Quantum and Nonlinear Optical Imaging

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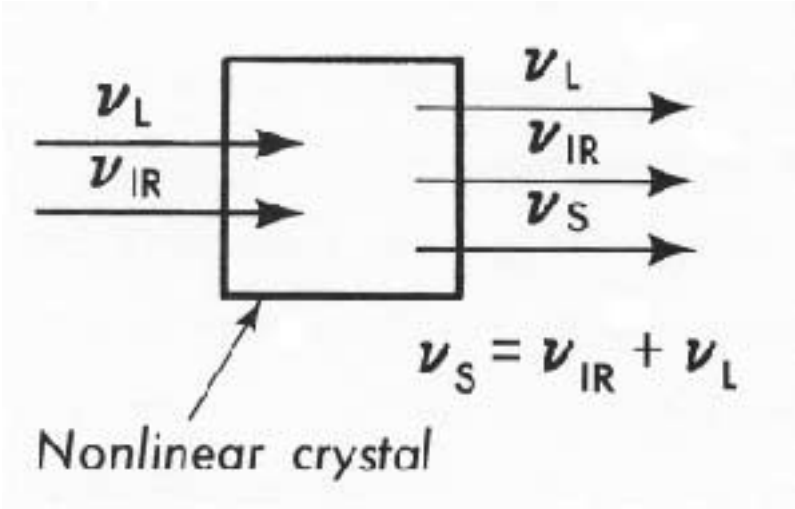
- Imaging upconversion
  (for astronomy and THz imaging)
- The promise of quantum imaging
  Quantum (?) lithography
  Quantum (?) coincidence imaging
- Generation of quantum states of light
  - Development of nonlinear optical materials (enabler)
    Composite materials
    Nanofabrication
  - Nonlinear optical microscopy
  - Underlying issues in nonlinear optics

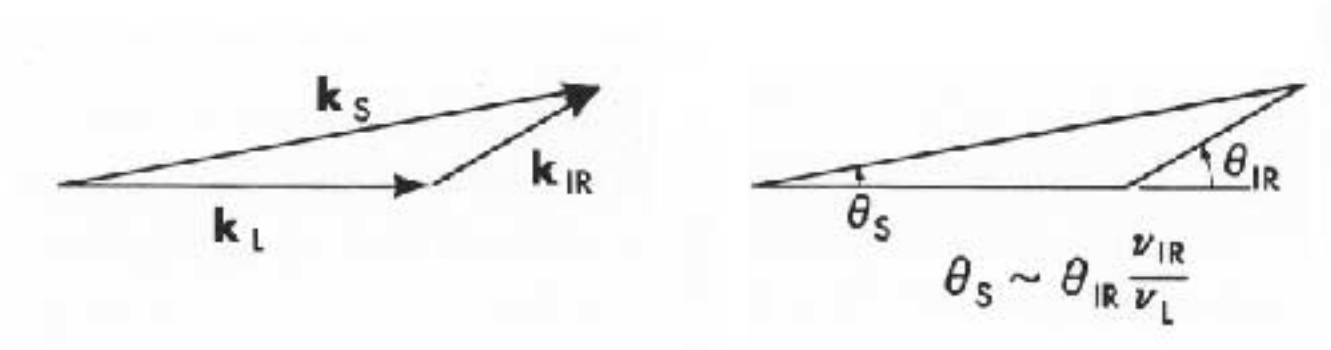
Presented at Quantum Imaging and Metrology, Pasadena, CA Nov. 14-15, 2000

Imaging Upconversion

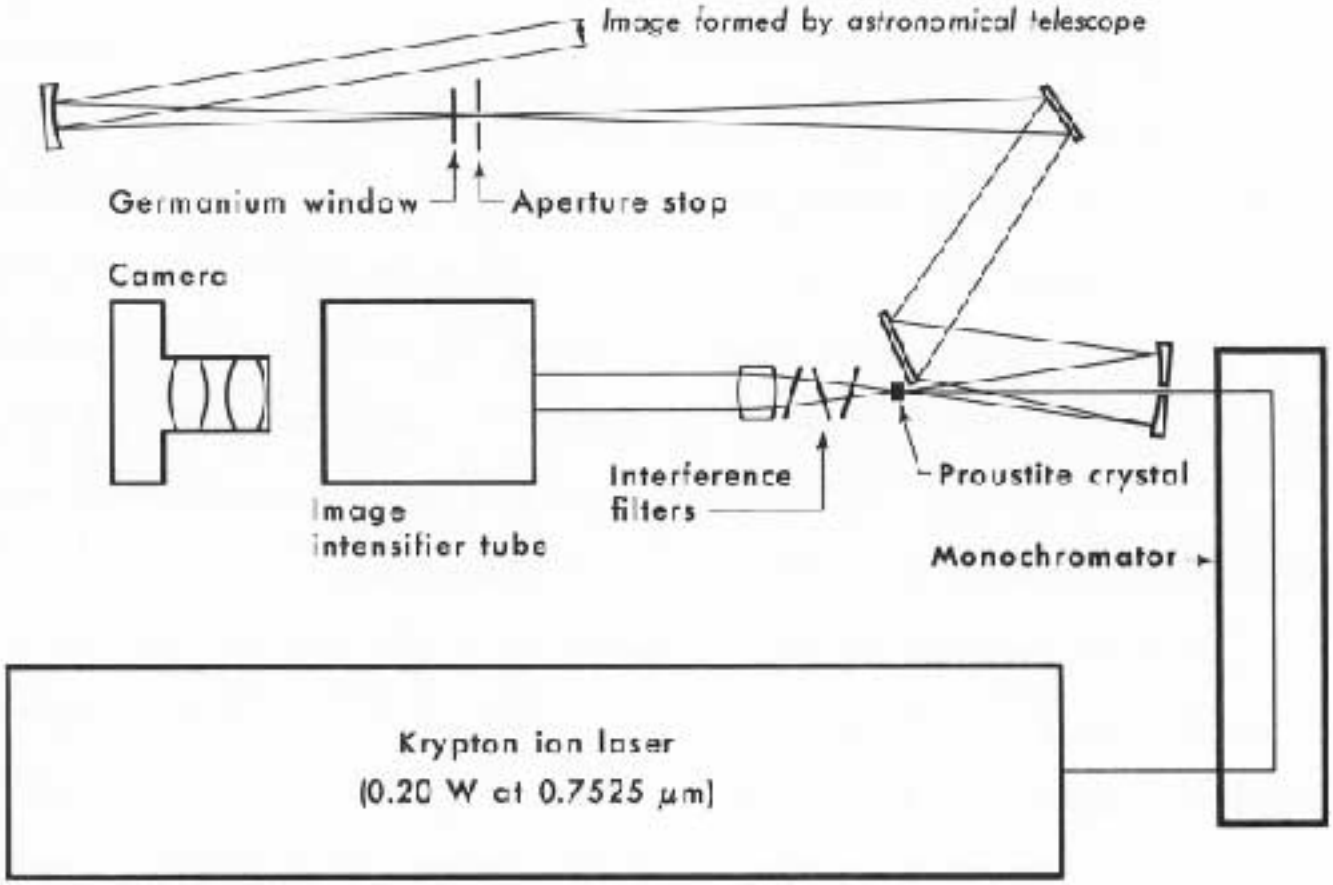
"Noise-free" conversion of infrared images to the visible.
Proposed by Midwinter and Warner (1967).



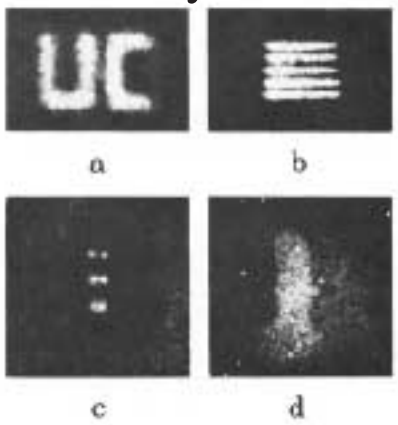
Phase-matching requirements ensure that image information is preserved.



