Nonlinear Optics: Past Successes and Future Challenges

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and

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From Photonics Spectra Magazine

Making Ottawa the world's photonics center

OTTAWA, Ontario, Canada –

A $55 million photonics center that was expected to break ground on the University of Ottawa campus in March will help fulfill the school's goal to make Ottawa the global hub of photonics.

Our research interests include

- Nanophotonics
- Plasmonics
- Photonic crystals
- Photonic device
- Applications of slow and fast light
- Quantum nonlinear optics
- Optical methods for quantum information

Why Study Nonlinear Optics?

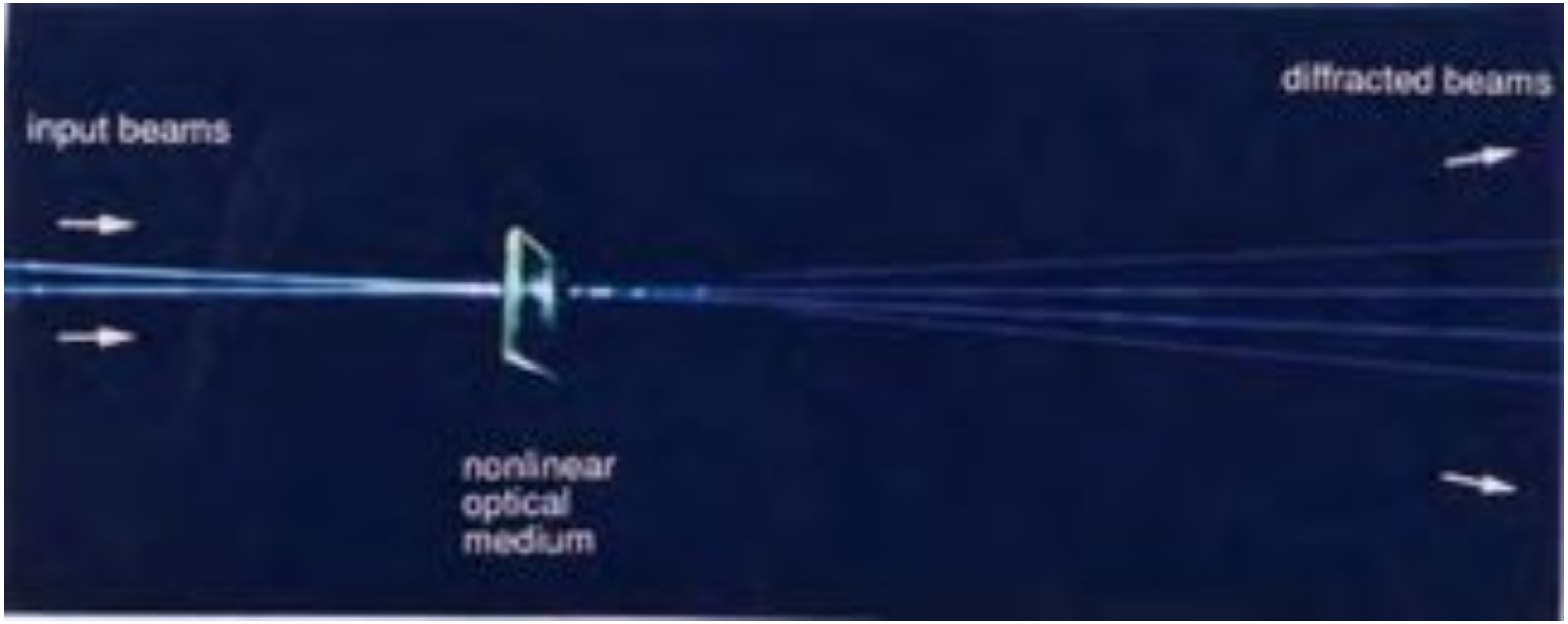
It is good fundamental physics.

It leads to important applications.

It is a lot of fun.

Demonstrate these features with examples in remainder of talk.

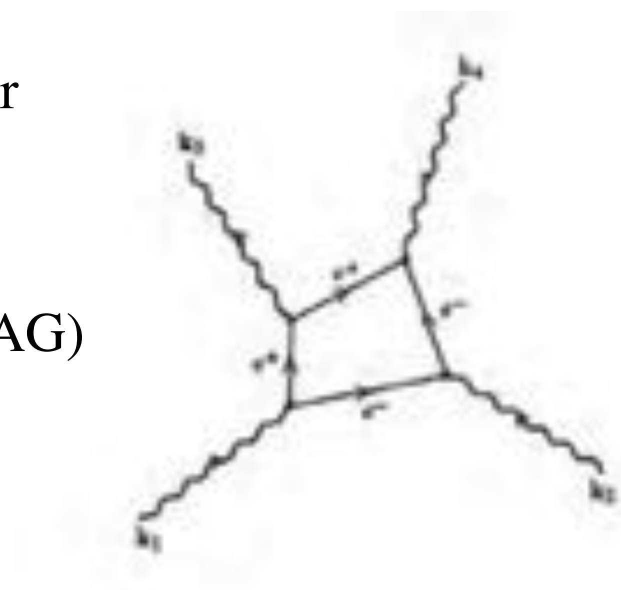
Nonlinear Optics and Light-by-Light Scattering



The elementary process of light-by-light scattering has never been observed in vacuum, but is readily observed using the nonlinear response of material systems.

Nonlinear material is fluorescein-doped boric acid glass (FBAG)

$n_2(\text{FBAG}) \approx 10^{14}\, n_2(\text{silica})$ [But very slow response!]



M. A. Kramer, W. R. Tompkin, and R. W. Boyd, Phys. Rev. A, 34, 2026, 1986.
W. R. Tompkin, M. S. Malcuit, and R. W. Boyd, Applied Optics 29, 3921, 1990.

Brief Introduction to Nonlinear Optics

Nonlinear Optics

THIRD EDITION

Robert W. Boyd

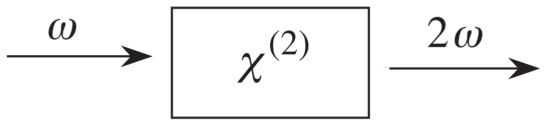
Simple Formulation of the Theory of Nonlinear Optics

$$P = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$$

Here P is the induced dipole moment per unit volume and E is the field amplitude

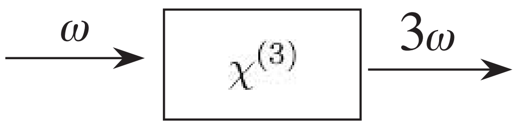
$\chi^{(1)}$ describes linear optics, e.g., how lenses work: 

$\chi^{(2)}$ describes second-order effects, e.g., second-harmonic generation (SHG)

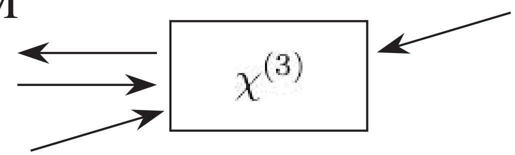


$\chi^{(3)}$ describes third-order effects such as third-harmonic generation, four-wave mixing, and the intensity dependence of the index of refraction.

THG



FWM



NL index

$$n = n_0 + n_2 I \quad \text{where} \quad n_2 = \frac{3}{4n_0^2\epsilon_0 c}\chi^{(3)}$$

Timeline – The Early Days of Nonlinear Optics

1958 - Schawlow and Townes; optical maser (laser) proposed

1960 - Maiman, ruby laser demonstrated

1961 - Franken, Hill, Peters, and Weinreich, second-harmonic generation (SHG) observed

1962 - Armstrong, Bloembergen, Ducing, and Pershan; systematic formulation of NLO

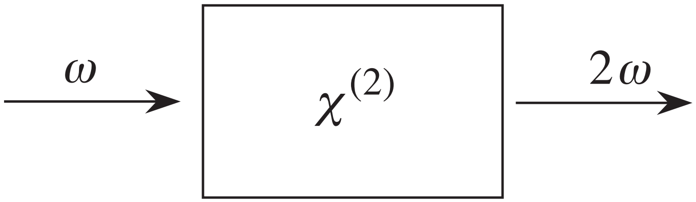
1962 - McClung, Hellwarth, Woodbury, and Ng, stimulated Raman scattering (SRS)

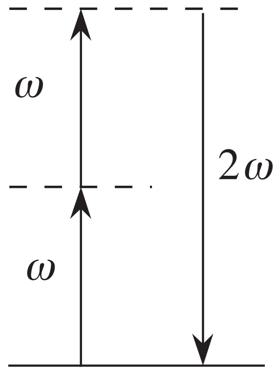
1964 - Chiao, Townes, and Stoicheff, stimulated Brillouin scattering (SBS)

