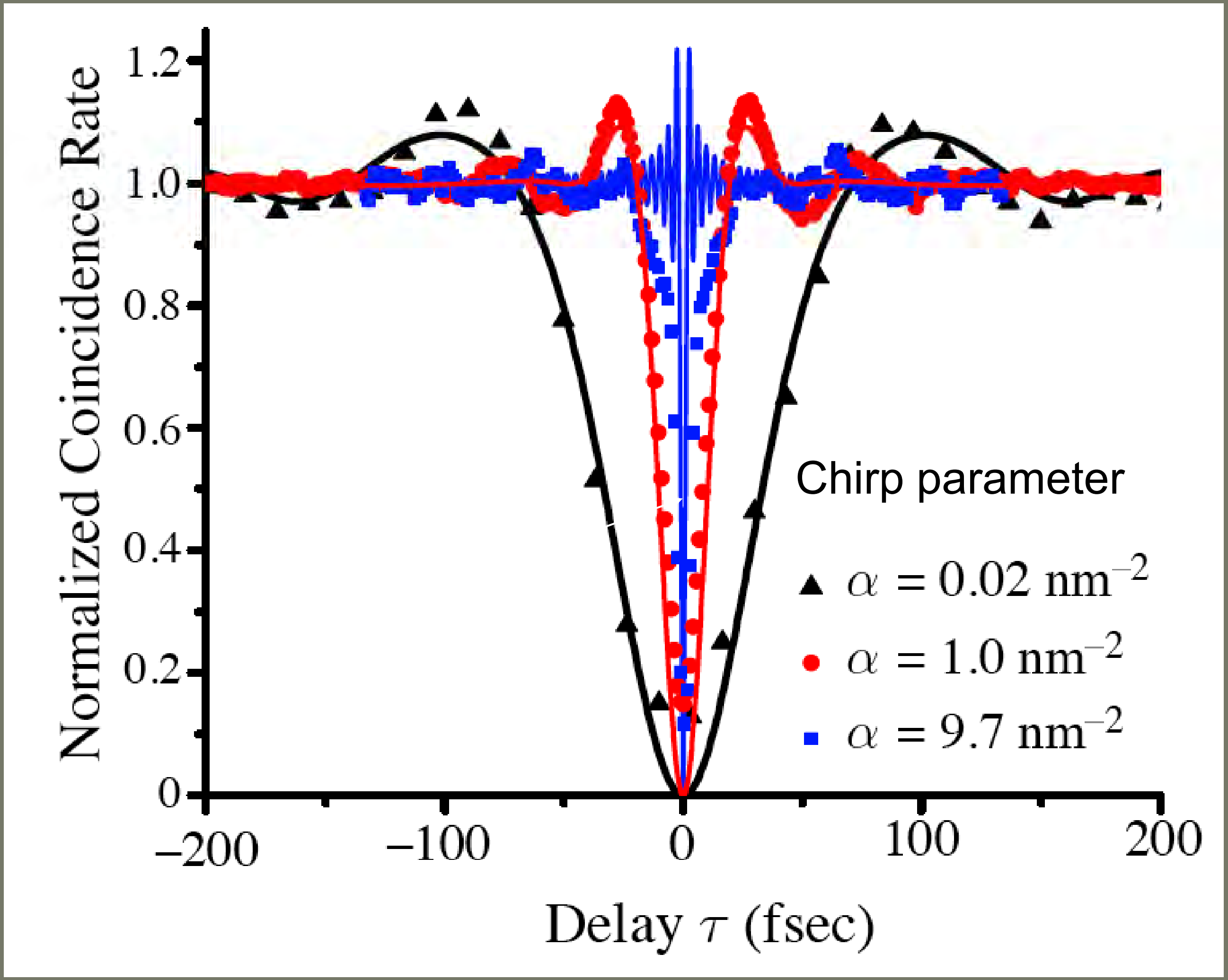


Increased Spectral Bandwidth

QOCT with Chirped-QPM Downconversion Enhances Resolution

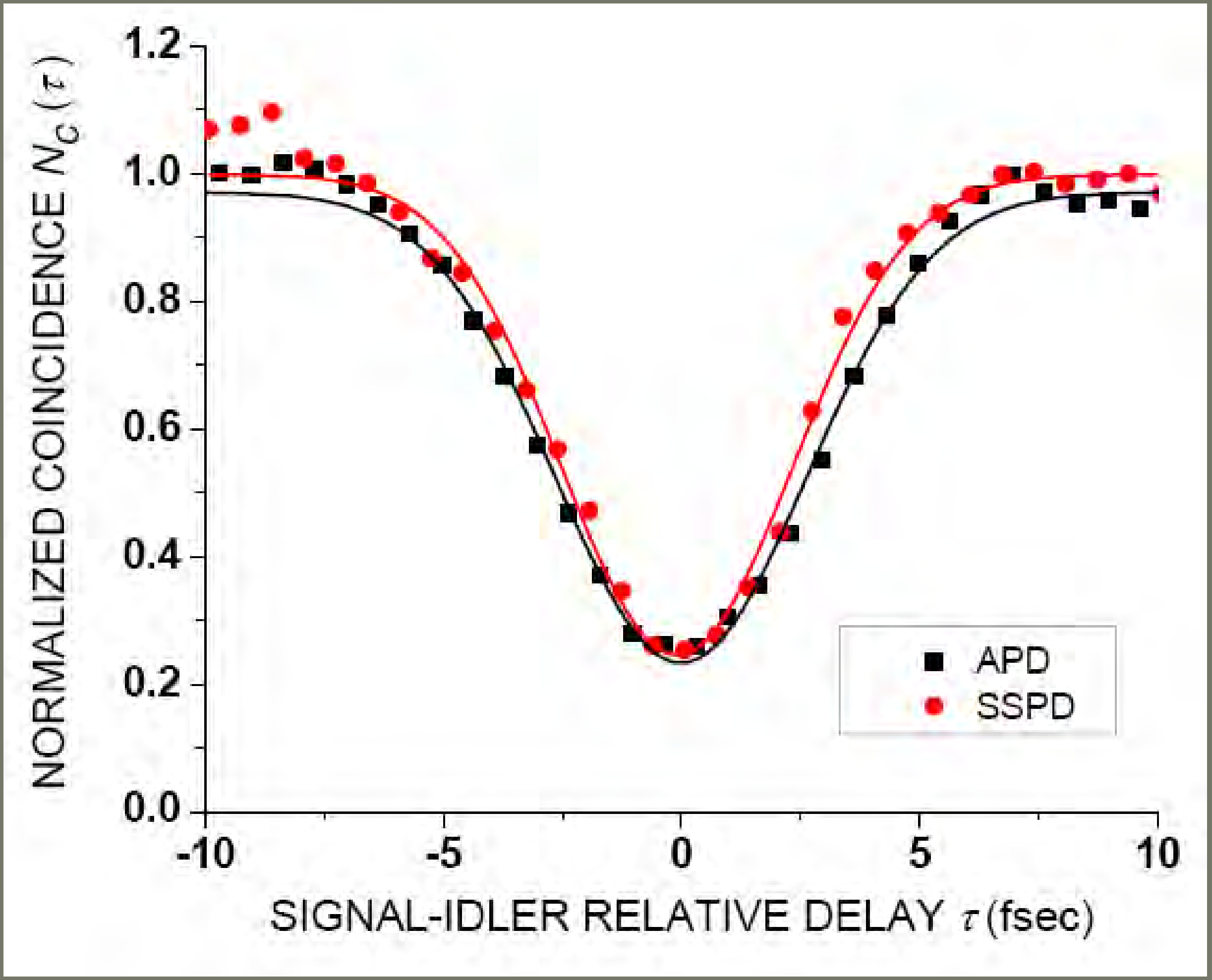
After Carrasco, Torres, Torner, Sergienko, Saleh, and Teich, "Enhancing the Axial Resolution of Quantum Optical Coherence Tomography by Chirped Quasi-Phase-Matching," *Opt. Lett.* **29**, 2429 (2004)