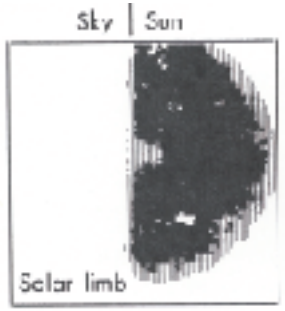
Astronomical Imaging Upconversion



laboratory sources



astronomical sources

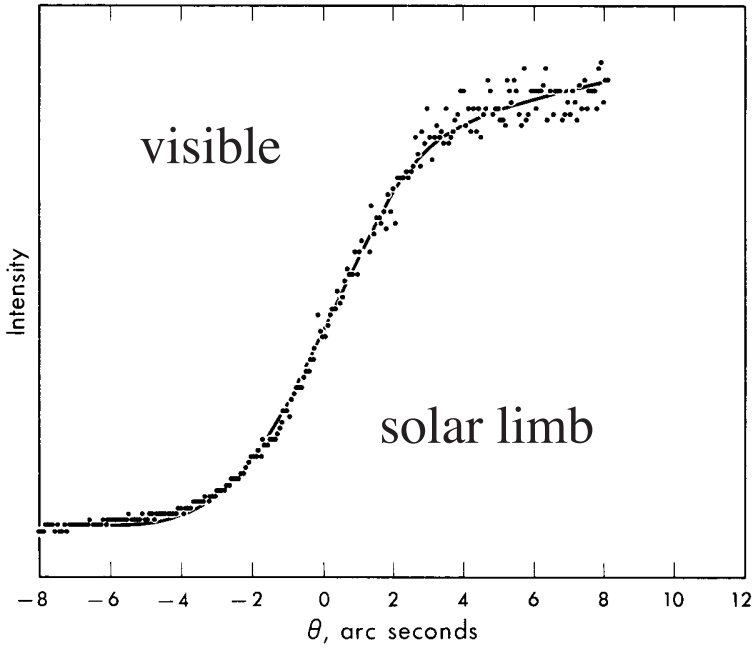


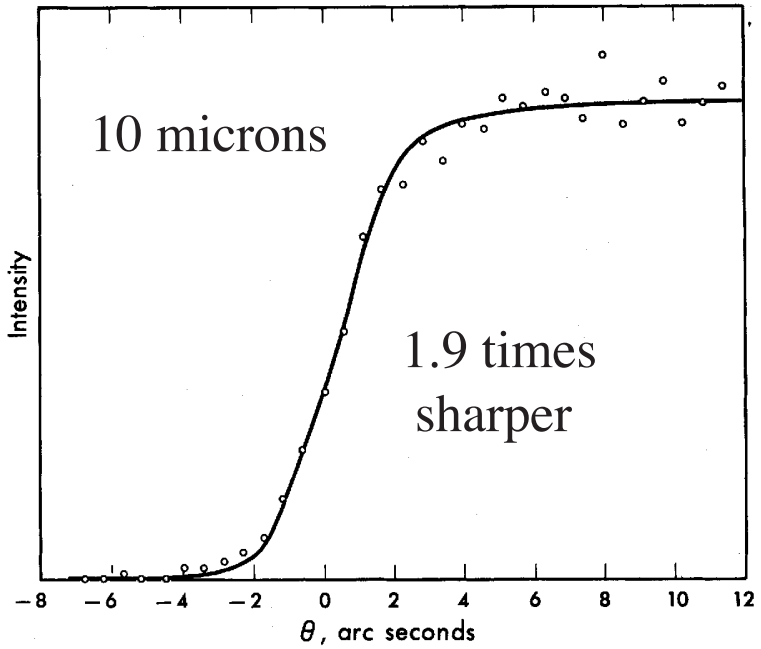
R. W. Boyd and C. H. Townes Appl. Phys. Lett. 33 440 (1977).

Resolution of Astronomical Telescopes

- Wavelength dependence under turbulence-dominated conditions
- Images are sharper in the infrared than in the visible!

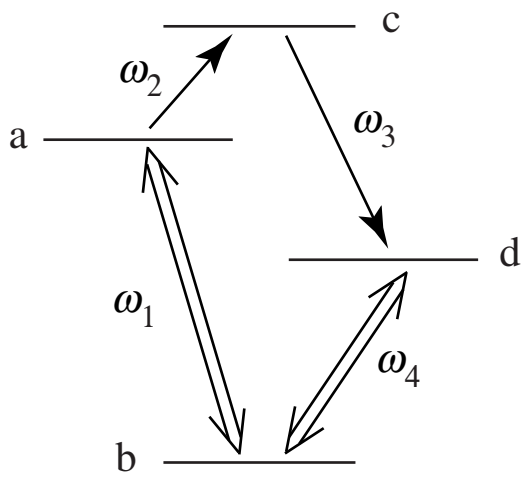
  (D. L. Fried, R. E. Hufnagel, V. I. Tatarski)
- IR data obtained using infrared upconversion



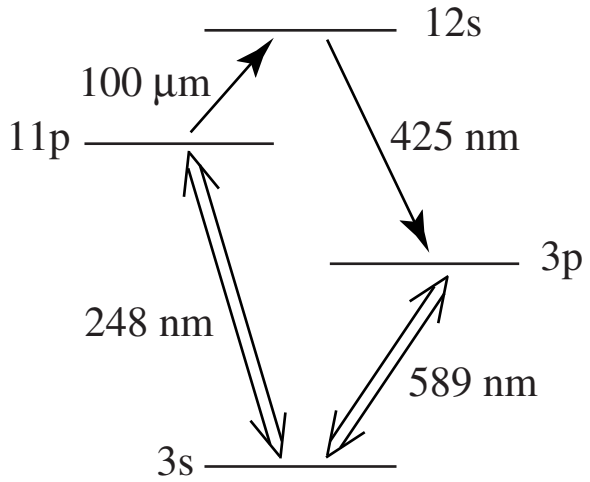


R. W. Boyd, J. Opt. Soc. Am. 68, 877, 1978.

Efficient Far IR and THz Imaging by use of EIT



Basic concept of our approach. Because of strong saturation of the lower transitions, upconversion occurs with essentially unit efficiency.



Sodium energy levels for the conversion of 100 micron radiation to the visible.

R. W. Boyd and M. O. Scully, Appl. Phys. Lett. 77, 3559, 2000.

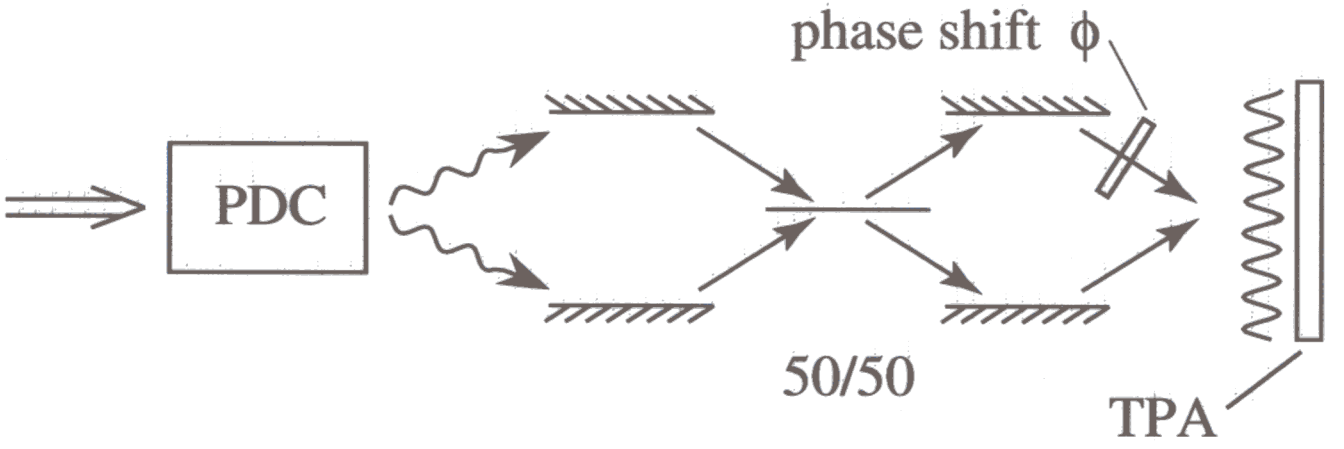
Efficient Far IR and THz Imaging by use of EIT

R W. Boyd and M. O. Scully

- EIT concepts allow “upconversion” of IR images to the visible with high quantum efficiency (approaching unit efficiency) .
- Upconversion is a “noise-free” process; only noise in output is (quantum) noise of IR signal.
- Technique holds promise of unprecedented sensitivity of FIR and THz detection (detection of single THz quanta)!
- Applications include FIR astronomy and THz imaging of biological tissue.
- Pitfall: very narrow spectral acceptance bandwidth.

Quantum Lithography and Microscopy

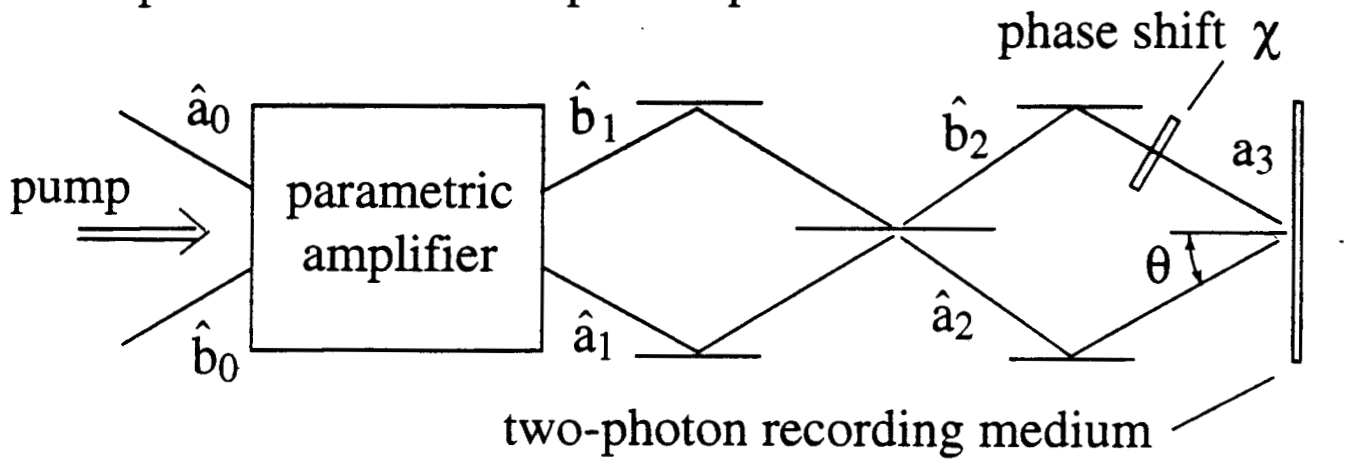
- Entangled photons can be used to form interference patterns with detail finer than the Rayleigh limit
- Process "in reverse" performs sub-Rayleigh microscopy



Boto et al, Phys. Rev. Lett. 85, 2733, 2000.

Use of High-Gain Parametric Amplifier

Is two-photon interference pattern preserved?