1964 - Chiao, Garmire, and Townes, self-trapping of light

Nonlinear Optics: Past Successes

Second-Harmonic Generation: The Prototypical Nonlinear Optical Process

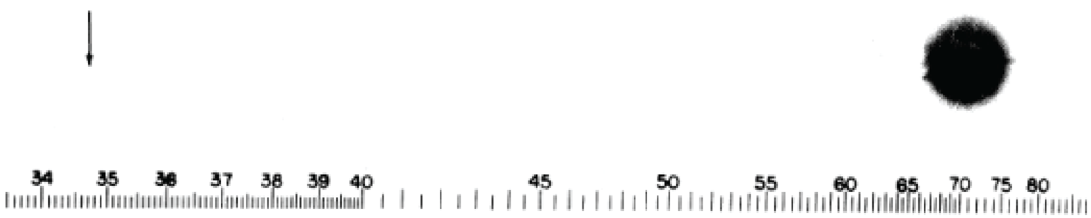




VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

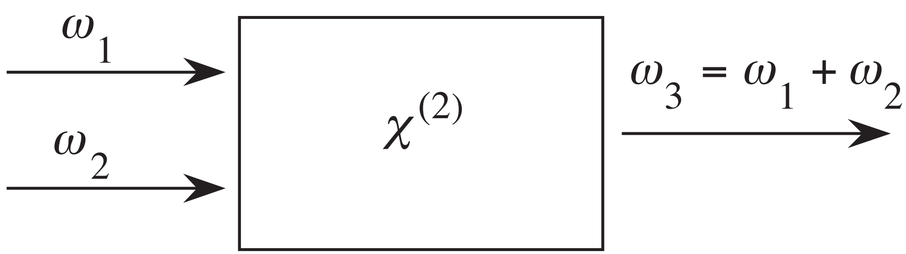
GENERATION OF OPTICAL HARMONICS*

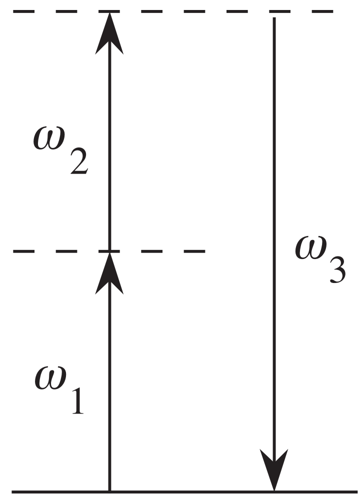
P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
(Received July 21, 1961)



Some Fundamental Nonlinear Optical Processes: II

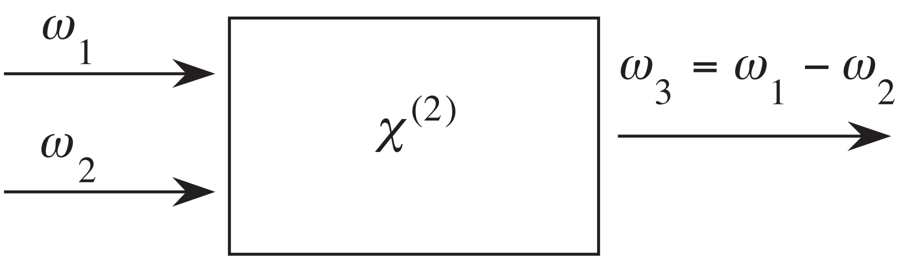
Sum-Frequency Generation

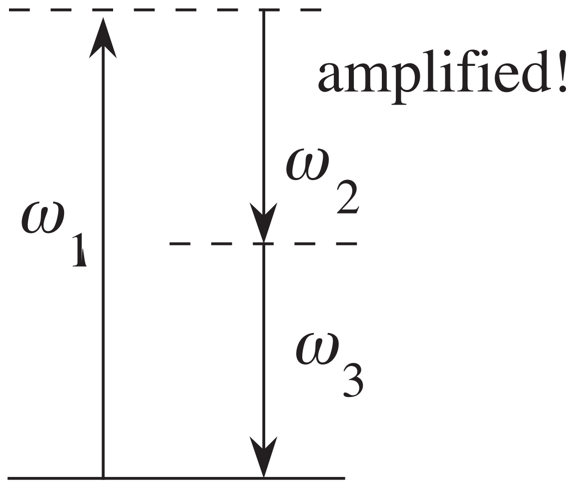




Difference-Frequency Generation and Optical Parametric Amplification

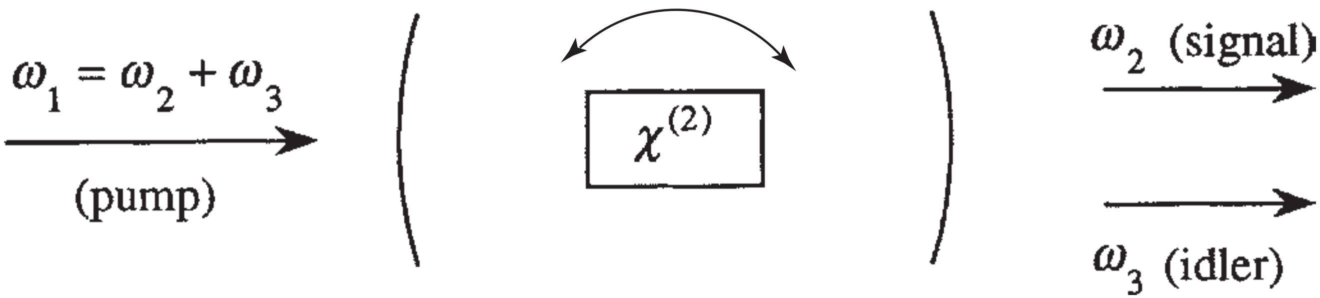
Difference-Frequency Generation



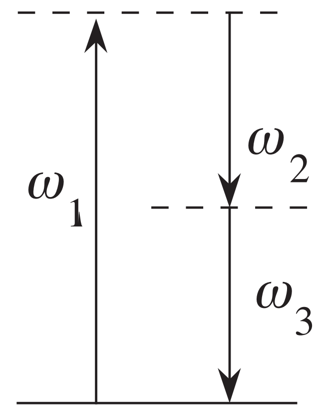


Optical Parametric Amplification

Optical Parametric Oscillator (very broadly tunable)

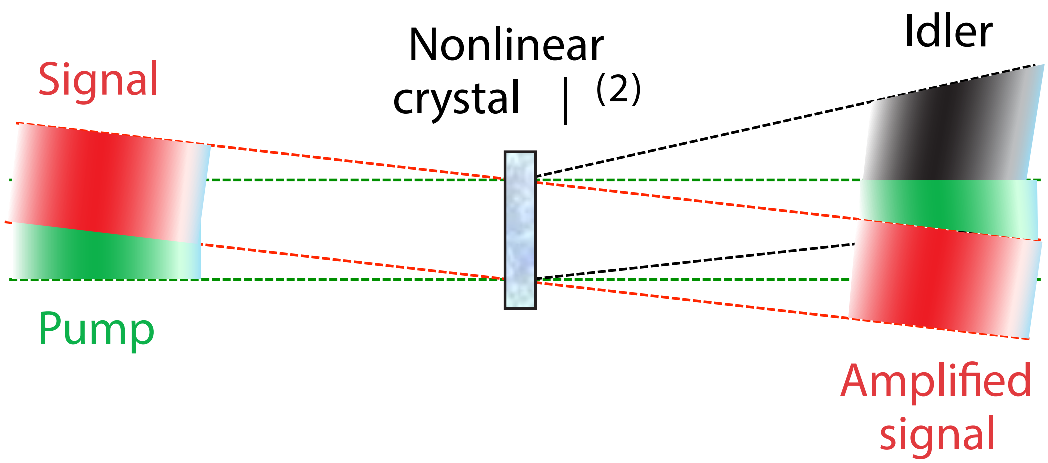


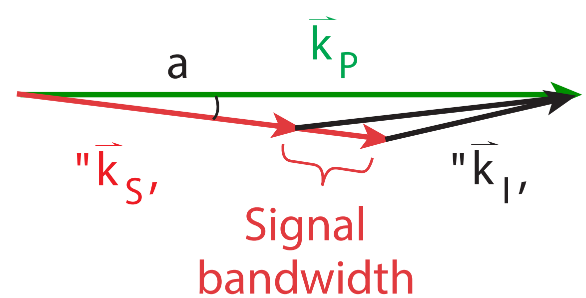
Optical Parametric Amplication Can Amplify Extremely Broadband Pulses



Can amplify extremely short laser pulses or broadband chirped pulses.

Goal: Design laser source capable of reaching focused intensities as large as 10^{24} W/cm^2.

