







Nonlinear Optics and Laser Science

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Arthur L. Schawlow Prize in Laser Science



For fundamental contributions to the field of nonlinear optics, including the development of approaches for controlling the velocity of light, of quantum imaging methods, and of composite nonlinear optical materials. controlling the velocity of light

Controlling the Velocity of Light

"Slow," "Fast" and "Backwards" Light

- Light can be made to go: slow: $v_g << c$ (as much as 10^6 times slower!) fast: $v_g > c$ backwards: v_g negative Here v_g is the group velocity: $v_g = c/n_g$ $n_g = n + \omega (dn/d\omega)$
- Velocity controlled by structural or material resonances





Review article: Boyd and Gauthier, Science 326, 1074 (2009).

Slow and Fast Light Using Isolated Gain or Absorption Resonances



Observation of Superluminal and "Backwards" Pulse Propagation

- A strongly counterintuitive phenomenon
- But entirely consistent with established physics
- Predicted by Garrett and McCumber (1970) and Chiao (1993).
- Observed by Gehring, Schweinsberg, Barsi, Kostinski, and Boyd Science 312, 985 2006.





SIL(0

Development of Miniaturized, Chip-Scale Spectrometers

Can We Beat the 1/L Resolution Limit of Standard Spectrometers?

• The limiting resolution of a broad class of spectrometers is given (in wavenumbers) by the inverse of a characteristic dimension *L* of the spectrometer

Fourier-transform spectrometer



Grating spectrometer



 $\Delta \nu (\mathrm{res}) \approx 1/L$

- We use slow-light methods to design spectrometers with resolution that exceeds this conventional limit by a factor as large as the group index.
- This ability allows us to miniaturize spectrometers with no loss of resolution, for "lab-on-a-chip" applications.

Our Goal

Replace this:



with this:



Our Approach: Chip-Scale Slow-Light Spectrometer

- The spectral sensitivity of an interferometer is increased by a factor as large as the group index of a material placed within the interferometer.
- We want to exploit this effect to build chip-scale spectrometers with the same resoluation as large laboratory spectrometers



• We use line-defect waveguides in photonic crystals as our slow light mechanism

Slow-down factors of greater than 100 have been observed in such structures.

Shi, Boyd, Gauthier, and Dudley, Opt. Lett. 32, 915 (2007) Shi, Boyd, Camacho, Vudyasetu, and Howell, PRL. 99, 240801 (2007) Shi and Boyd, J. Opt. Soc. Am. B 25, C136 (2008).



Laboratory Characterization of the Slow-Light Mach-Zehnder Interferometer



Interference fringes



- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm⁻¹
- (Slow-light waveguide is only 1 mm long!)

Magaña-Loaiza, Gao, Schulz, Awan, Upham, Dolgaleva, and Boyd, in review.

On-chip spectrometer based on high-Q photonic crystal cavities



Cavity design



Spectroscopy results



Liapis, Gao, Siddiqui, Shi, Boyd, Appl. Phys. Lett. 108, 021105 (2016).

quantum imaging

Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing! (imaging under adverse situations, bio, two-color, etc.)
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)

 Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
 Boundary et al., Phys. Rev. A 52 R3429 (1995).
 G

 Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
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 Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004) Gatti, Brambilla, and Lugiato, PRL 90 133603 (2003) Gatti, Brambilla, Bache, and Lugiato, PRL 93 093602 (2003)



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Is Ghost Imaging a Quantum Phenomenon?

VOLUME 90, NUMBER 13 PHYSICA

PHYSICAL REVIEW LETTERS

week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

INFM, Dipartimento di Scienze CC.FF.MM., Università dell'Insubria, Via Valleggio 11, 22100 Como, Italy (Received 11 October 2002; published 3 April 2003)

We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

DOI: 10.1103/PhysRevLett.90.133603

PACS numbers: 42.50.Dv, 03.65.Ud

Near- and Far-Field Ghost Imaging Using Quantum Entanglement



Good imaging observed in both the near and far field

Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

Near- and Far-Field Ghost Imaging With a Classical Source



• Good imaging can be obtained only in near field or far field.

• Detailed analysis shows that in the quantum case the spacebandwidth exceeded the classical limit by a factor of three.

Wavelength-Shifted (Two-Color Ghost) Microscopy

- Pump at 355 nm produces signal at 460 nm and idler at 1550 nm
- Object is illuminated at 1550 nm, but image is formed (in coincidence) at 460 nm
- Wavelength ratio of 3.4 is the largest yet reported.



Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

Quantum Imaging by Interaction-Free Measurement



M. Renninger, Z. Phys. 15S, 417 (1960).

R. H. Dicke, Am. J. Phys. 49, 925 (1981).

A. Elitzur and L. Vaidman, Found. Phys. 23, 987 (1993).

L. Vaidman, Quant. Opt. 6, 119 (1994).

P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. 74, 4763 (1995)

A. G. White, J. R. Mitchell, O. Nairz, and P. G. Kwiat, Phys. Rev. A 58, 605 (1998).

Interaction-Free Measurements and Entangled Photons



- Does an interaction-free measurement constitute a "real" measurement?
- Does it lead to the collapse of the wavefunction of its entangled partner?
- More precisely, does the entire two-photon wavefunction collapse?

Experimental Results

Interaction-free ghost image of a straight wire

coincidence counts



singles counts



- Note that the interaction-free ghost image is about five times narrower than full spot size on the ICCD camera
- This result shows that interaction-free measurements lead to wavefunction collapse, just like standard measurements.

With Frédéric Bouchard, Harjaspreet Mand, and Ebrahim Karimi,

composite nonlinear optical materials

Nanocomposite Materials for Nonlinear Optics



- In each case, scale size of inhomogeneity << optical wavelength
- Thus all optical properties, such as *n* and $\chi^{(3)}$, can be described by effective (volume averaged) values

Recent review: Dolgaleva and Boyd, Advances in Optics and Photonics 4, 1–77 (2012).

Enhanced NLO Response from Layered Composite Materials

A composite material can display a larger NL response than its constituents!

Alternating layers of TiO₂ and the conjugated polymer PBZT.



 $\nabla \cdot \mathbf{D} = 0$ implies that $(\varepsilon \mathbf{E})_{\perp}$ is continuous.

Measure NL phase shift as a function of angle of incidence.

35% enhancement in $\chi^{(3)}$

Fischer, Boyd, Gehr, Jenekhe, Osaheni, Sipe, and Weller-Brophy, Phys. Rev. Lett. 74, 1871 (1995).



Quadratic EO effect

3.2 times enhancement!

Nelson and Boyd, APL 74 2417 (1999)

Gold-Doped Glass: A Maxwell-Garnett Composite



Red Glass Caraffe Nurenberg, ca. 1700

Huelsmann Museum, Bielefeld

Developmental Glass, Corning Inc.

gold volume fraction approximately 10⁻⁶ gold particles approximately 10 nm diameter



- Composite materials can possess properties very different from those of their constituents.
- Red color is because the material absorbs very strong in the blue, at the surface plasmon frequency

$$\frac{\text{Metal} / \underline{\text{Dielectric Composites}}}{\text{Very large local field effects}}$$

$$\frac{\text{Very large local field effects}}{E_{h}} = \frac{3E_{h}}{E_{m}+2E_{h}} E_{o}$$

$$E_{h} = Z E_{o}$$

$$(E_{m} \text{ is negative } !)$$

$$At \text{ resonance}$$

$$Z = \frac{3E_{h}}{E_{m}+2E_{h}} \rightarrow \frac{3E_{h}}{iE_{m}''} \approx (3 + 0 30) i$$

Counterintuitive Consequence of Local Field Effects

Both constituents are reverse saturable absorbers \implies Im $\chi^{(3)} > 0$

Effective NL susceptibility of composite

$$\chi_{eff}^{(3)} = \int \mathcal{I}^2 |\mathcal{I}|^2 \chi_{Au}^{(3)} + (1-f) \chi_{dye solv}^{(3)}$$

$$Z = \frac{3E_h}{E_m + 2E_h} = pure imaginary at resonance$$

A cancellation of the two contributions to $X^{(3)}$ can occur, even though they have same sign.

Counterintuitive Consequence of Local Field Effects

Cancellation of two contributions that have the same sign Gold nanoparticles in a reverse saturable absorber dye solution (13 μ M HITCI)



D.D. Smith, G. Fischer, R.W. Boyd, D.A.Gregory, JOSA B 14, 1625, 1997.

Huge Nonlinear Optical Response of ITO near its Epsilon-Near-Zero Wavelength

Indium tin oxide (ITO) displays enormously strong NLO properties:

- n_2 is 2.5 x 10⁵ times that of fused silica
- nonlinear change in refractive index as large as 0.8
- response time of 270 fs



$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c \, n_0 \, \text{Re}(n_0)}$$



Some possible applications and implications

- Efficient all-optical switching
- New regime of spatial soliton propagation
- Control of radiative processes

Alam, De Leon, Boyd Science, 2016.

Arthur L. Schawlow