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)

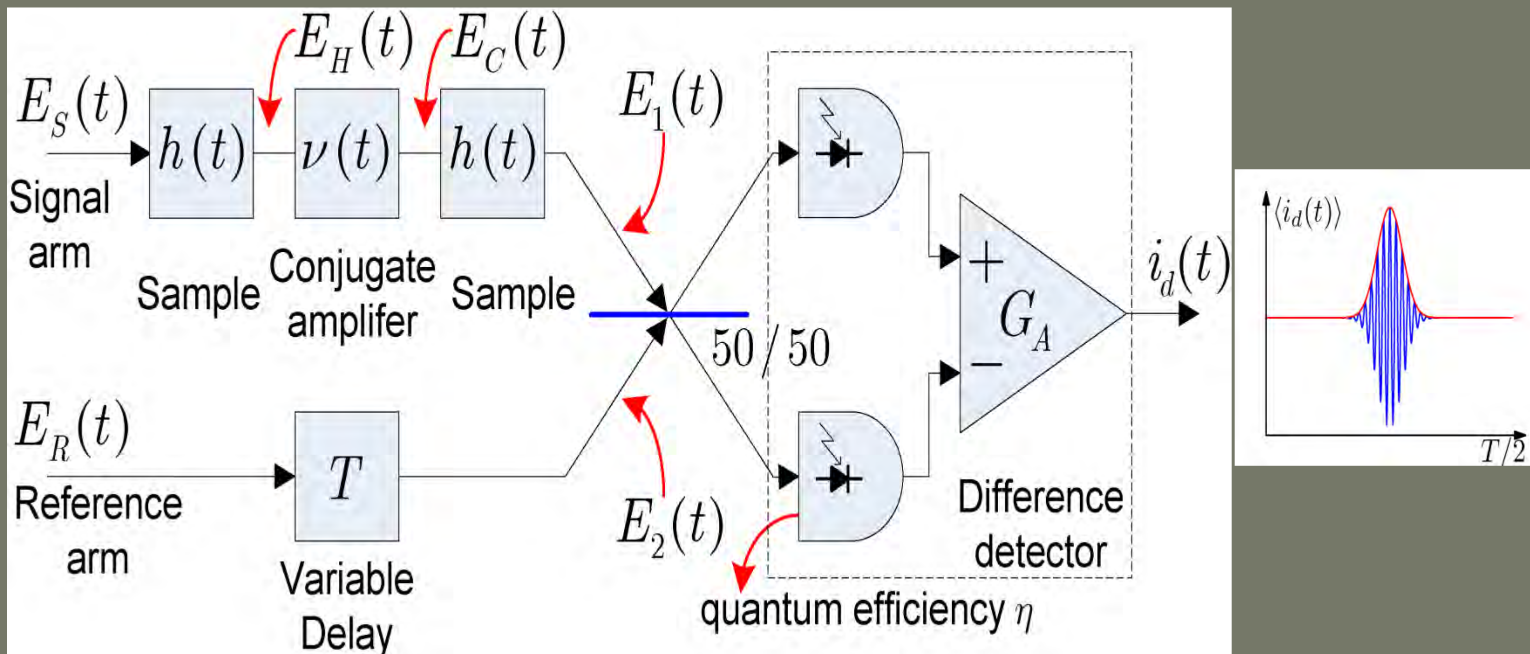
Enhancement of QOCT Resolution via Increase in Detector Bandwidth



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)

Quantum-Mimetics

Phase-Sensitive Optical Coherence Tomography



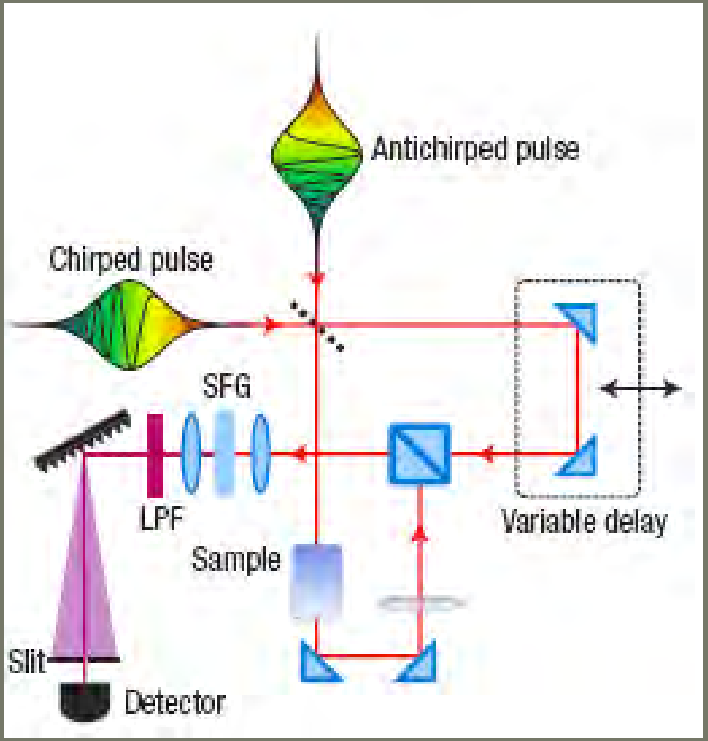
After Erkmen and Shapiro, “Phase-Conjugate Optical Coherence Tomography,” *Phys. Rev. A* **74**, 041601 (2006)

FOR REVIEW & OUTLOOK REGARDING OCT, QOCT, AND VARIATIONS, SEE:

Teich, Saleh, Wong, and Shapiro, “Variations on the Theme of Quantum Optical Coherence Tomography: A Review,” *Quantum Inform. Process.* 11, 903-923 (2012)

Quantum-Mimetics

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



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

See also: Mazurek, Schreiter, Prevedel, Kaltenbaek, and Resch, “Dispersion-Cancelled Biological Imaging with Quantum-Inspired Interferometry,” *Sci. Reports* **3**, 1582 (2013)