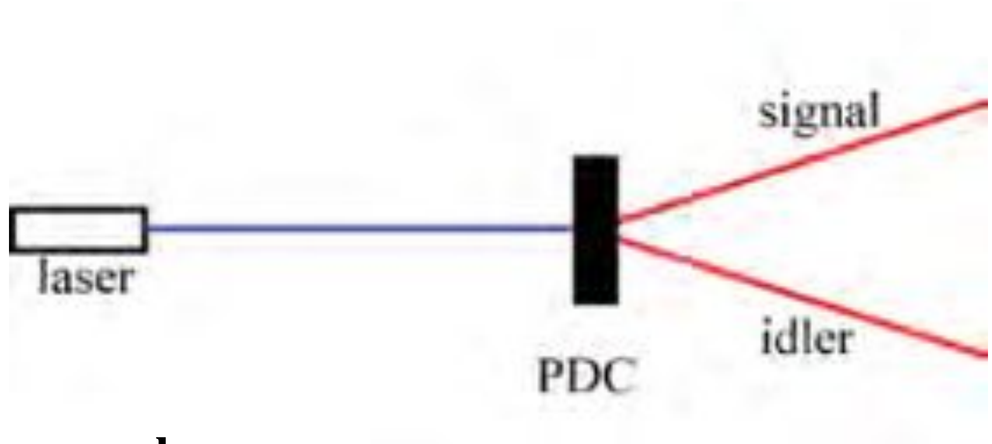


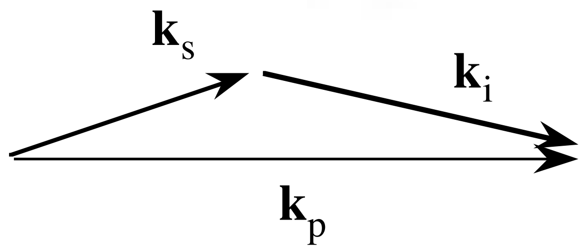


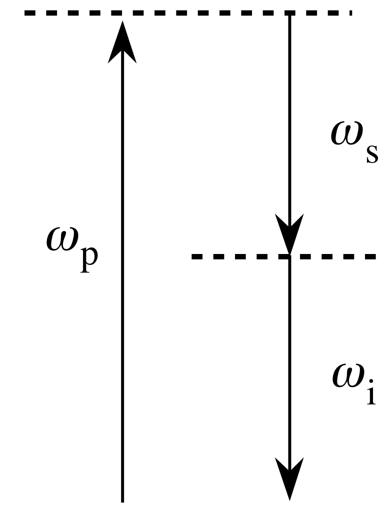
Work of Jake Bromage and others at U. Rochester LLE.

See also Lozhkarev et al. Laser Phys. Lett. 4, 421 (2007) and Y. Tang et al. Opt. Lett. 33, 2386 (2008).

Parametric Downconversion: A Source of Entangled Photons







The signal and idler photons are entangled in:

(a) polarization

(b) time and enegy

(c) position and transverse momentum

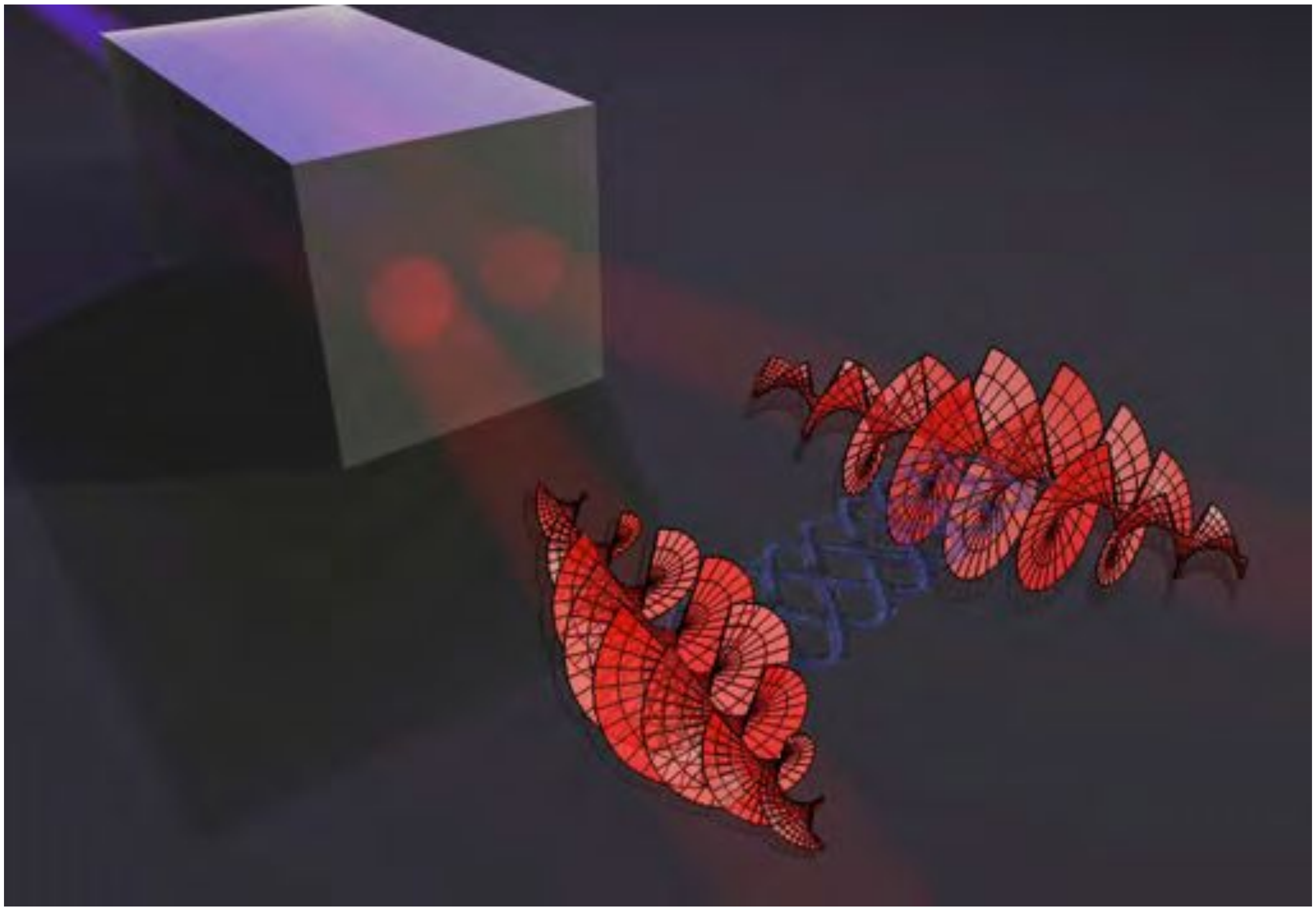
(d) angular position and orbital angular momentum

Entanglement is important for:

(a) Fundamental tests of QM (e.g., nonlocality)

(a) Quantum technologies (e.g., secure communications)

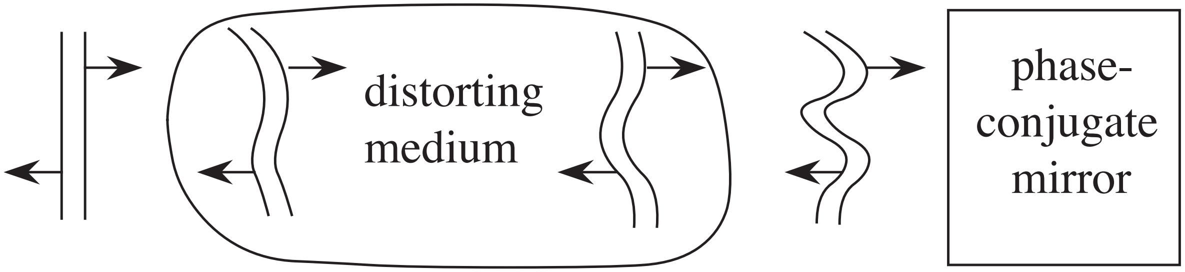
Nonlinear Optics Leads to Creation of Entangled Photons



Quantum Correlations in Optical Angle-Orbital Angular Momentum Variables,
Leach et al., Science 329, 662 (2010).

Optical Phase Conjugation: A Nonlinear Optics Success Story

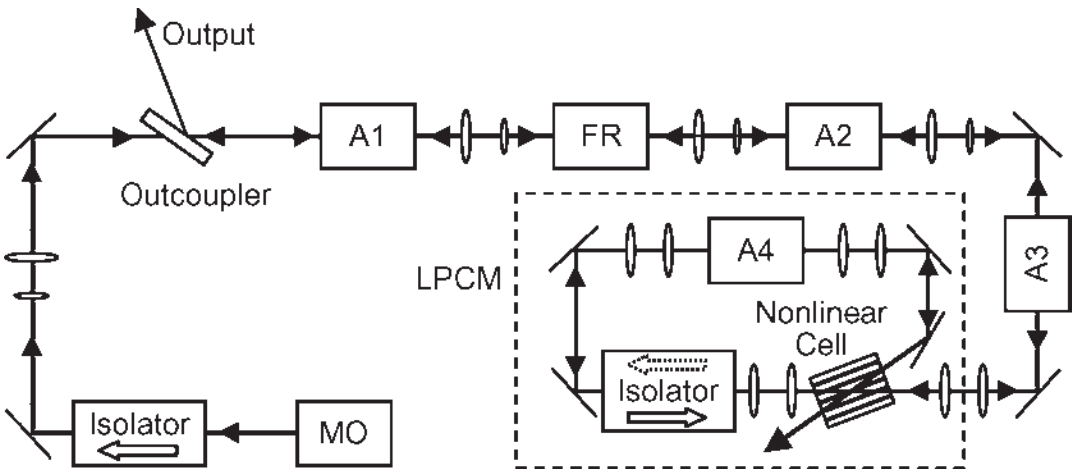
- A phase conjugate mirror (a nonlinear optical device) can remove the influence of aberrations in double pass.