- Transfer equations of OPA

$$\hat{a}_1 = U\hat{a}_0 + V\hat{b}_0^\dagger, \quad \hat{b}_1 = U\hat{b}_0 + V\hat{a}_0^\dagger$$

where

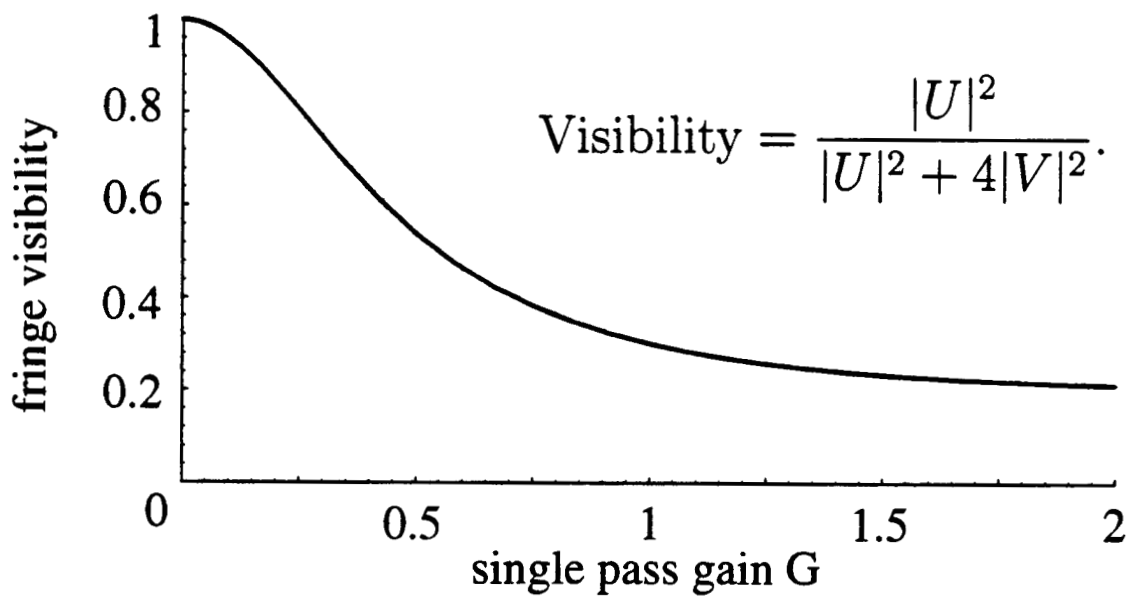
$$U = \cosh G \qquad V = -\,i\exp(i\varphi)\sinh G$$

- Field at recording medium

$$\hat{a}_3 = \frac{1}{\sqrt{2}}\left[(-e^{i\chi}+i)(U\hat{a}_0 + V\hat{b}_0^\dagger) + (ie^{i\chi}-1)(U\hat{b}_0 + V\hat{a}_0^\dagger)\right]$$

- Two-photon absorption probablility

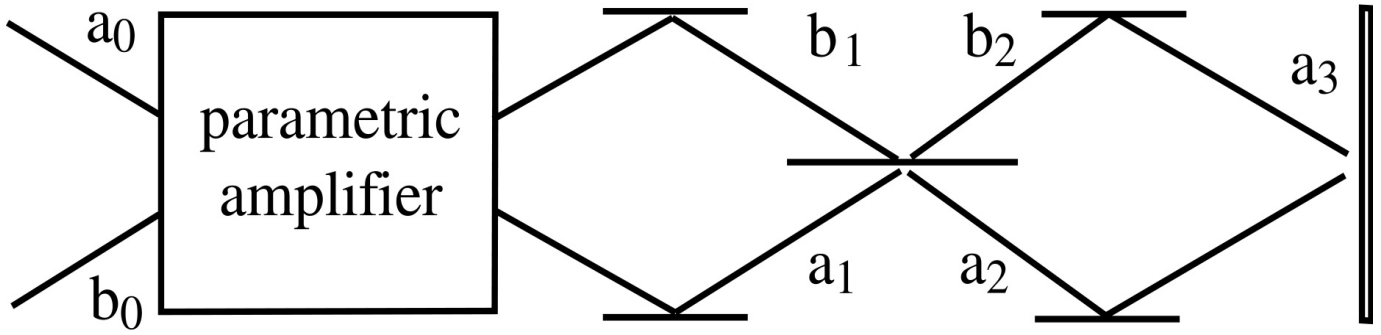
$$\langle 0,0|\hat{a}_3^\dagger\hat{a}_3^\dagger\hat{a}_3\hat{a}_3|0,0\rangle = 4|V|^2\left[|U|^2\cos^2\chi + 2|V|^2\right]$$



$$\text{Visibility} = \frac{|U|^2}{|U|^2 + 4|V|^2}.$$

(Phys. Rev. Lett. 86, 1389, 2001)

QUANTUM LITHOGRAPHY PROPOSAL



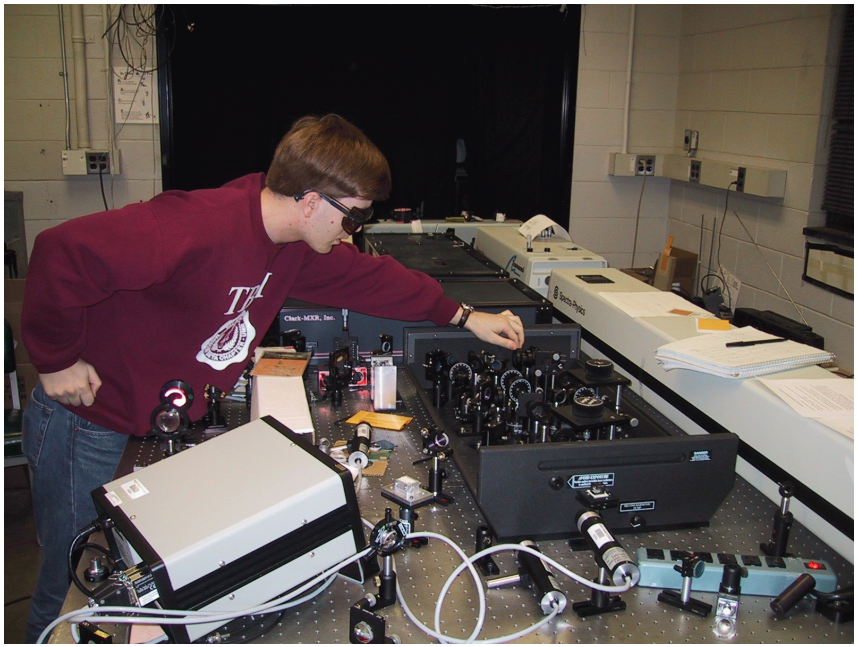
G. S. Agarwal, R. W. Boyd, E. M. Nagasako, S. J. Bentley, Phys. Rev. Lett., 86, 1389, 2001.

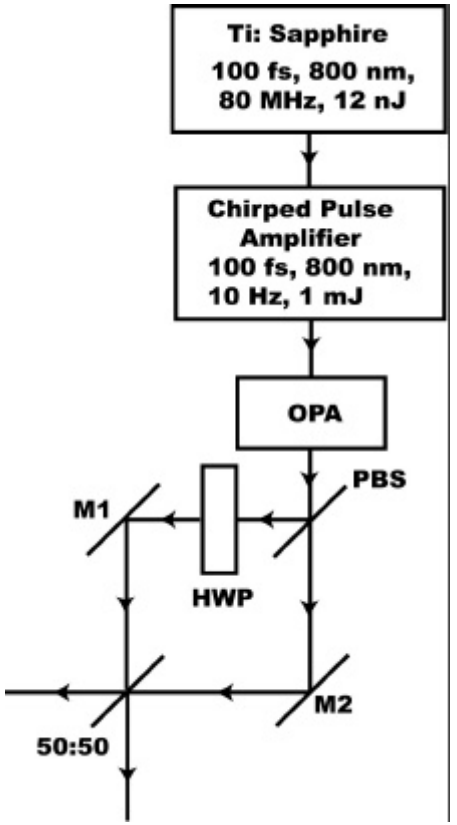
E. M. Nagasako, S. J. Bentley R. W. Boyd, and G. S. Agarwal, Phys. Rev. A, 64, 043802 (2001).