CHALLENGES FOR CHIRPED-PULSE INTERFEROMETRY INCLUDE:

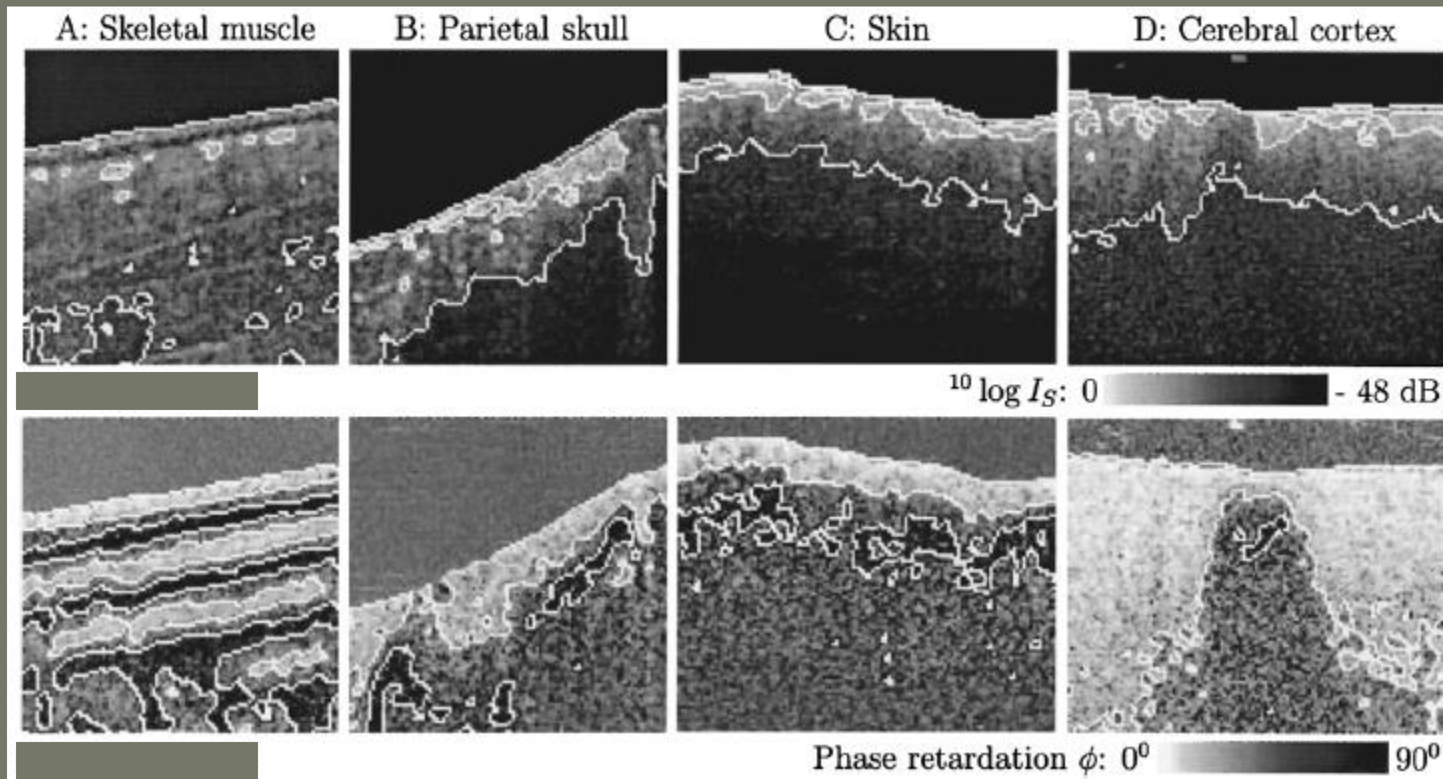
- ❖ **Difficulty in eliminating backscattered strong sum-frequency generation (SFG)**
- ❖ **Difficulty operating broadband phase filter**

Polarization-Sensitive OCT

POLARIZATION
reveals the details

OCT →

PS-OCT →



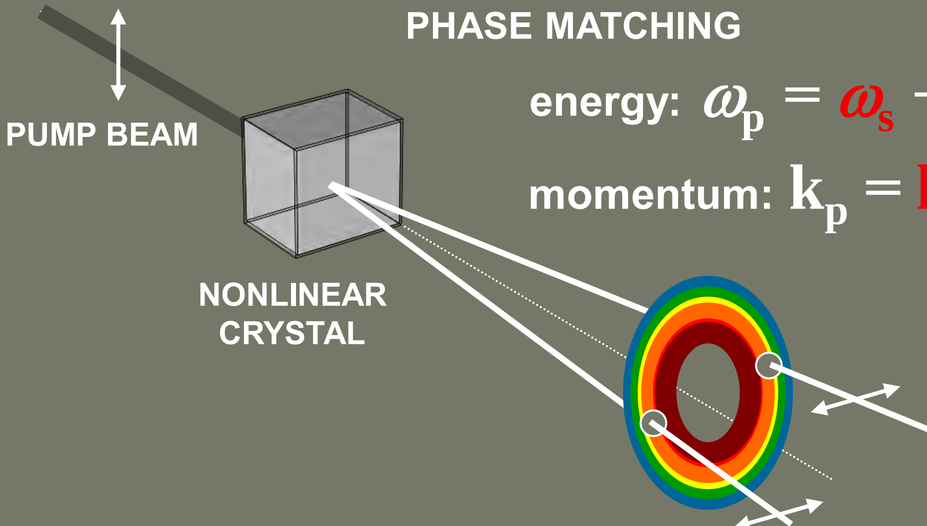
- TISSUES WITH COLLAGEN OR ELASTIN FIBERS, E.G. MUSCLE, TENDONS
- NORMAL AND THERMALLY DAMAGED SOFT TISSUE

Shuliang Jiao and Lihong Wang, *OE Magazine*, pp. 20- 22 (July 2003)