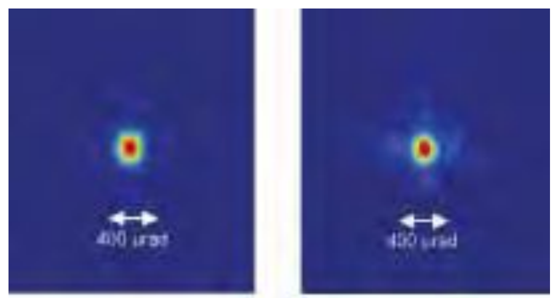


(Zeldovich, Pilipetsky, Shkunov, Yariv, Hellwarth, Fisher, 1980s).

- Phase conjugation is extremely useful in high power laser systems

2-kW average power phase-conjugate master oscillator power amplifier





near-diffraction-limited output

Zakharenkov, Clatterbuck, Shkunov, Betin, Filgas, Ostby, Strohkendl, Rockwell, and Baltimore, IEEE JSTQE (2007).

Intense Field and Attosecond Physics

E 70, NUMBER 11 PHYSICAL REVIEW LETTERS 15 MARCH

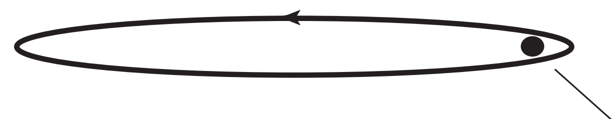
Above Threshold Ionization Beyond the High Harmonic Cutoff

K. J. Schafer,[1] Baorui Yang,[2] L. F. DiMauro,[2] and K. C. Kulander[1]
[1] *Lawrence Livermore National Laboratory, Livermore, California 94550*
[2] *Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973*
(Received 2 December 1992)

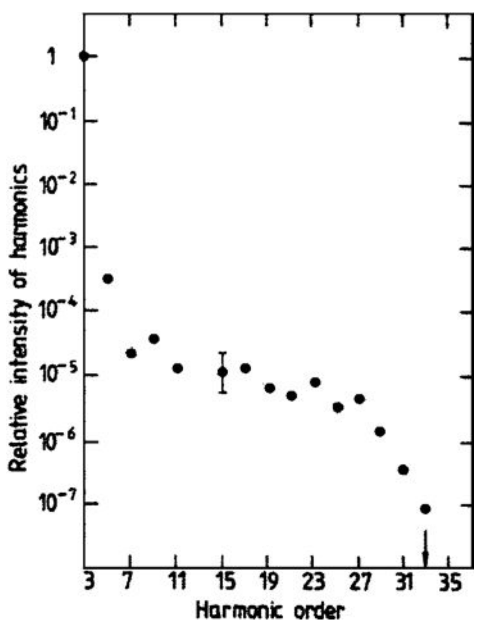
VOLUME 71, NUMBER 13 PHYSICAL REVIEW LETTERS 27 SEPTEMBER 1993

Plasma Perspective on Strong-Field Multiphoton Ionization

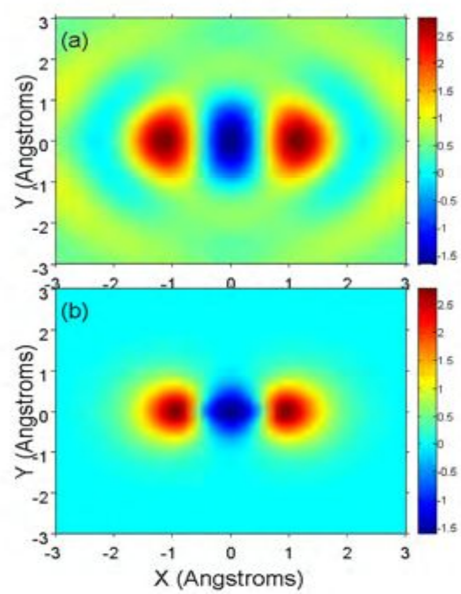
P. B. Corkum
National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6
(Received 9 February 1993)



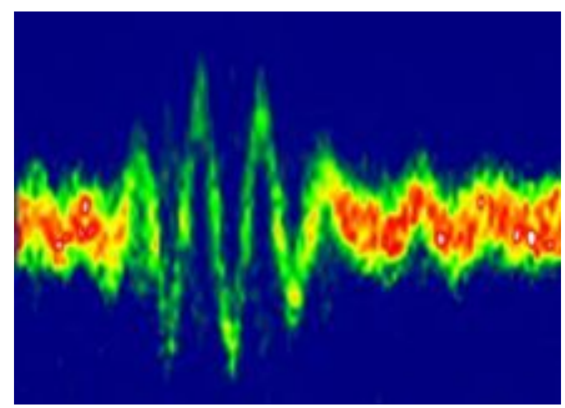
atomic core



High-harmonic generation



Measuring the molecular nitrogen wavefunction

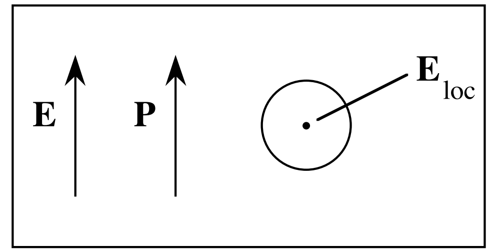


Attosecond pulses to sample a visible E-field

Theory of nonlinear optics

Local Field Effects in Nonlinear Optics

Bloembergen (1962, 1965) showed that



$$\chi^{(3)}(\omega = \omega + \omega - \omega) = N\gamma^{(3)}|L(\omega)|^2[L(\omega)]^2.$$

where $\gamma^{(3)}$ is the second hyperpolarizability and where

$$L(\omega) = \frac{\epsilon(\omega) + 2}{3}$$

For the typical value $n = 2$, $L = 2$, and $L^4 = 16$. Local field effects can be very large in nonlinear optics! But can we tailor them for our benefit?

We have been developing new photonic materials with enhanced NLO response by using composite structures that exploit local field effects.

Enhanced NLO Response from Layered Composite Materials

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

Alternating layers of TiO_2 and the conjugated polymer PBZT.

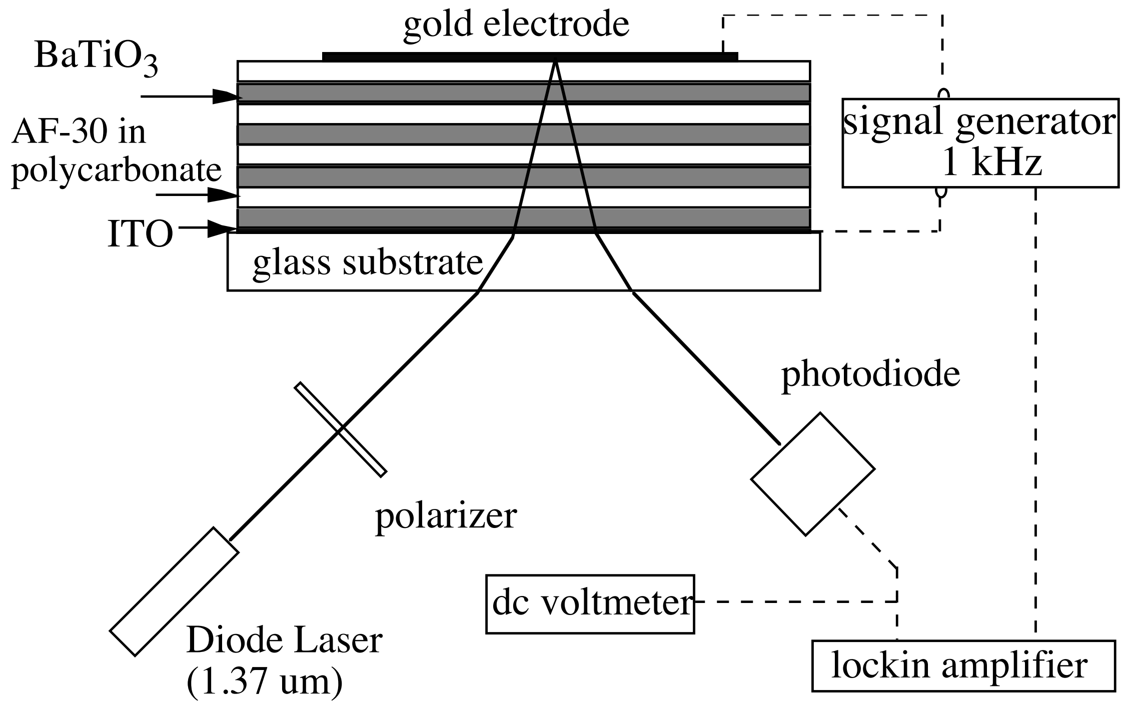
$\nabla \cdot \mathbf{D} = 0$ implies that $(\varepsilon \mathbf{E})_\perp$ is continuous.