E. M. Nagasako, S. J. Bentley and R. W. Boyd, and G. S. Agarwal, J. Mod. Optics, 49, 529 2002

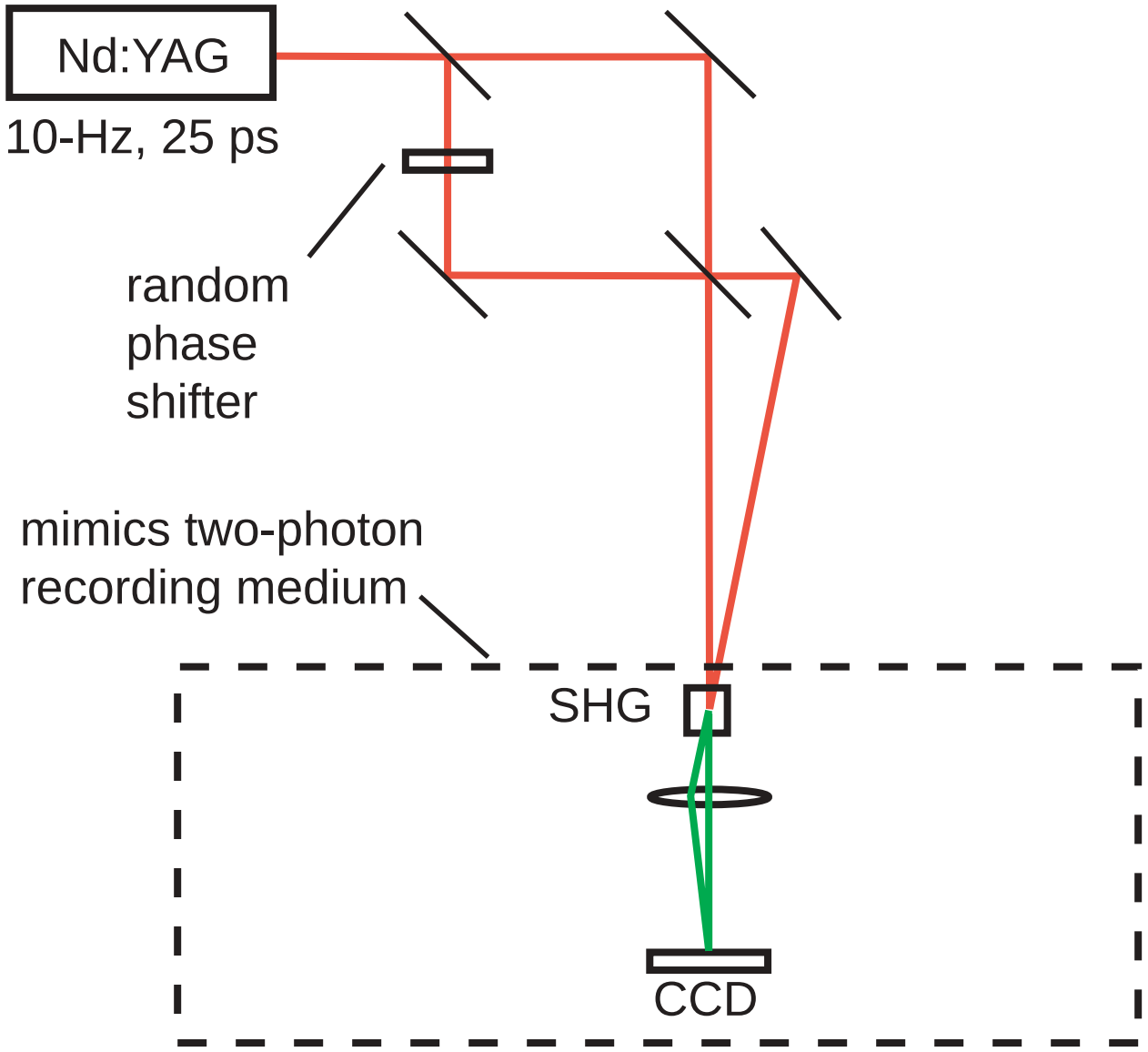
QUANTUM LITHOGRAPHY RESEARCH

Experimental Layout

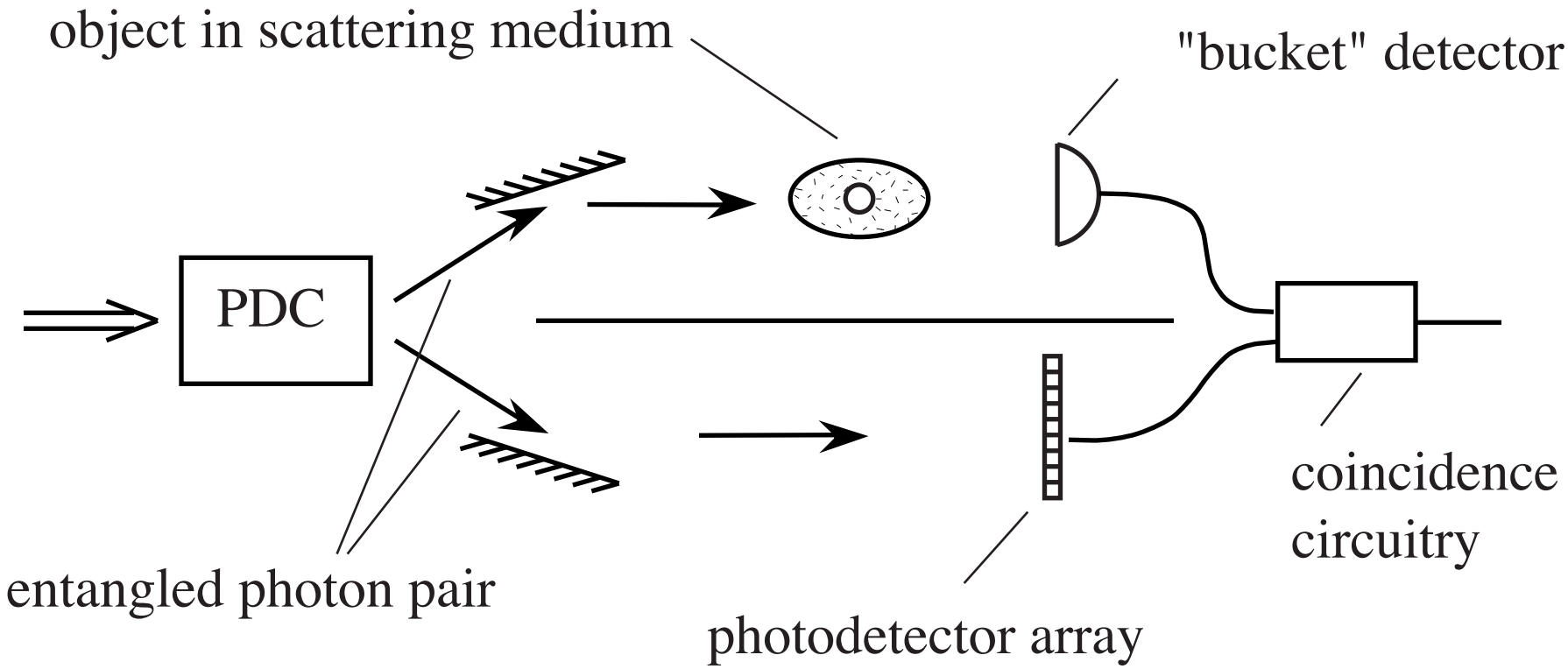




Classical Sub-Rayleigh Lithography Setup



Quantum (?) Coincidence Imaging

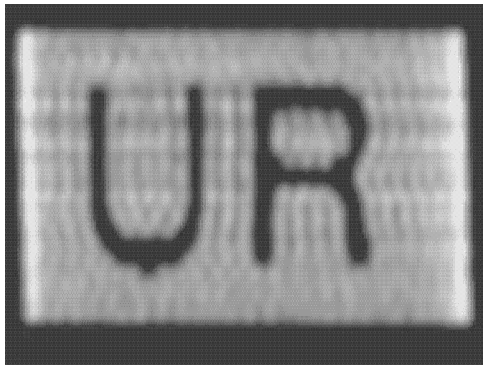


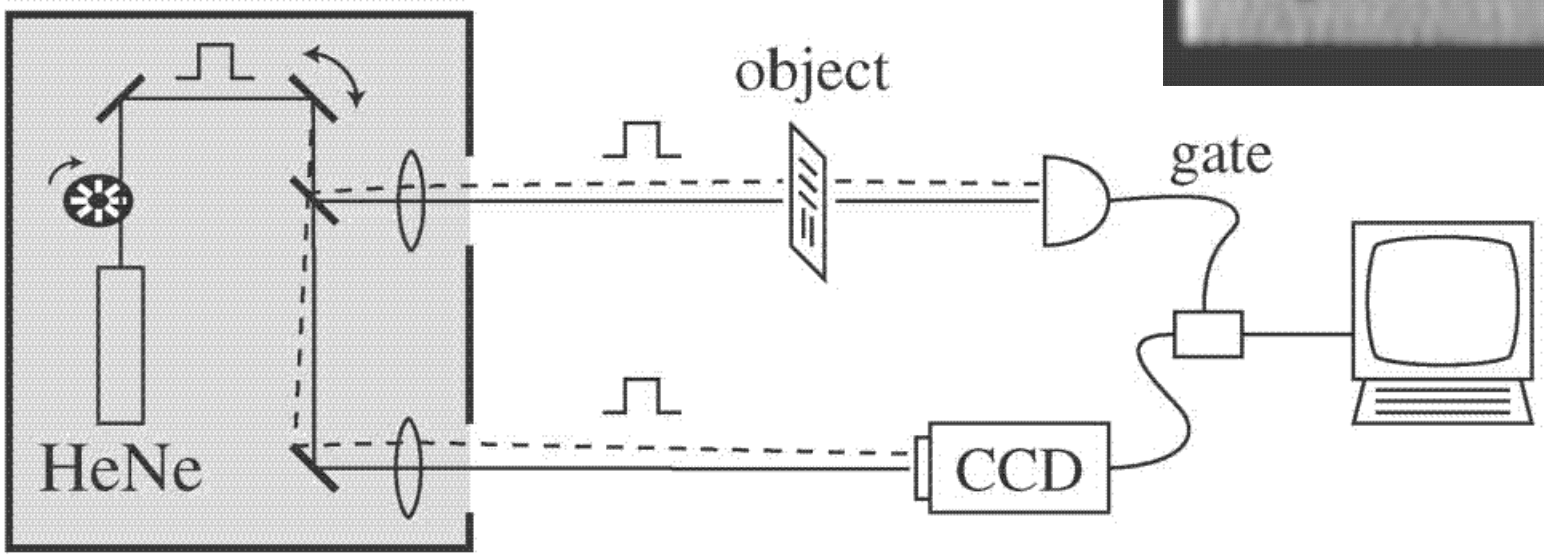
Obvious applicability to remote sensing!

Strekalov et al., Phys. Rev. Lett. **74**, 3600 (1995).
Pittman et al., Phys. Rev. A **52** R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. **87**, 123602 (2001).

Classical Coincidence Imaging

We have performed coincidence imaging with a demonstrably classical source.