J. de Boer et al., *IEEE J. Select. Top. Quantum Electron.* **5**, 1200-1204 (1999)

Properties of Type-I and Type-II Entangled Photons

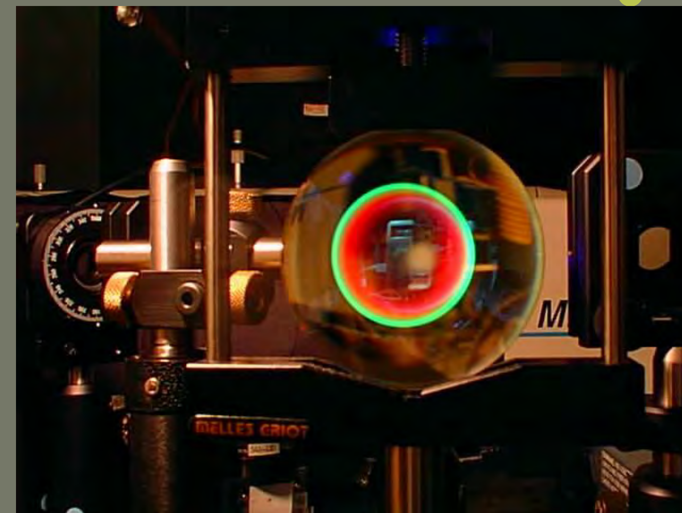
(a) TYPE-I SPDC



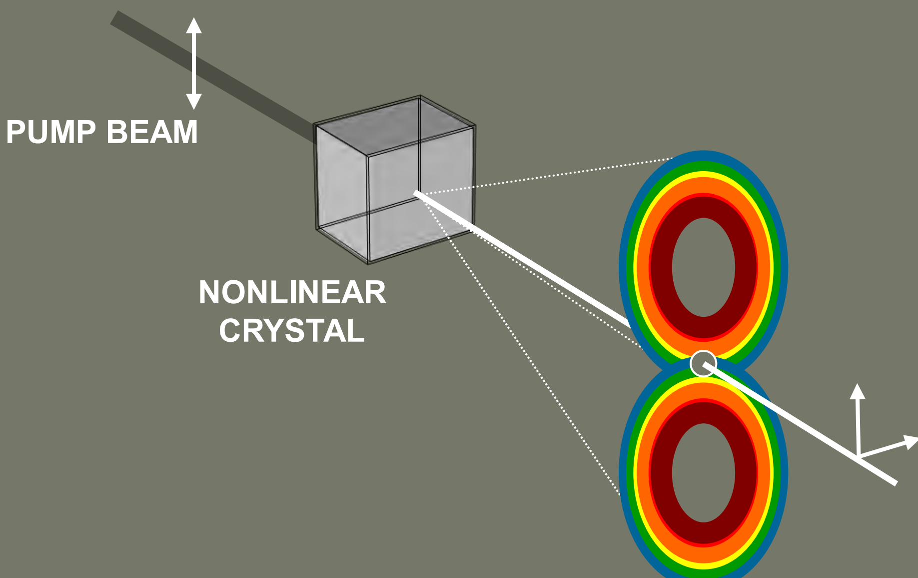
PHASE MATCHING

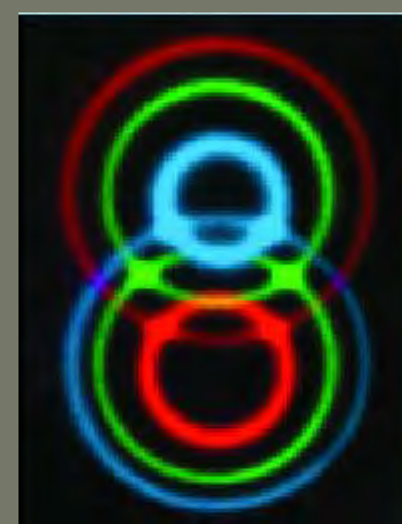
energy: $\omega_p = \omega_s + \omega_i$