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

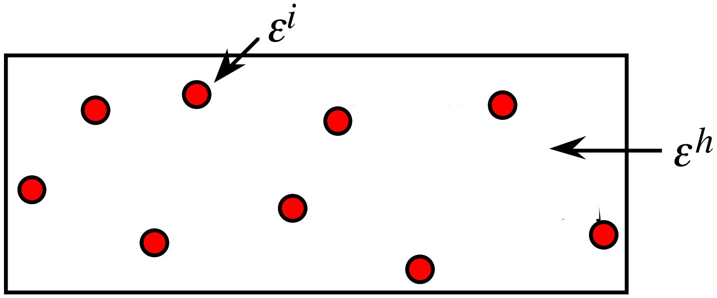


3.2 times enhancement!

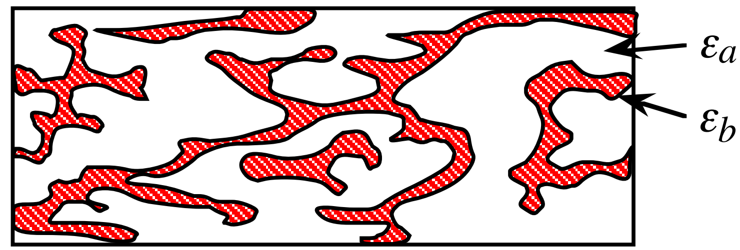
Nelson and Boyd, APL 74 2417 (1999)

Metamaterials and Nanocomposite Materials for Nonlinear Optics

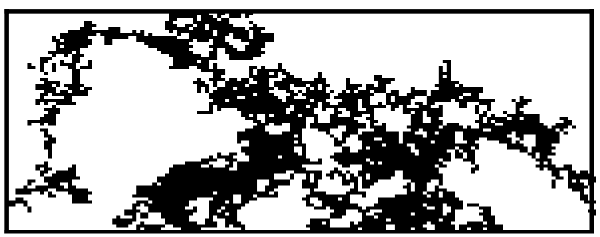
- Maxwell Garnett



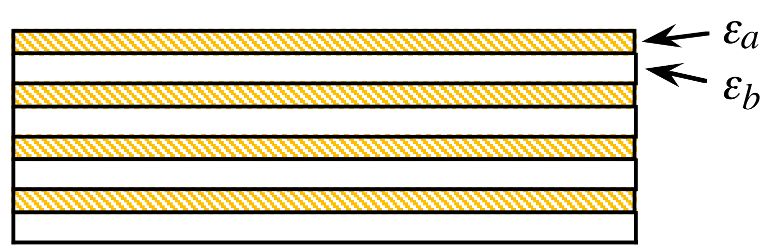
- Bruggeman (interdispersed)



- Fractal Structure



- Layered



- 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).

Slow Light, Fast Light, and their Applications

Controlling the Velocity of Light

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

– Light can be made to go:

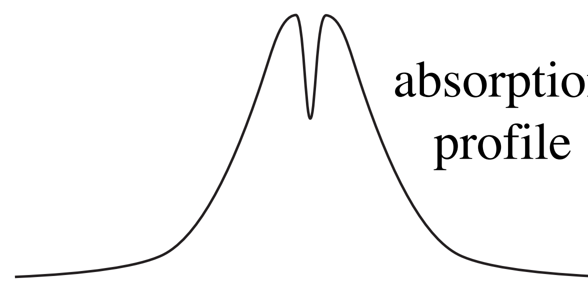
slow: $v_g << c$ (as much as 10^6 times slower!)

fast: $v_g > c$

backwards: v_g negative

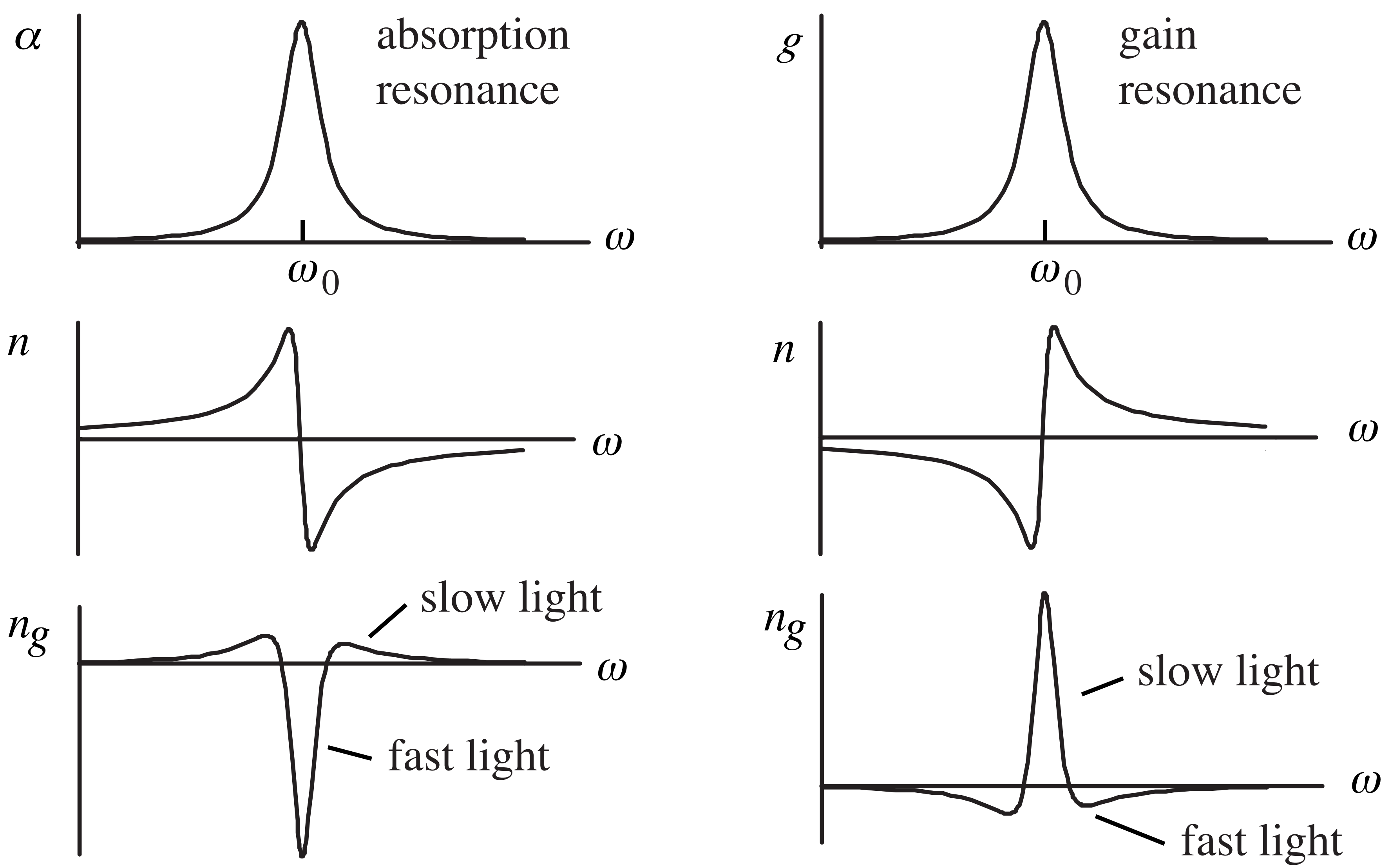
Here v_g is the group velocity: $v_g = c/n_g \quad n_g = n + \omega\,(dn/d\omega)$