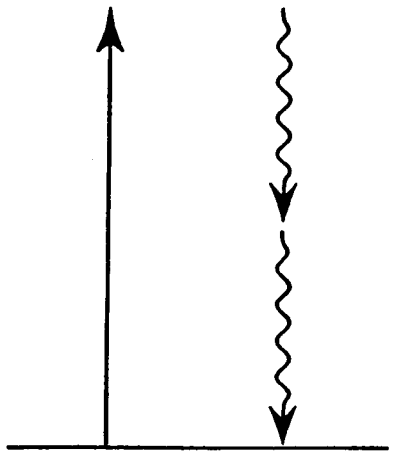




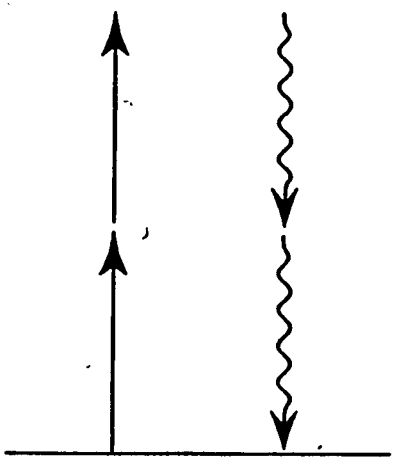
Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601(2002).

Two Routes to Entanglement

$\chi^{(2)}$



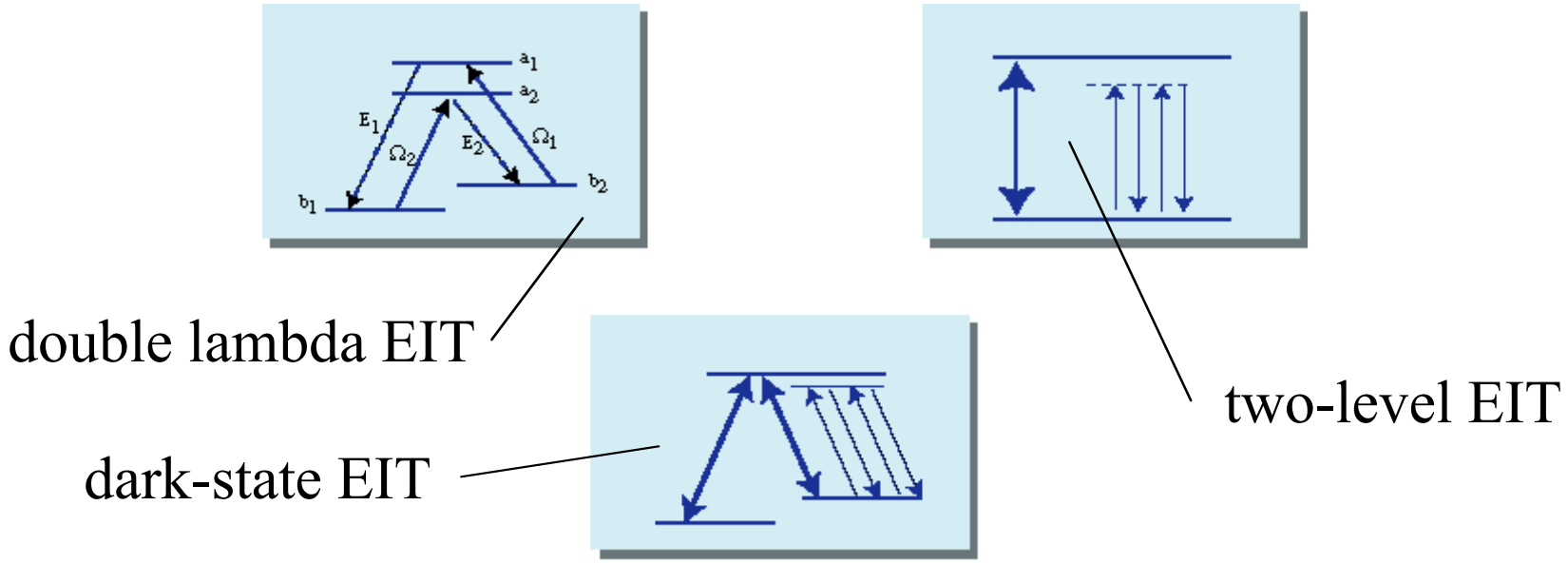
$\chi^{(3)}$



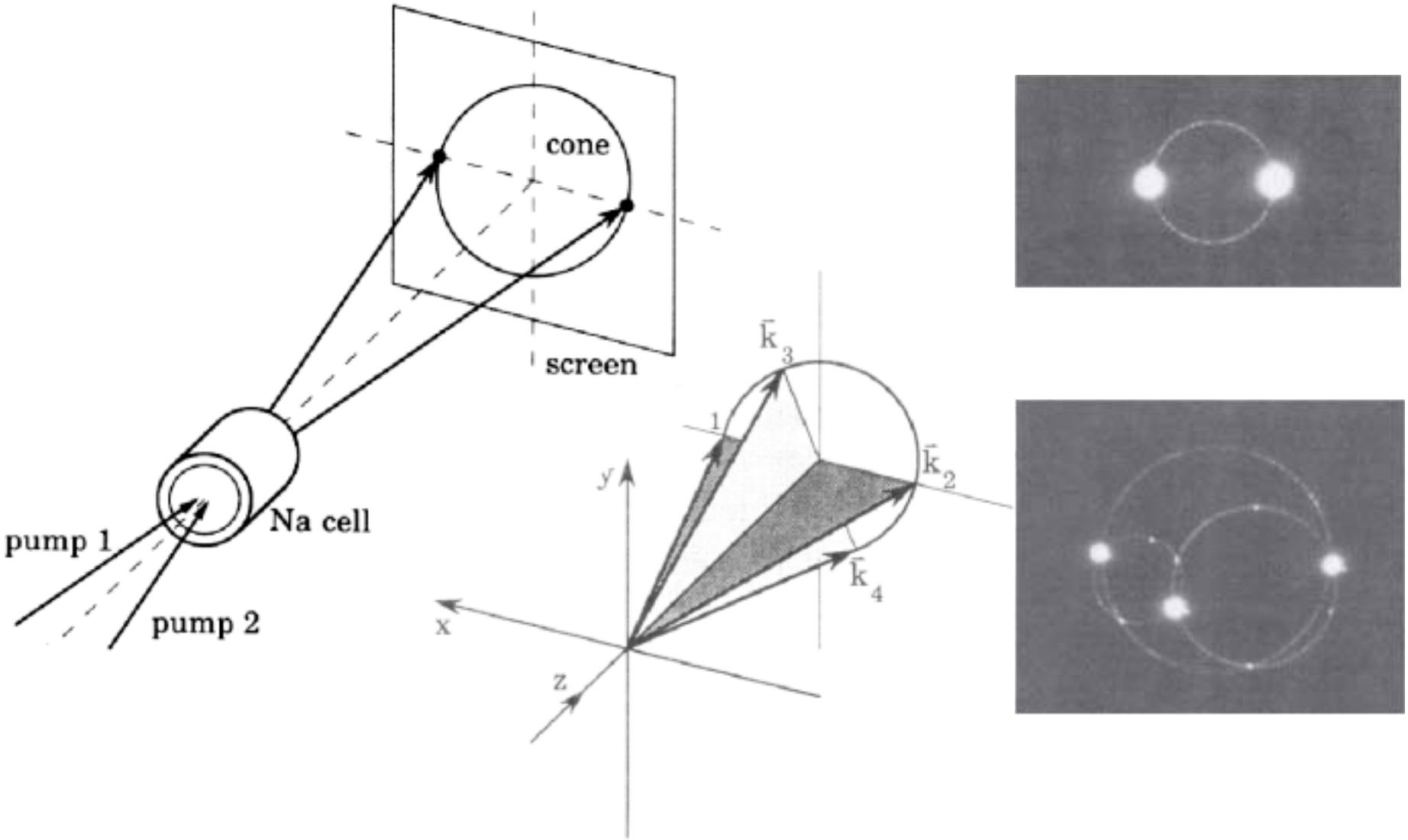
Generation of Quantum States of Light by Use of Electromagetically Induced Transparency

Robert W. Boyd and C. R. Stroud, Jr., University of Rochester

- Quantum states of light useful for applications including precision measurements and secure communications
- EIT enables the efficient creation of quantum states of light by eliminating spontaneous emission background noise.