momentum: $\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$

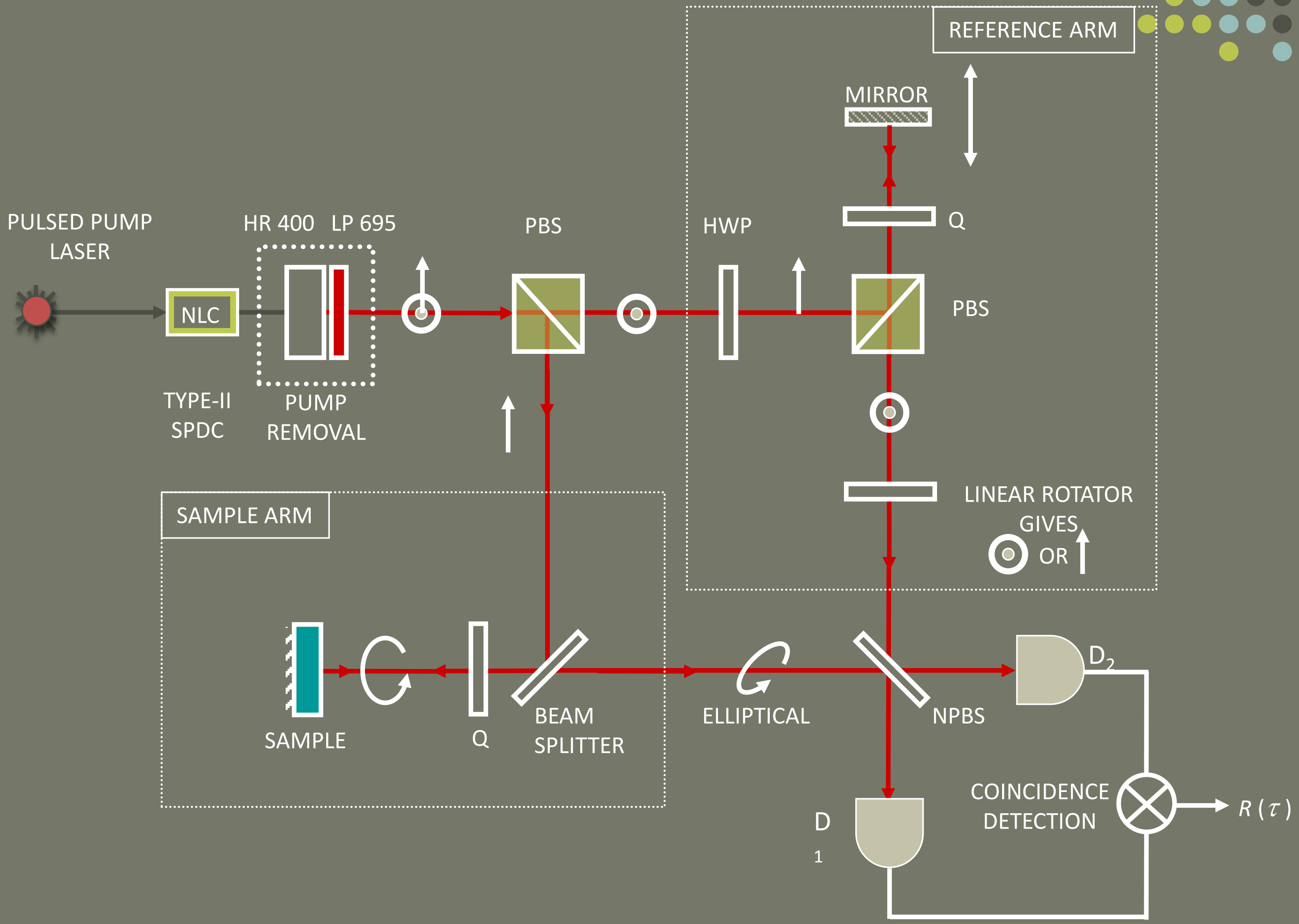


(b) TYPE-II SPDC



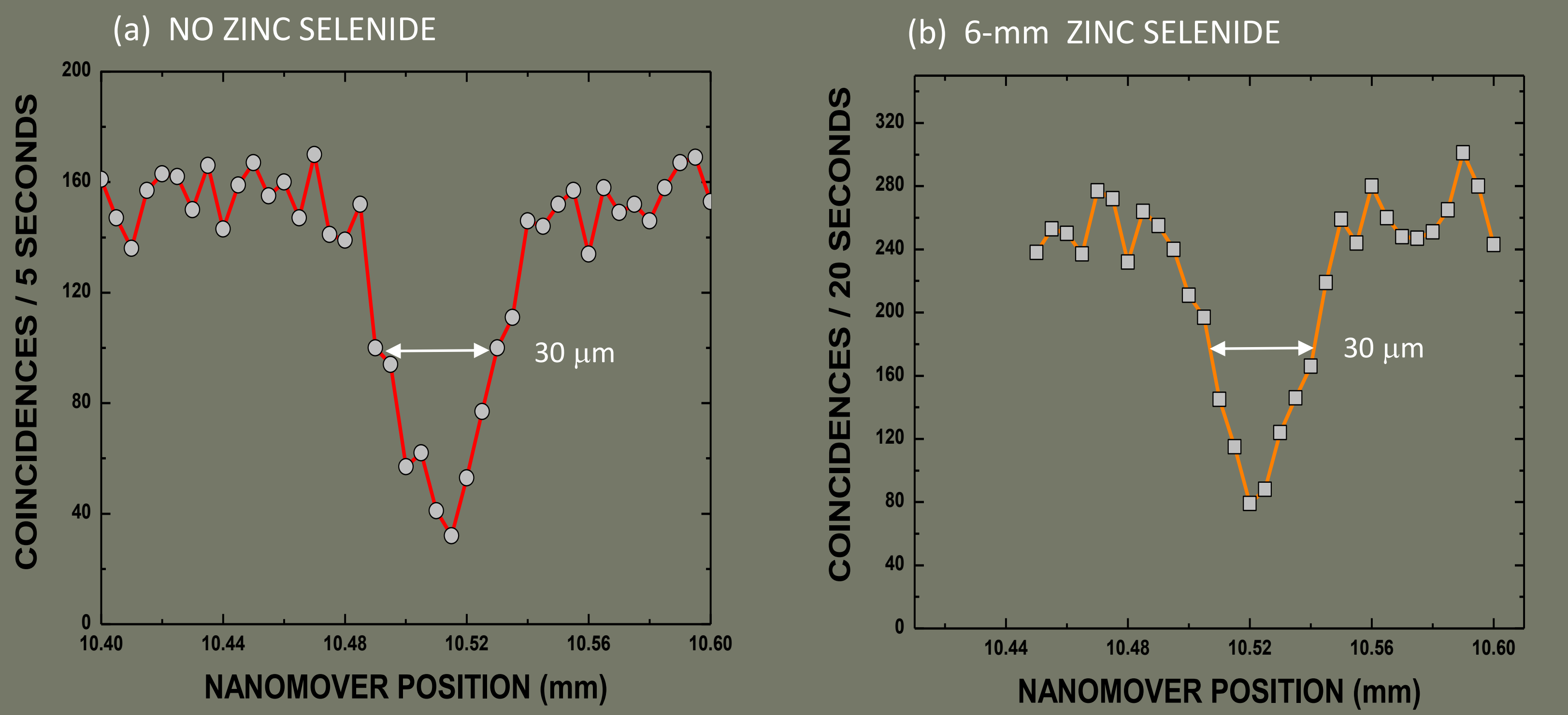


Polarization-Sensitive QOCT: Theory



After Booth, Di Giuseppe, Saleh, Sergienko, and Teich, "Polarization-Sensitive Quantum-Optical Coherence Tomography," *Phys. Rev. A* **69**, 043815 (2004)

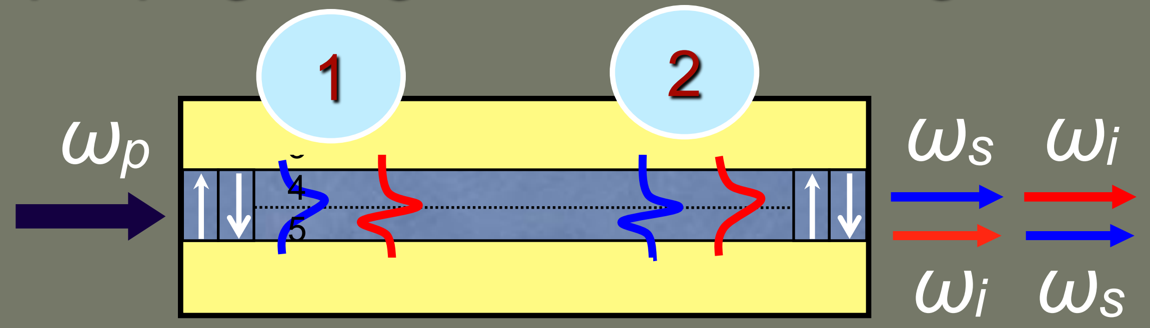
Polarization-Sensitive QOCT: Experiment



After Booth, Saleh, and Teich, "Polarization-Sensitive Quantum-Optical Coherence Tomography: Experiment," *Opt. Commun.* **284**, 2542 (2011)