– Velocity controlled by structural or material resonances



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

Slow and Fast Light Using Isolated Gain or Absorption Resonances



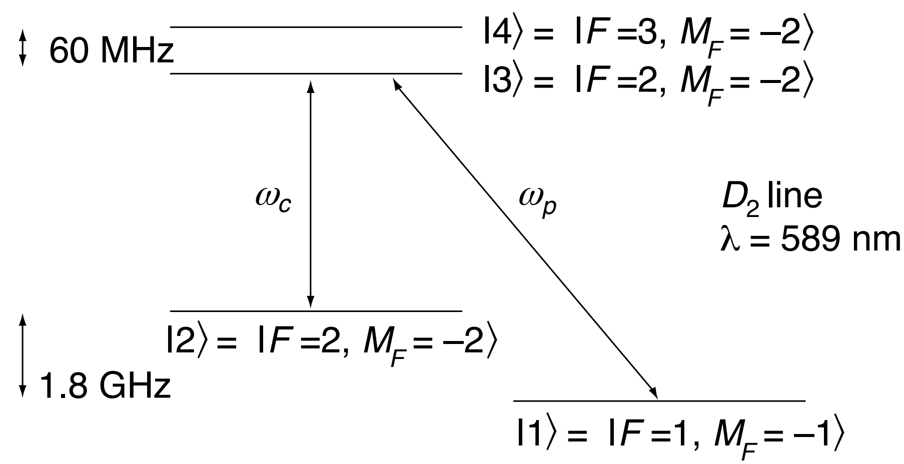
$$n_g = n + \omega\,(dn/d\omega)$$

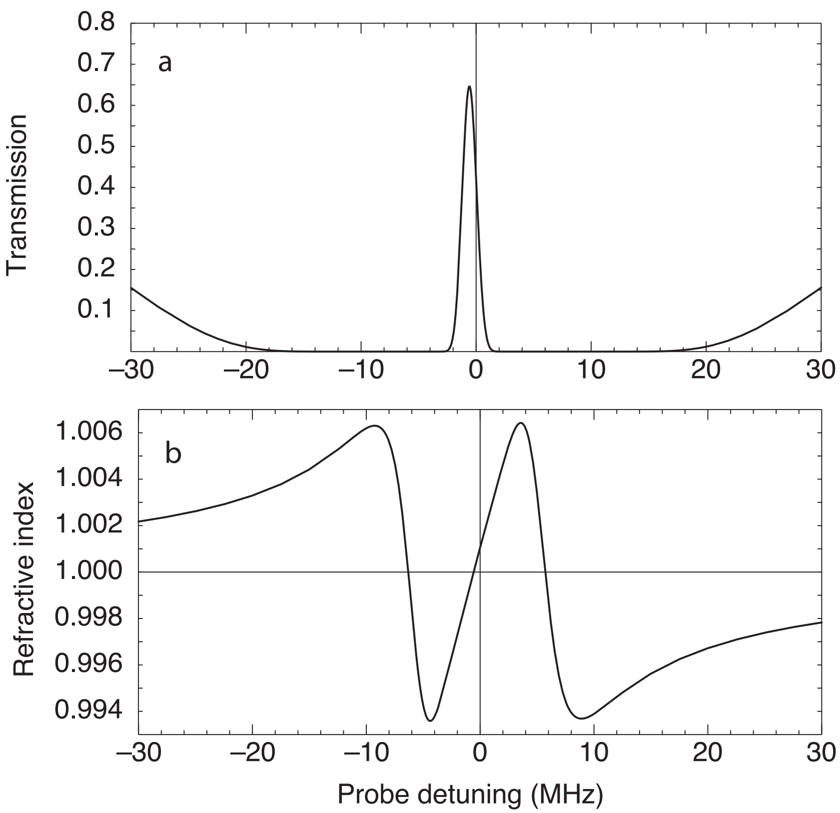
Light speed reduction to 17 metres per second in an ultracold atomic gas

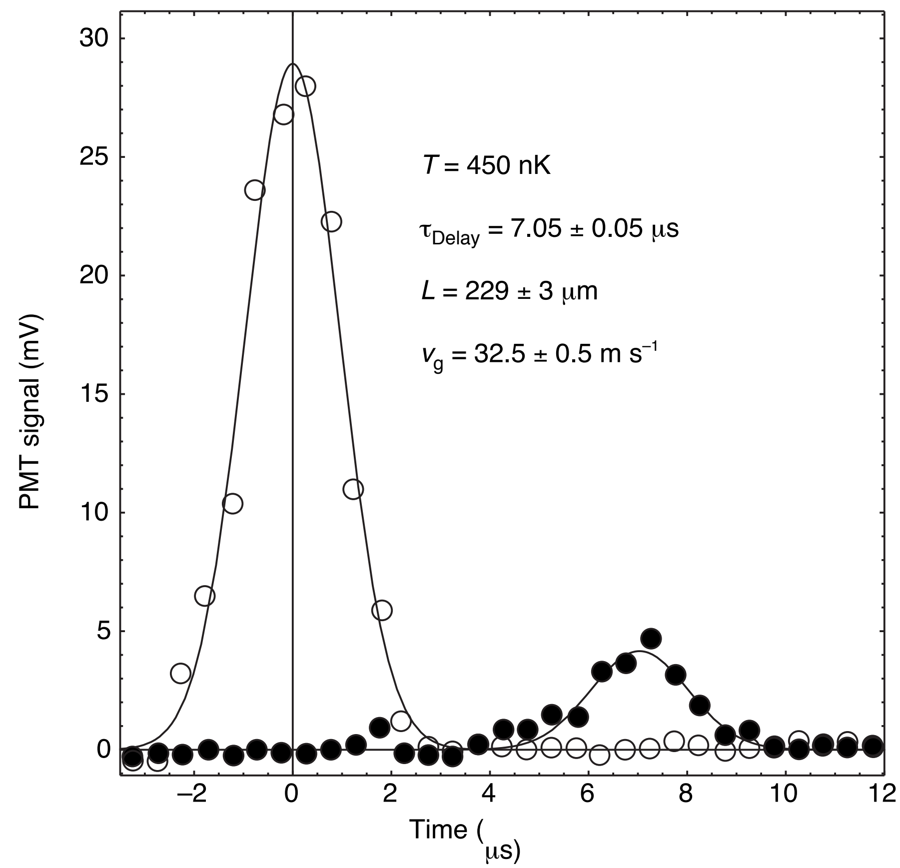
Lene Vestergaard Hau*[2], S. E. Harris[3], Zachary Dutton*[2] & Cyrus H. Behroozi*§

* Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA
[2] Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[3] Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA

NATURE | VOL 397 | 18 FEBRUARY 1999 |www.nature.com







Note also related work by Chu, Wong, Welch, Scully, Budker, Ketterle, and many others

Goal: Slow Light in a Room-Temperature Solid-State Material

Crucial for many real-world applications

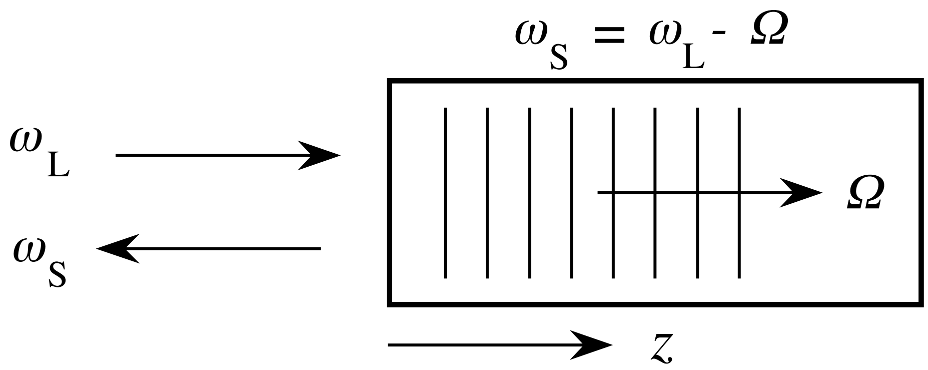
We have identified two preferred methods for producing slow light

(1) Slow light *via* coherent population oscillations (CPO)

(2) Slow light *via* stimulated Brillouin scattering (SBS)

UNIVERSITY of ROCHESTER

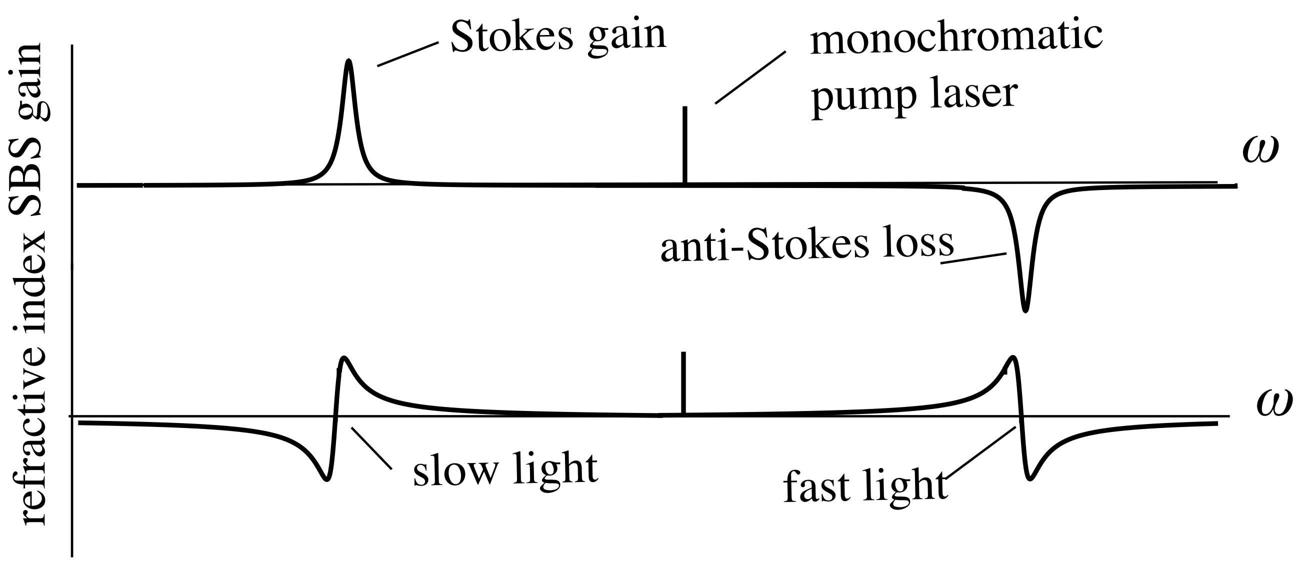
Slow Light by Stimulated Brillouin Scattering (SBS)