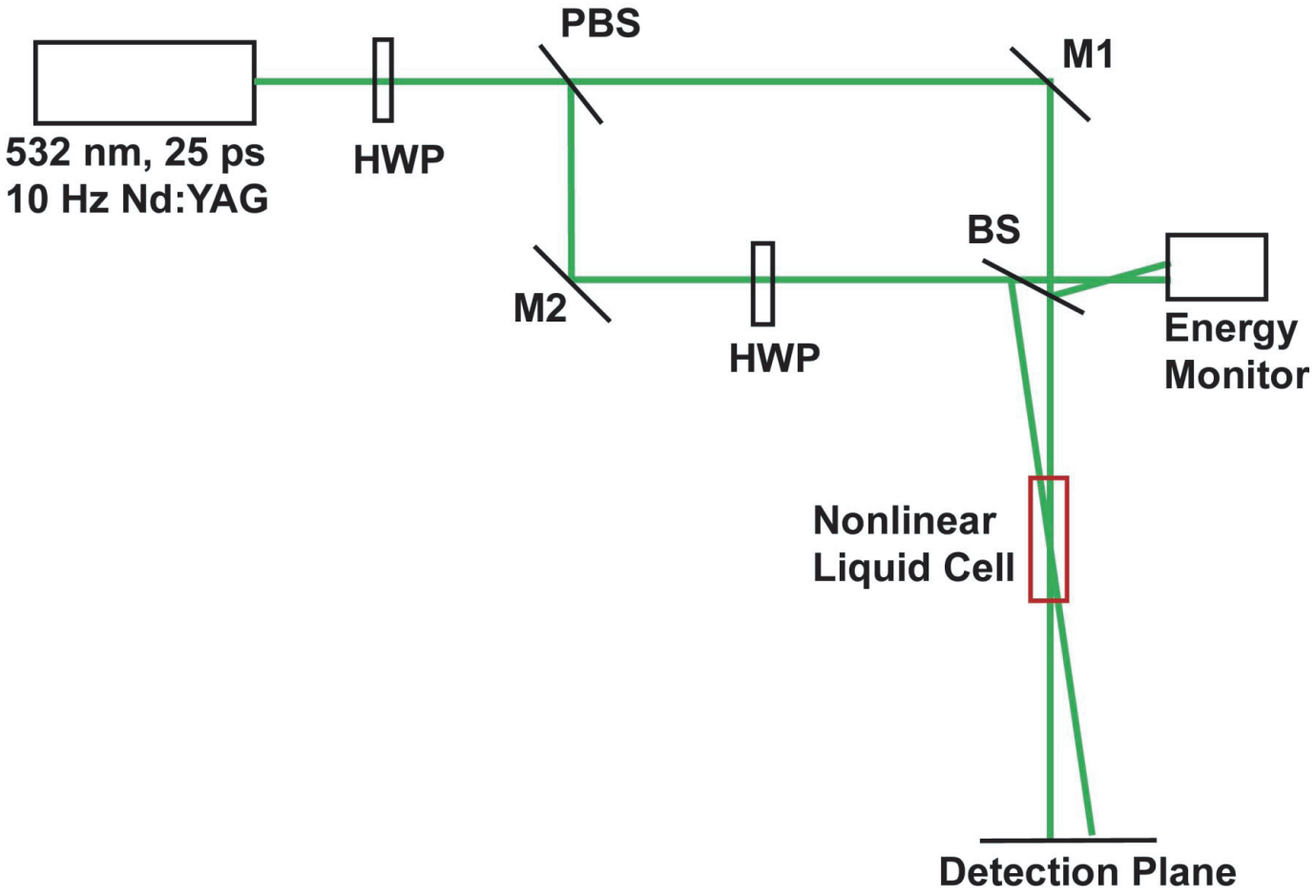


Generation of Quantum States of Light by Two-Beam Excited Conical Emission



Kauranen et al, Opt. Lett. 16, 943, 1991; Kauranen and Boyd, Phys. Rev. A, 47, 4297, 1993.

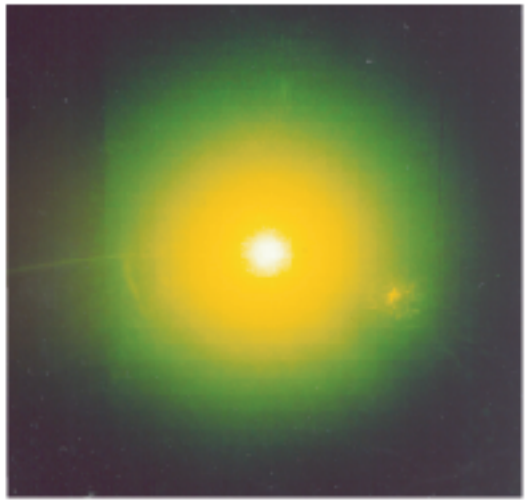
Experimental Configuration



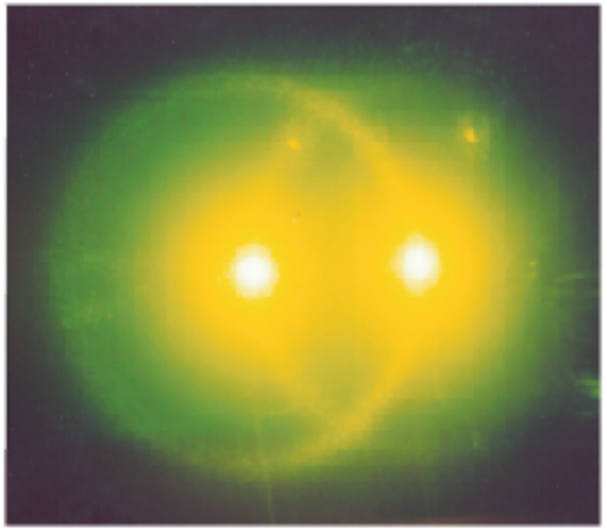
- Used 3-cm and 10-cm cells
- Used CS_2, CCl_4, and toluene
- Pulse intensities ~ 1-80 MW/cm^2
- Crossing angles ~ 0.003-0.04 rad

Conical Emission Patterns

Single input beam

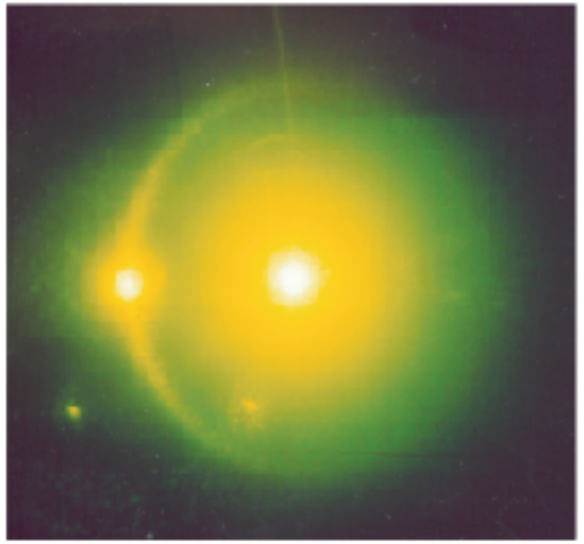


Two input beams
(equal intensity)
(parallel polarization)



Two cones formed, each centered on other beam.

Two input beams
(unequal intensity)
(parallel polarization)

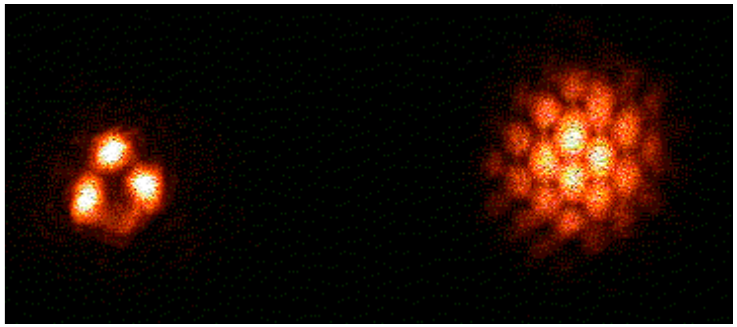


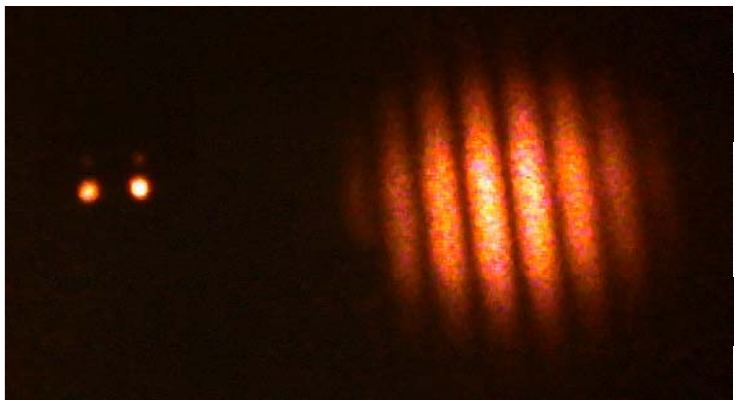
Only stronger input beam can act as pump for cone generation.