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

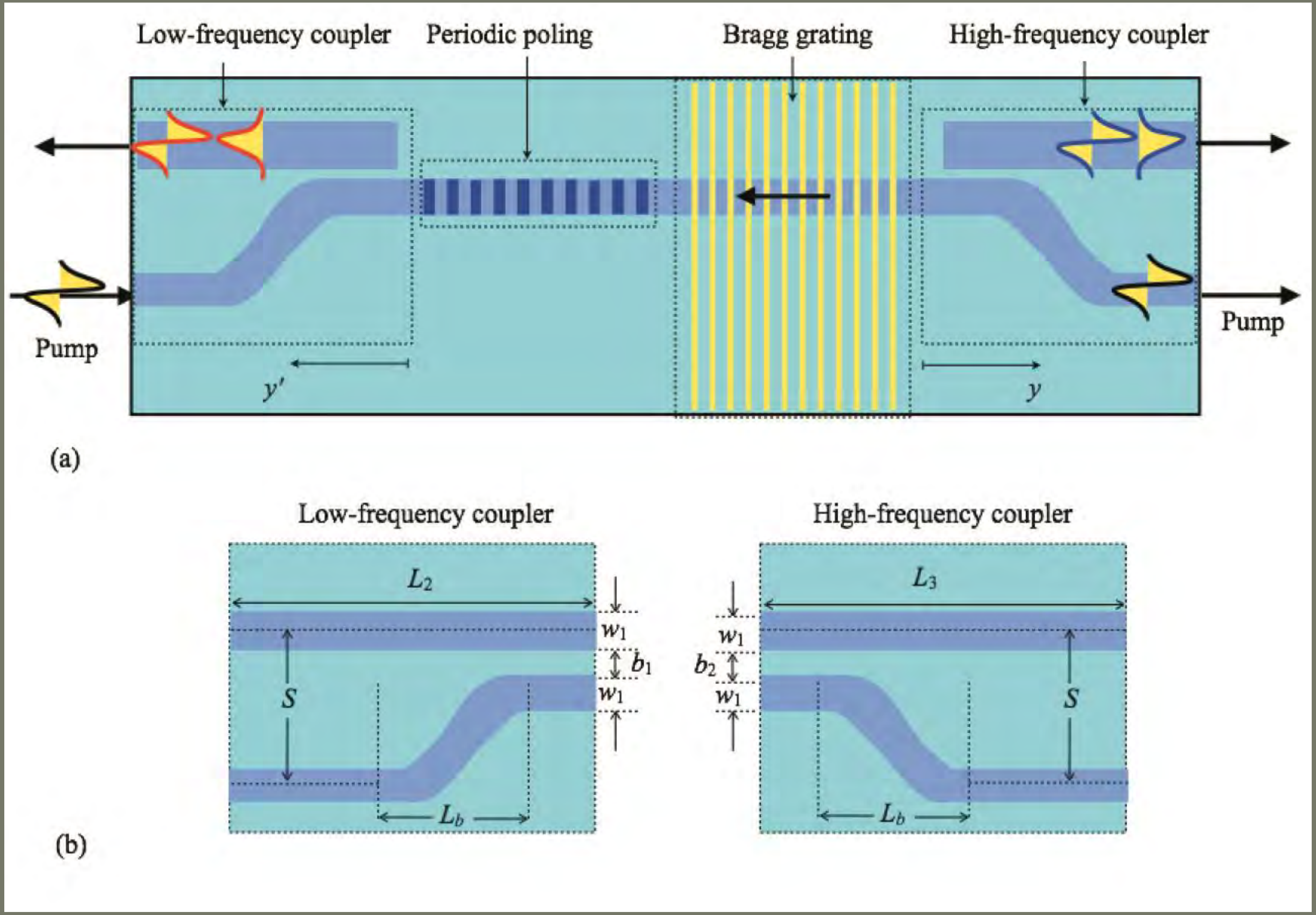
$$\Delta\beta_1 = \Delta\beta_2 \longrightarrow \Lambda_1 = \Lambda_2$$

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)

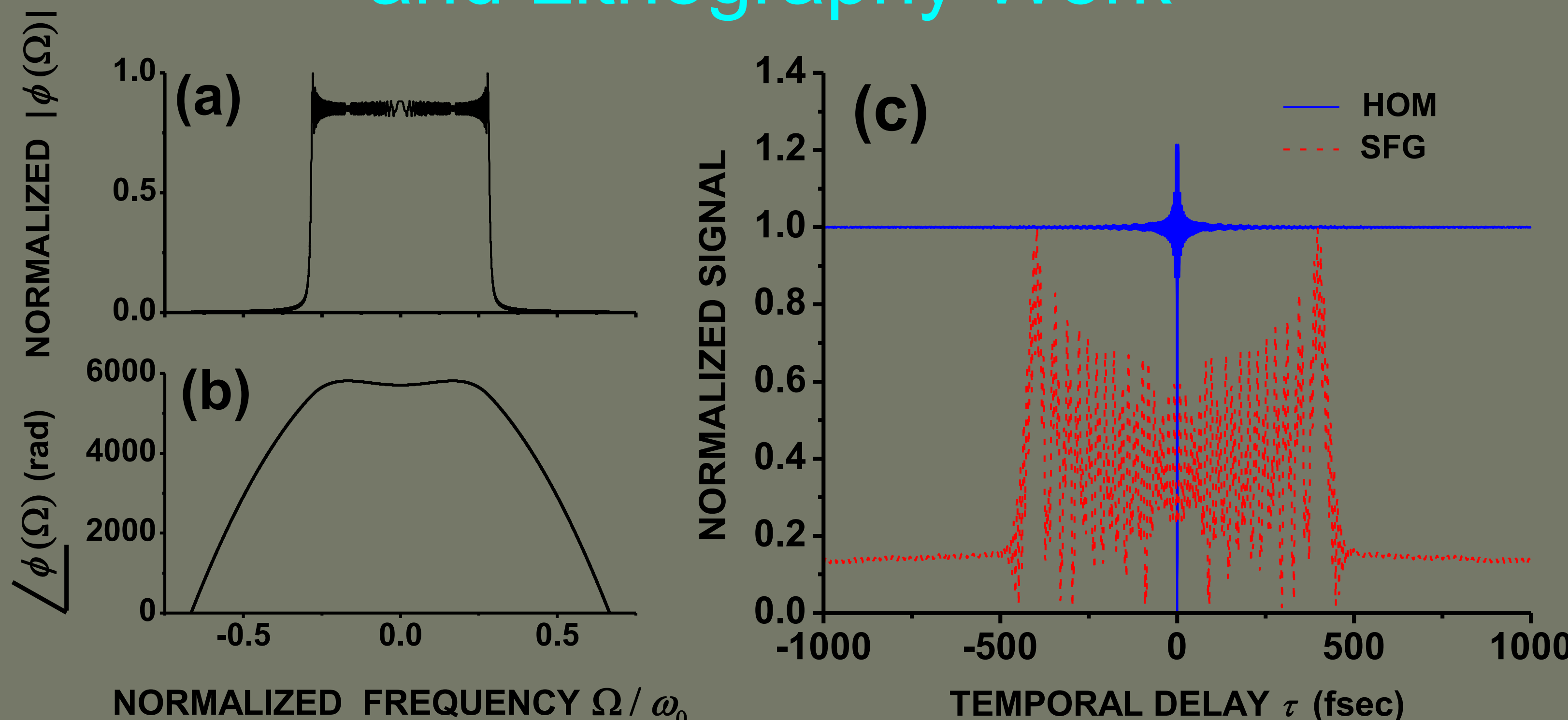
Modal, Spectral, and Polarization Entanglement in Photonic Circuits

Example: Modal entanglement of nondegenerate photons via frequency separation



After Saleh, Di Giuseppe, Saleh, and Teich, "Photonic circuits for generating modal, spectral, and polarization entanglement," *IEEE Photonics Journal* **2**, 736 (2010)