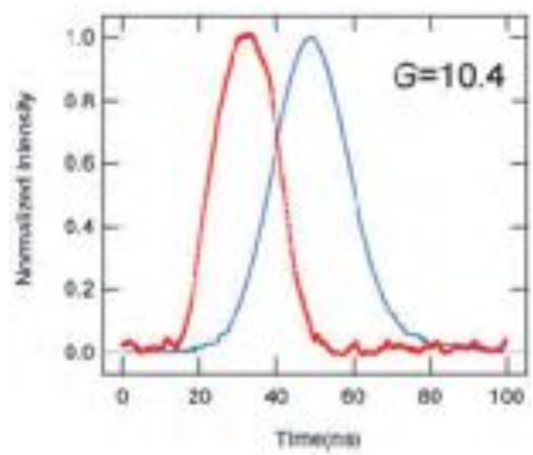


$$\frac{dI_S}{dz} = -gI_LI_S$$

$$g = \frac{\gamma_e^2\omega^2}{nv\,c^3\varrho_0\Gamma_B}.$$

We often think of SBS as a pure gain process, but it also leads to a change in refractive index

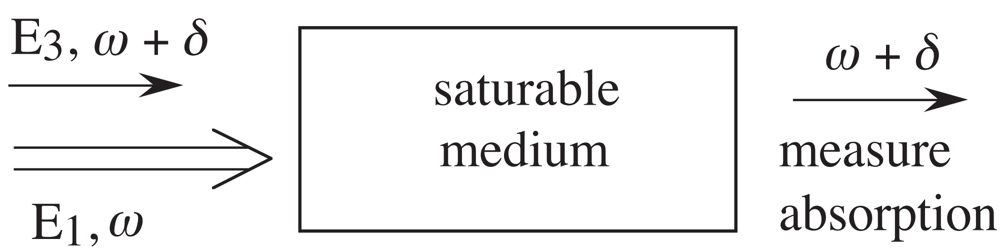


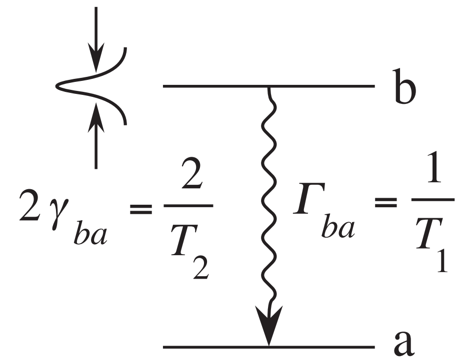


The induced time delay is $\Delta T_d \approx \dfrac{G}{\Gamma_B}$ where $G = g\, I_P\, L$ and Γ_B is the Brillouin linewidth

Okawachi, Bigelow, Sharping, Zhu, Schweinsberg, Gauthier, Boyd, and Gaeta Phys. Rev. Lett. 94, 153902 (2005).
Related results reported by Song, González Herráez and Thévenaz, Optics Express 13, 83 (2005).

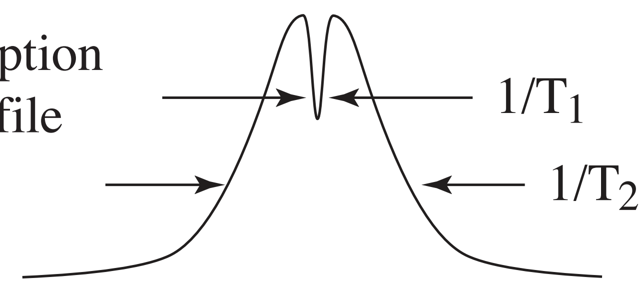
Slow Light via Coherent Population Oscillations





$n_g = n + \omega(dn/d\omega)$ $\qquad T_2 << T_1$

absorption profile

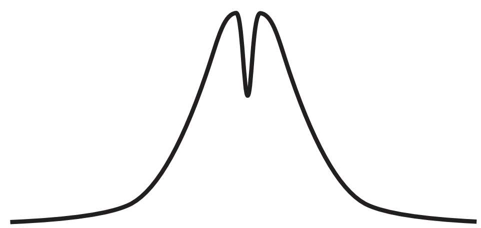


- Want a narrow feature in absorption profile to give a large $dn/d\omega$
- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Ultra-slow light ($n_g > 10^6$) observed in ruby and ultra-fast light ($n_g = -4 \times 10^5$) observed in alexandrite.
- Slow and fast light effects occur at room temperature!

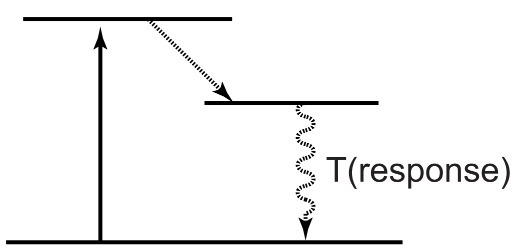
PRL 90,113903(2003); Science, 301, 200 (2003)

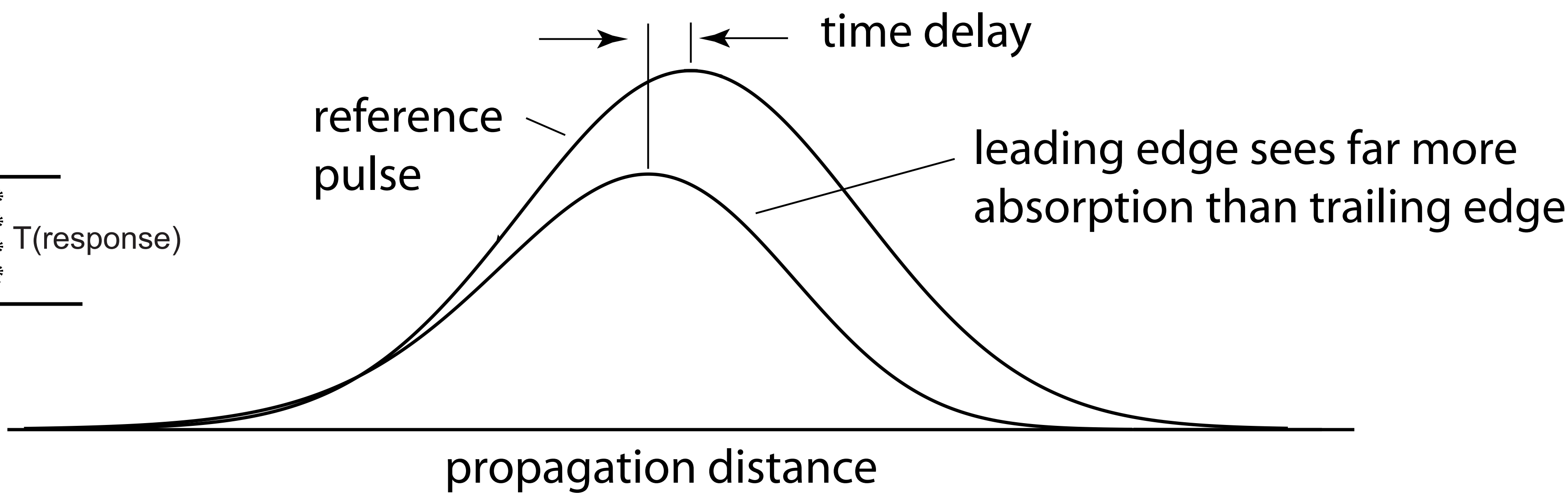
Relation of CPO to the Basov Mechanism

- CPO slow light: a strong pump beam creates a narrow transparency window, and strong spectral variation of the refractive index leads to a large group index.



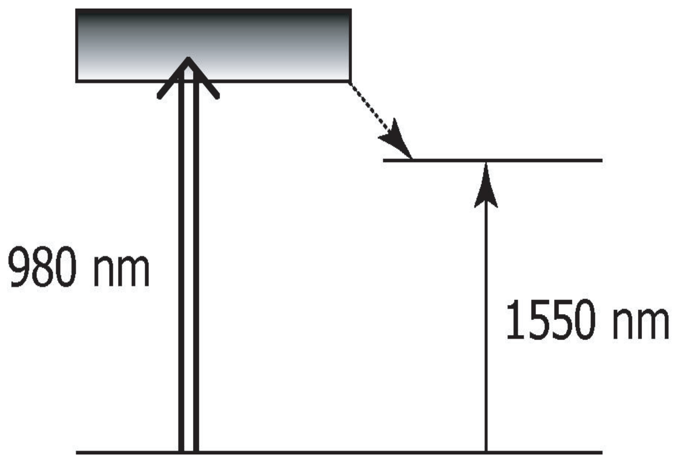
- Basov mechanism: an isolated intense pulse passing through a saturable material experiences a time delay.
  - Assume that $T_{pulse} << T_1$ = time scale for saturation changes
  - Then absorption decreases with time during pulse due to saturation