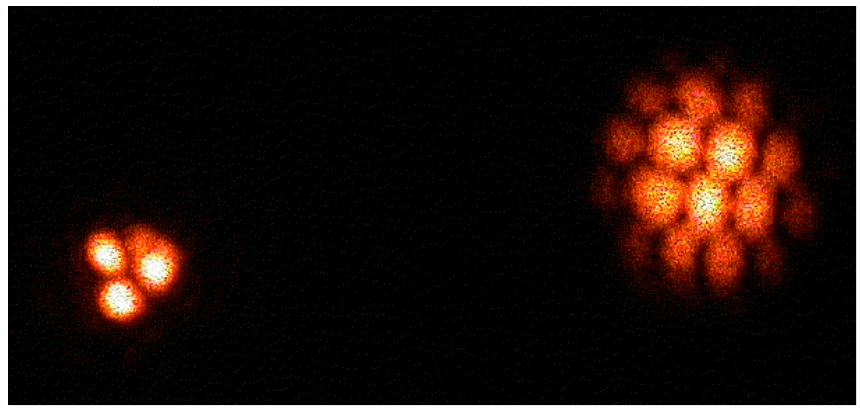
Generated in carbon disulfide

Hexagonal pattern formation in a feedback-free nonlinear optical system

The Institute of OPTICS UR LLE



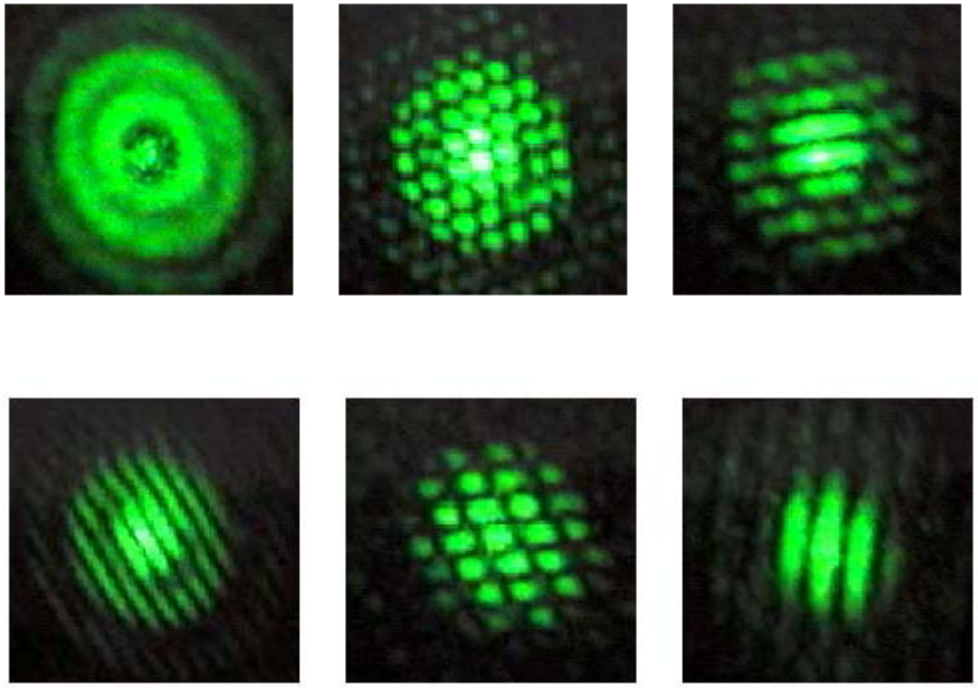




Feedback-free hexagonal (honeycomb) pattern formation was reported recently in atomic sodium vapor

Bennink R. et al., *PRL*, 88 (11) 113901 (2002)

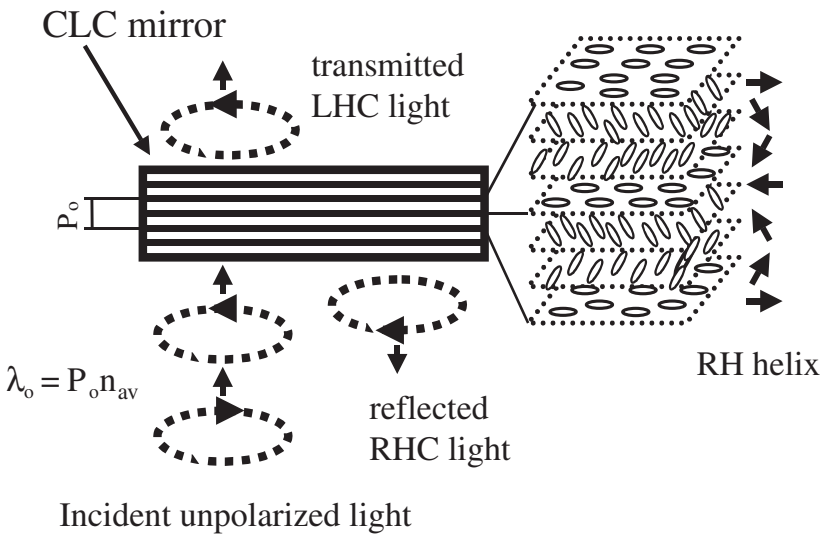
Feedback-free pattern formation in dye-doped liquid crystals and isotropic liquids



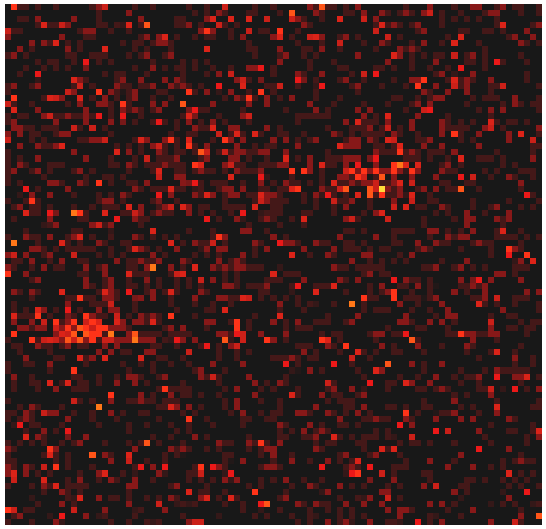
Lukishova, Boyd, Lepeshkin, Marshall and Schmid

Source of Polarized, Single-Photons on Demand

- Useful for secure communication by quantum cryptgraphy
- Embed isolated dye molecules in chiral nematic liquid crystal
- Host acts as self-assembled photonic bandgap material
- Host composition helps prevent dye from bleaching
- Fluorescence shows strong antibunching



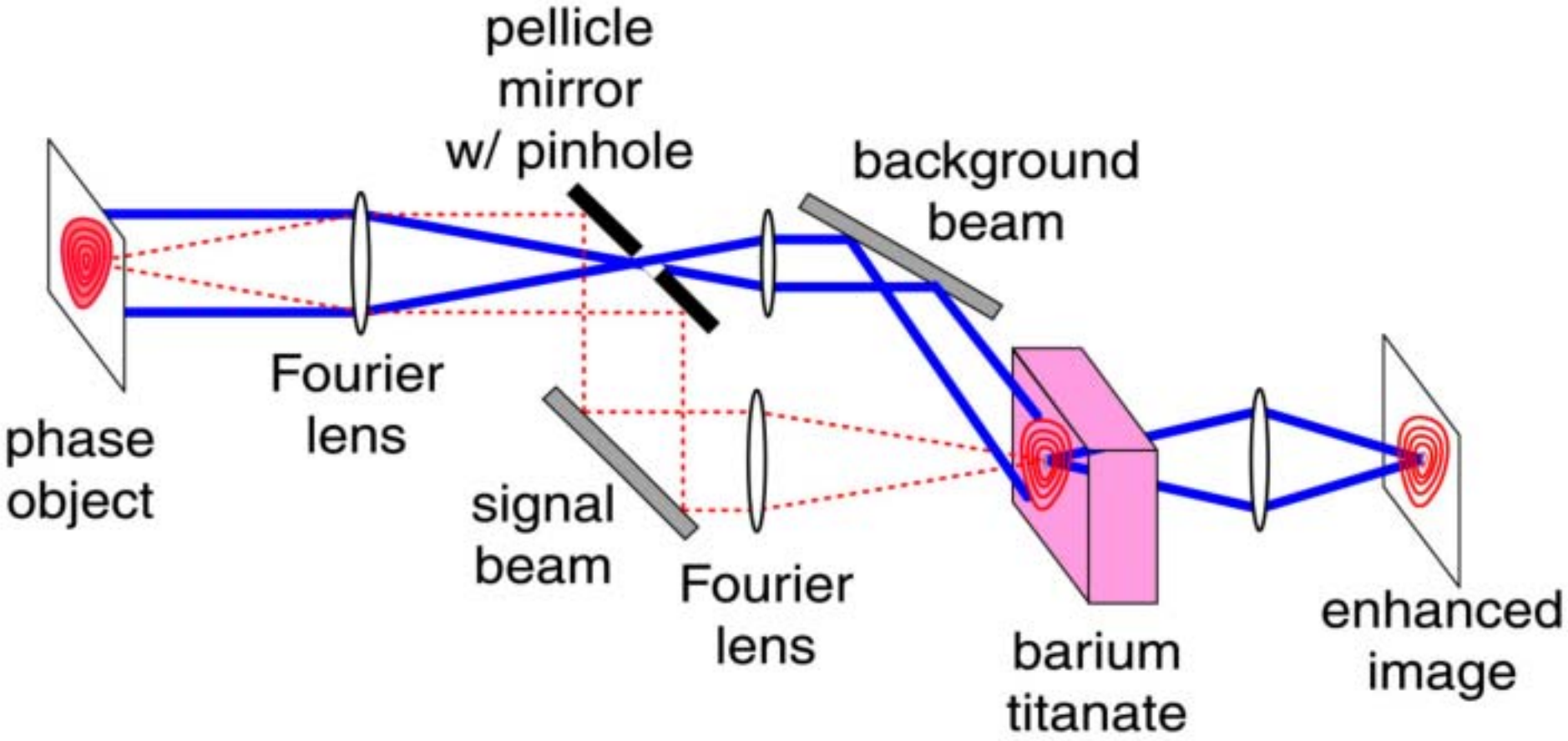
Experimental procedure



Single-molecule fluorescence

Implementation with S. Lukishova

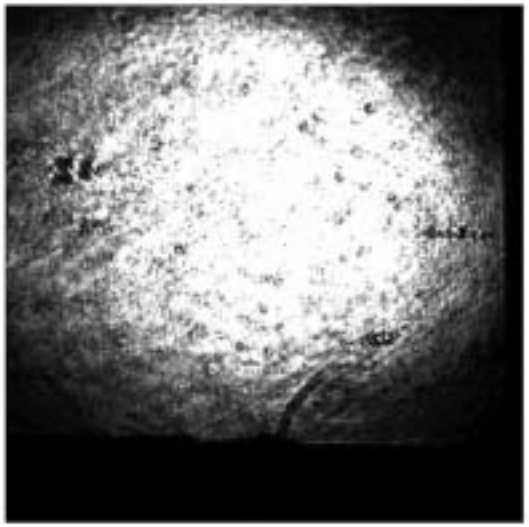
Nonlinear Optical Microscopy



J. E. Heebner and R. W. Boyd, Optics Communications, 182, 243-247, 2000.

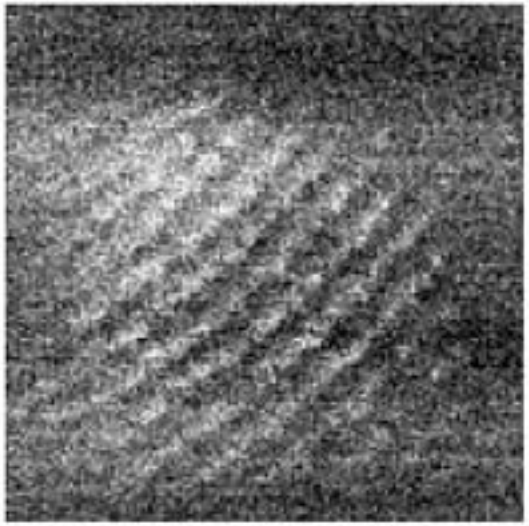
Fingerprint Enhancement

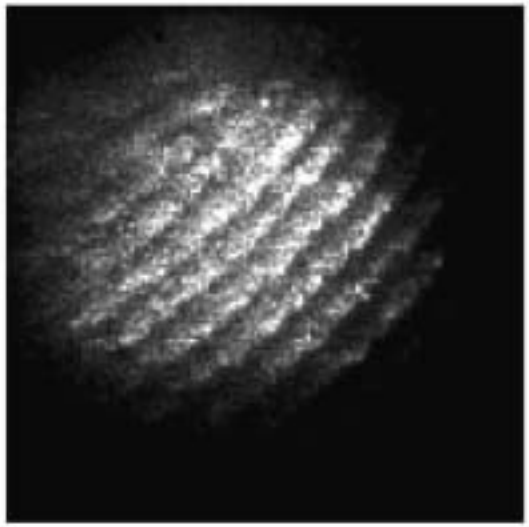
raw image (invisible)