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



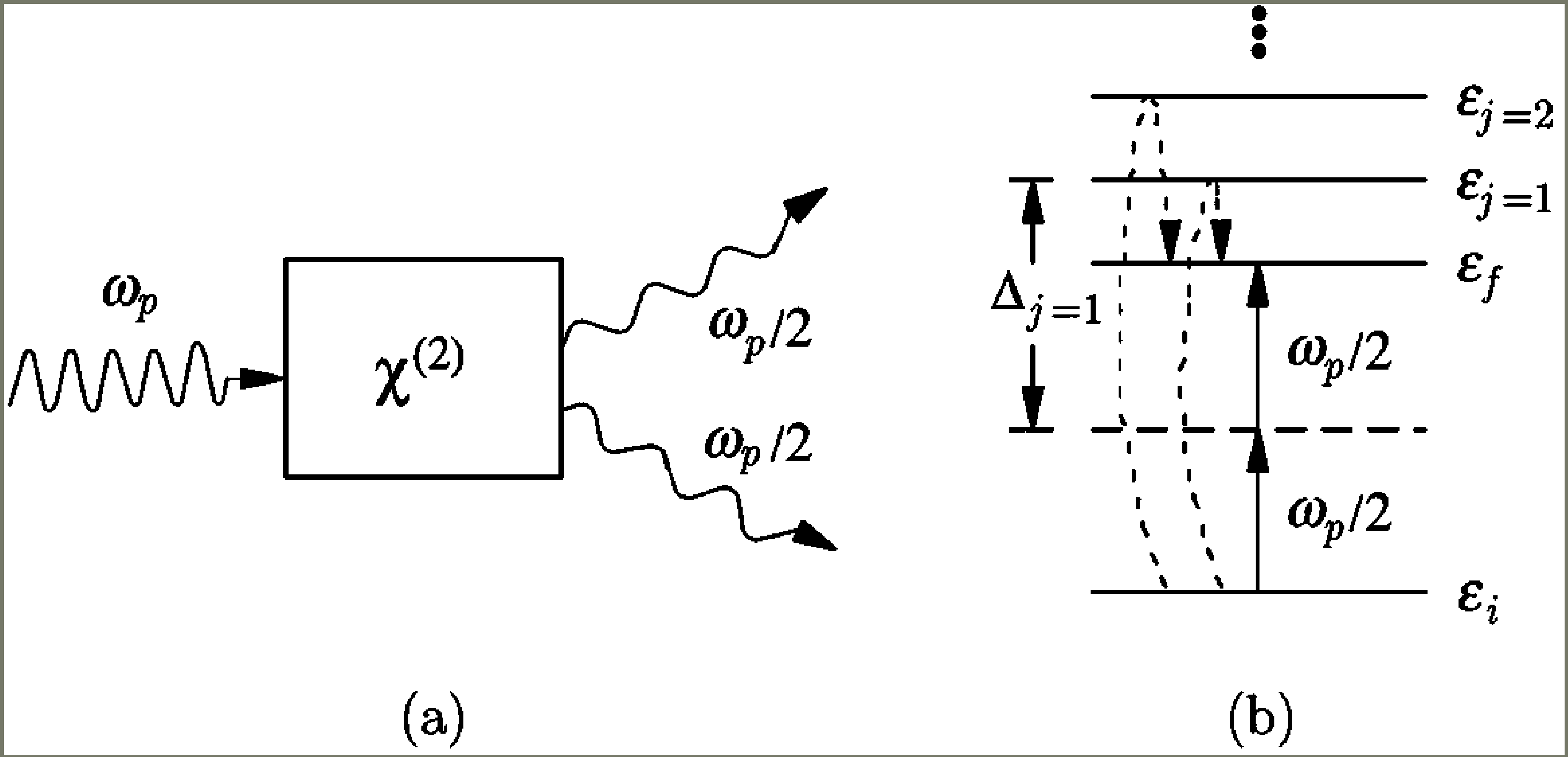
After Nasr, Carrasco, Saleh, Sergienko, Teich, Torres, Torner, Hum, and Fejer, "Ultrabroadband Biphotons Generated via Chirped Quasi-Phase-Matched Optical Parametric Down-Conversion," *Phys. Rev. Lett.* **100**, 183601 (2008)

SEE RELATED PAPERS:

Harris, "Chirp and Compress: Toward Single-Cycle Biphotons," *Phys. Rev. Lett.* 98, 063602 (2007)

Tanaka, Okamoto, Lim, Subashchandran, Okano, Zhang, Kang, Chen, Wu, Hirohata, Kurimura, and Takeuchi, "Noncollinear Parametric Fluorescence by Chirped Quasi-Phase Matching for Monocycle Temporal Entanglement," *Opt. Express* **20**, 25228-25238 (2012)

Entangled-Photon Virtual-State Spectroscopy



Entangled-Photon Generation

Entangled-Photon Absorption via Virtual States(dashed)

After Saleh, Jost, Fei, and Teich, "Entangled-Photon Virtual-State Spectroscopy," *Phys. Rev. Lett.* **80**, 3483 (1998)

Entangled-Photon Virtual-State Spectroscopy

- Extraction of information about the virtual states that contribute to two-photon excitation, *including states whose energies exceed that of the initial-to-final state transition*

- The technique is implemented by carrying out *continuous-wave* absorption measurements *without changing the wavelength of the source*, i.e., by using a monochromatic pump and degenerate SPDC

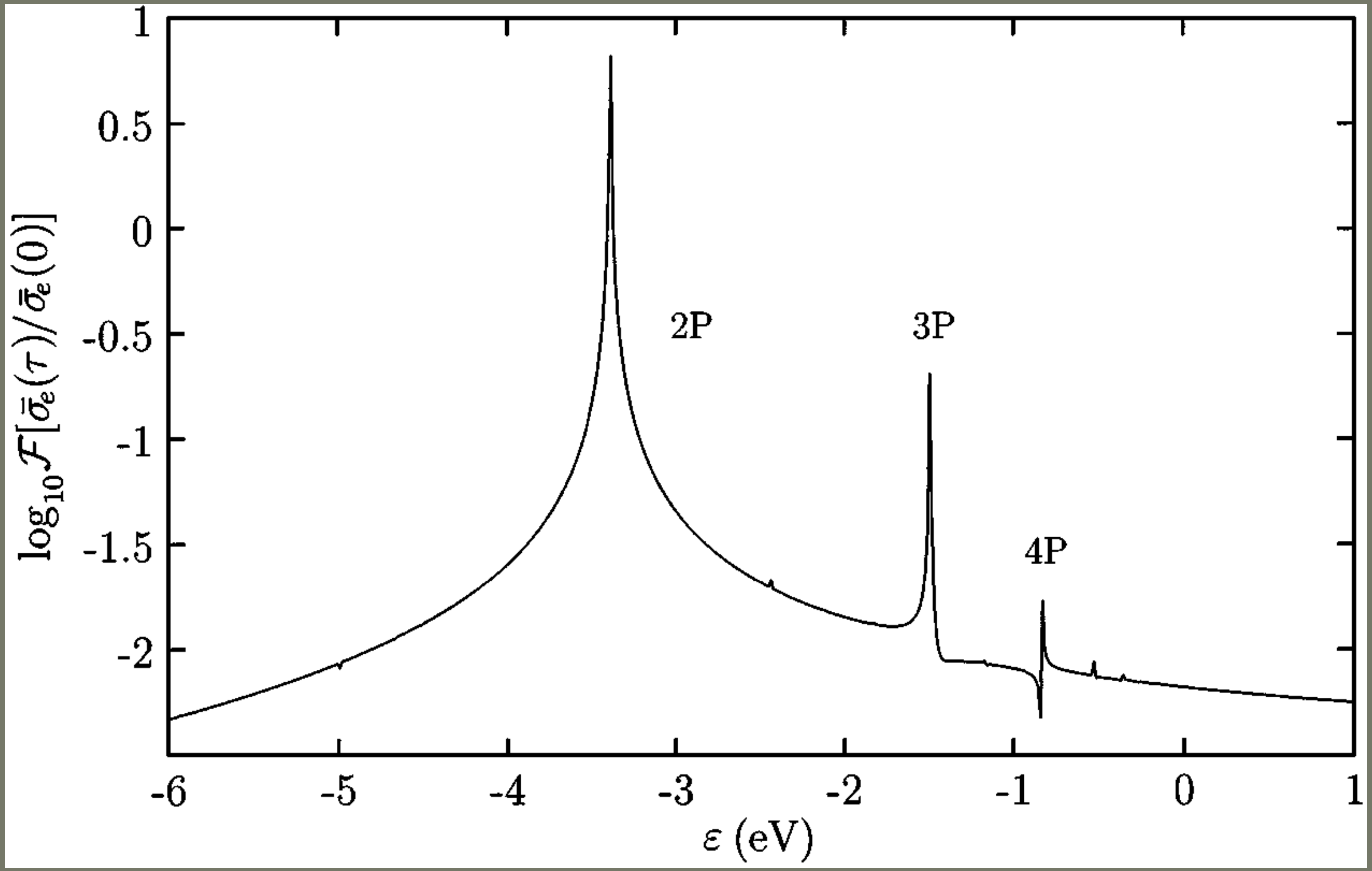
- Implementation of the technique requires not only entanglement, but also a *particular form for the joint spectrum* of the entangled photons

- The approach differs fundamentally from other spectroscopic techniques, including those that rely on other types of nonclassical light sources and on pulsed coherent excitations or multidimensional pump-probe spectroscopy

- The enabling feature of obtaining information about the virtual-state spectrum arises from the composition of the entangled-photon absorption cross section as a *coherent summation of two-photon interaction terms*

Entangled-Photon Virtual-State Spectroscopy

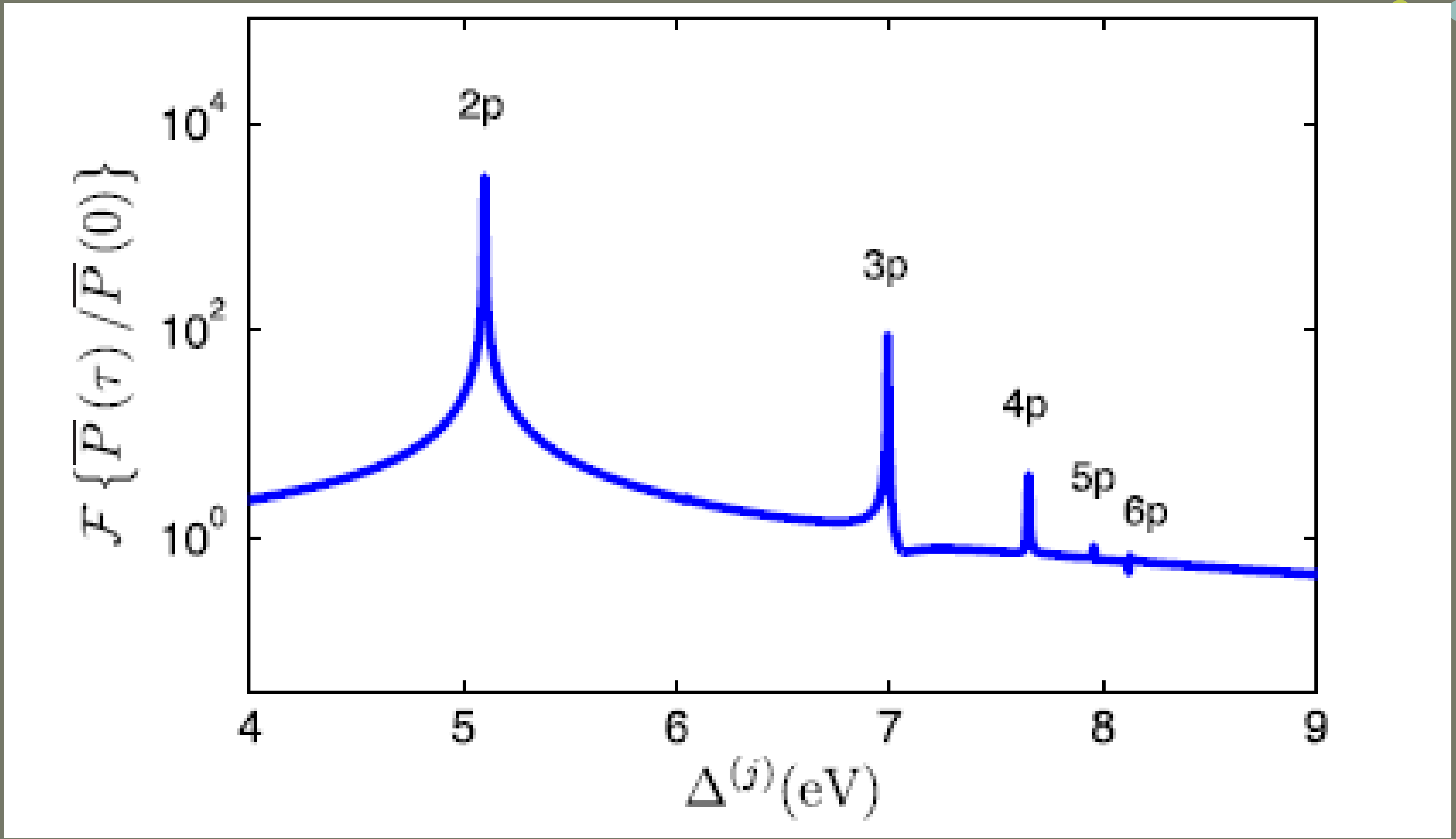
(1S → 2S Two-Photon Transition in Atomic Hydrogen)



Fourier transform of simulated normalized weighted- and-averaged atomic hydrogen 1*S*-2*S* cross section

After Saleh, Jost, Fei, and Teich, "Entangled-Photon Virtual-State Spectroscopy," *Phys. Rev. Lett.* **80**, 3483 (1998)

Entangled-Photon Virtual-State Spectroscopy
(1S → 2S Two-Photon Transition in Atomic Hydrogen)



Fourier transform of simulated normalized weighted- and-averaged 1*S*-2*S* cross section with sinc-function joint spectrum

After León-Montiel, Svozilík, Salazar-Serrano, and Torres, "Role of the Spectral Shape of Quantum Correlations in Two-Photon Virtual-State Spectroscopy," *New J. Phys.* **15**, 053023 (2013)

ACKNOWLEDGMENTS

Boston University:

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

BU Engineering
College of
BOSTON UNIVERSITY

the photonics center at boston university

NSF

Army Research Office

CenSSIS
The Center for Subsurface Sensing and Imaging Systems

The David and Lucile Packard Foundation

ZEISS

DARPA