filtered image (too weak!)

digitally amplified (noisy)

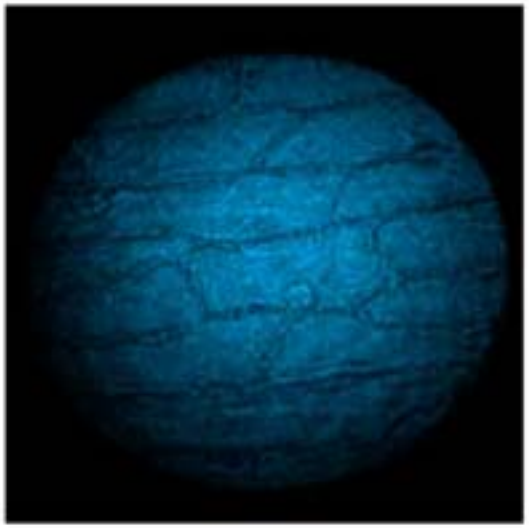




optically pre-amplified (PhORCE)

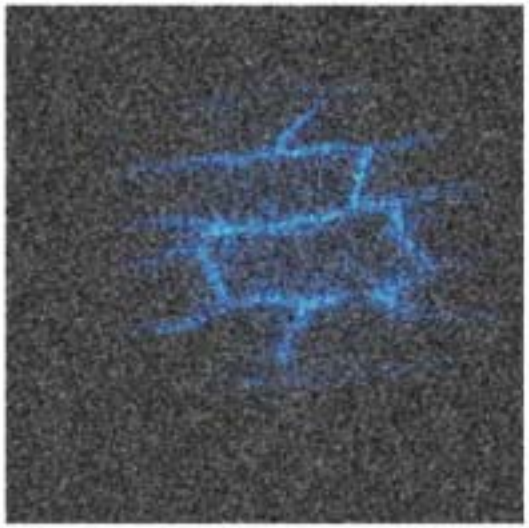
Onion Skin Cell Visualization

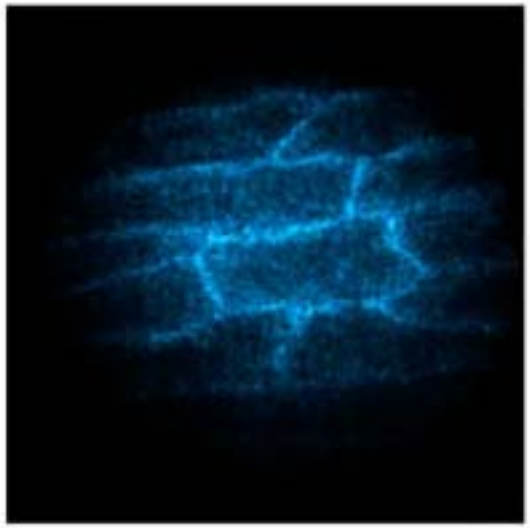
raw image (barely visible)



filtered image (too weak!)

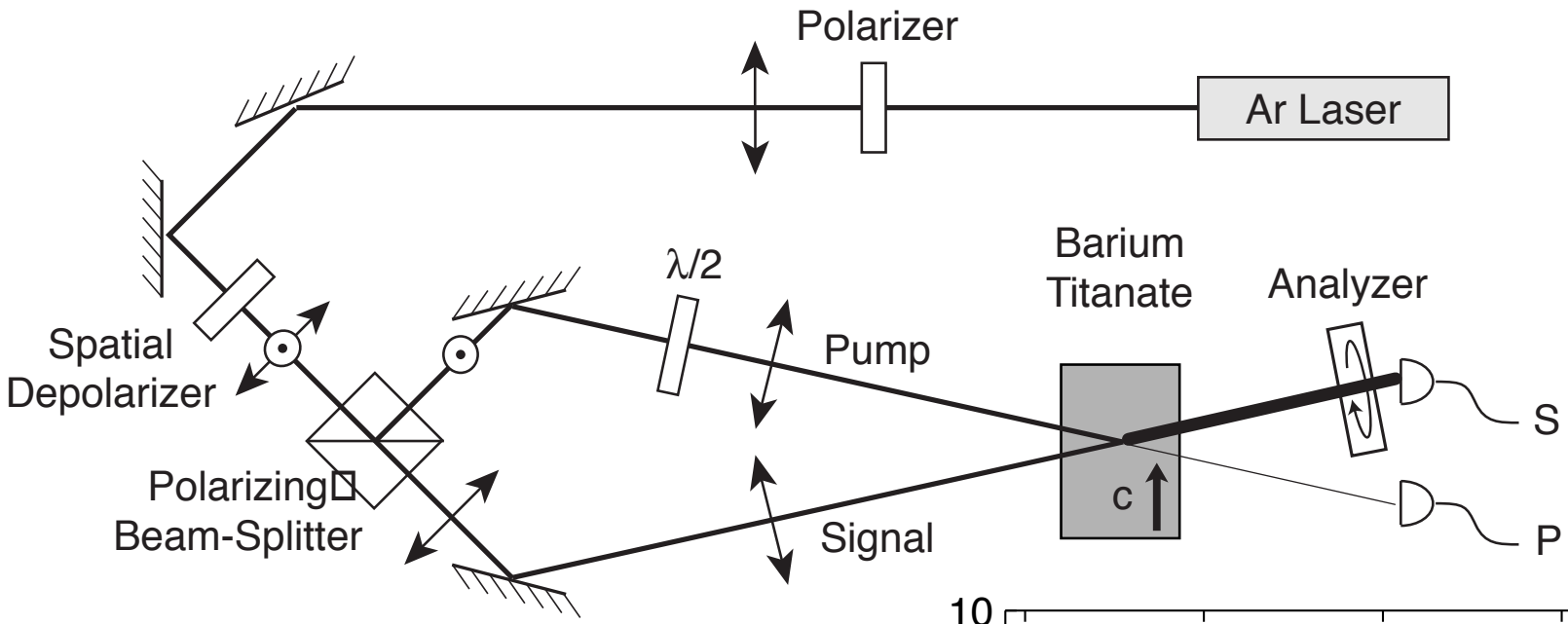
digitally amplified (noisy)

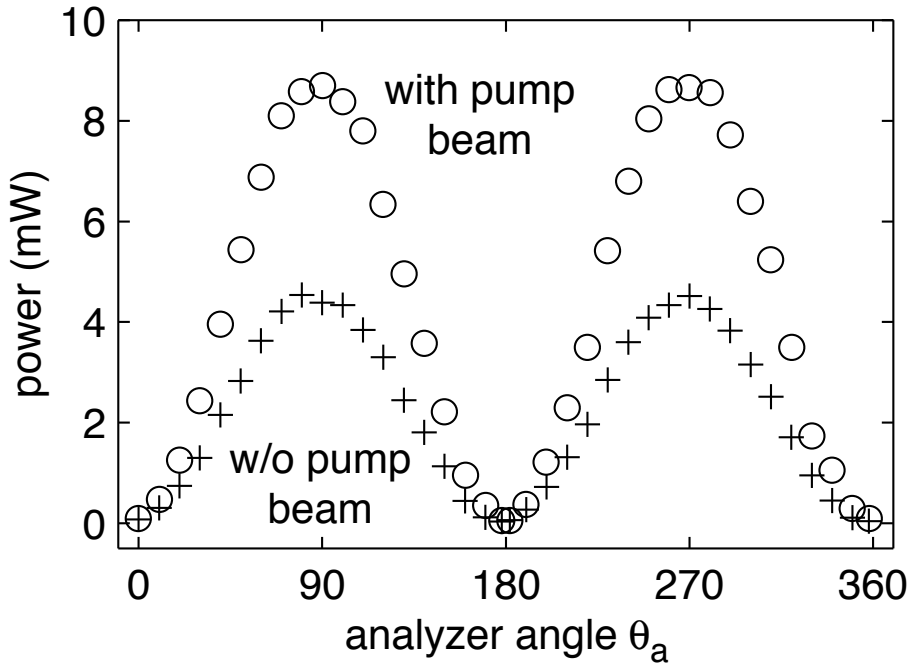




optically pre-amplified (PhORCE)

Construction of a Photorefractive Polarizer With Greater Than 50% Transmission





Heebner, Bennink, Boyd, and Fisher, Opt. Lett. 25, 257, 2000.