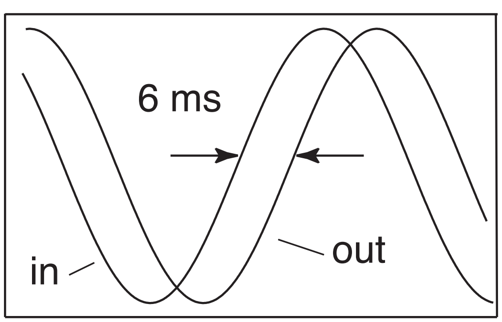


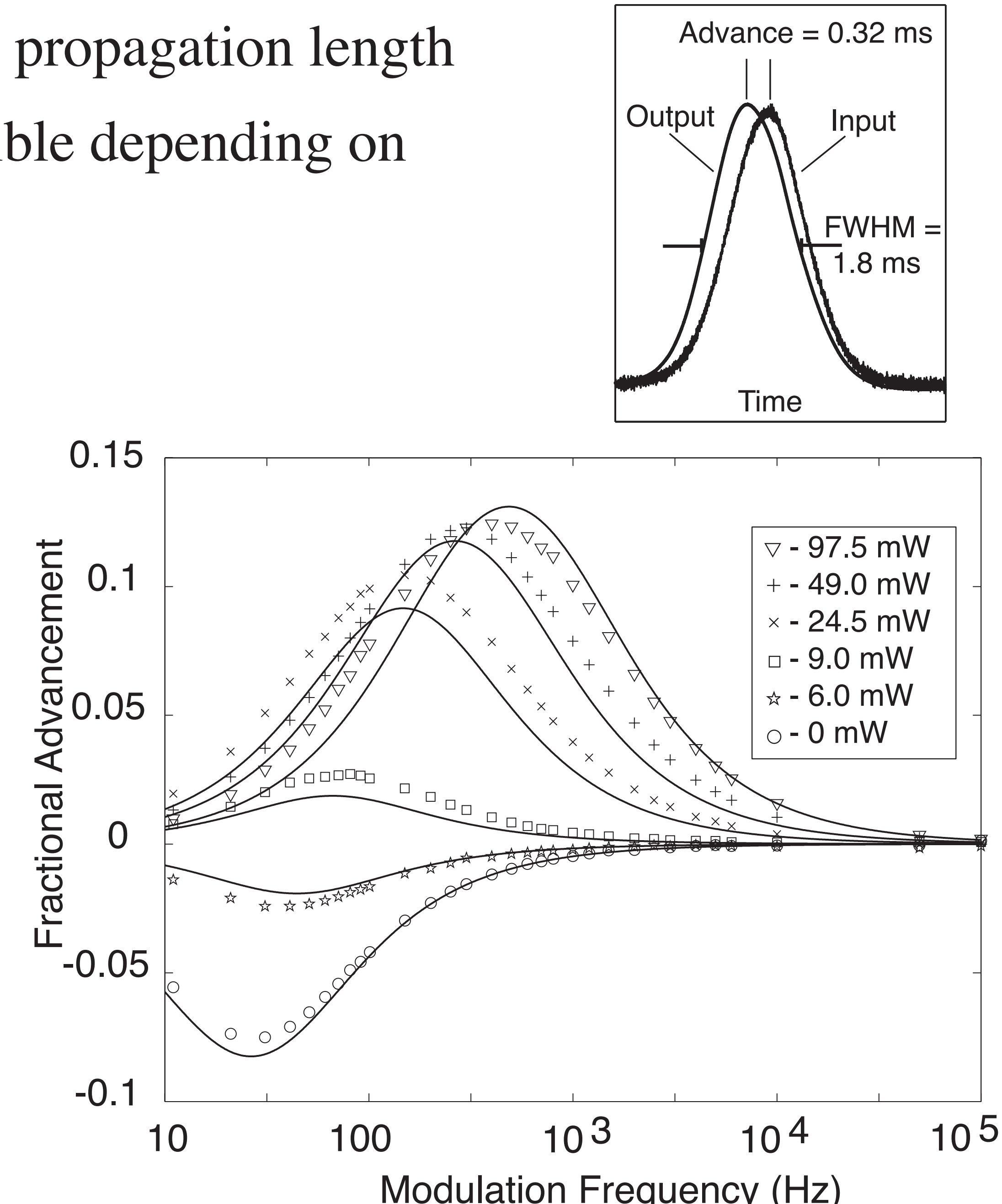


Slow and Fast Light in an Erbium Doped Fiber Amplifier

- Fiber geometry allows long propagation length
- Saturable gain or loss possible depending on pump intensity





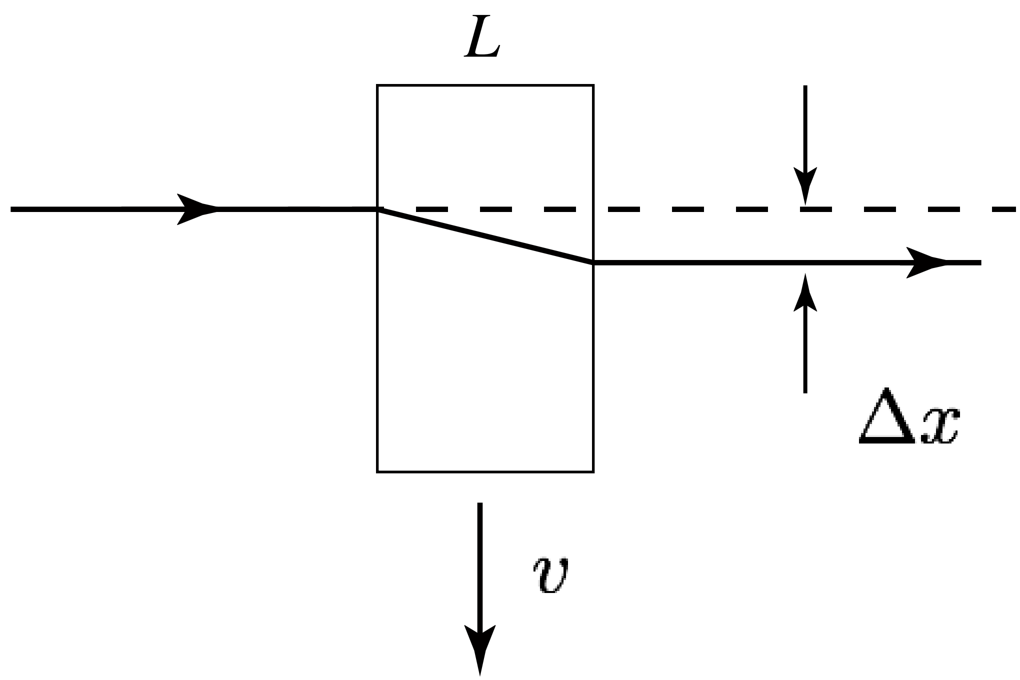


Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

Fun Physics with Slow and Fast Light

Topic 1: Photon Drag Effects with Slow Light

Transverse Photon Drag



$$\Delta x = (vL/c)(n_g - 1/n_\phi)$$

For L = 25 mm, v = 2000 cm/s, displacement = 6 nm.

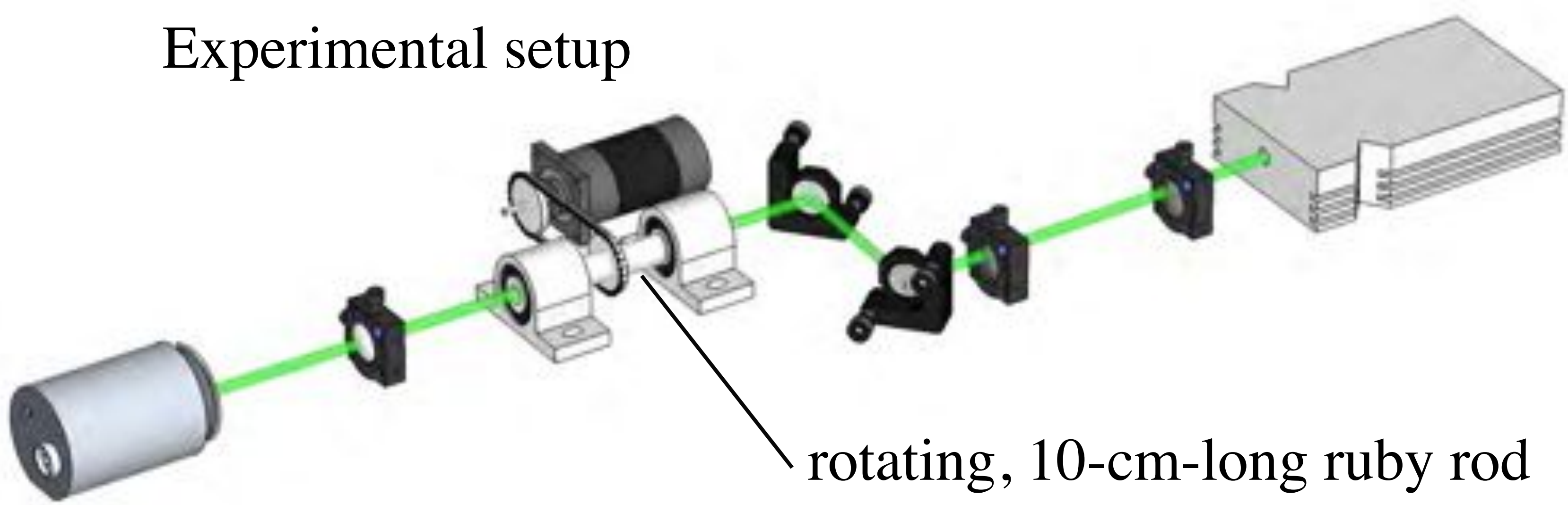
Measured by R.V. Jones, 1972.

Observation of Rotary Photon Drag

The world as seen through a spinning window.

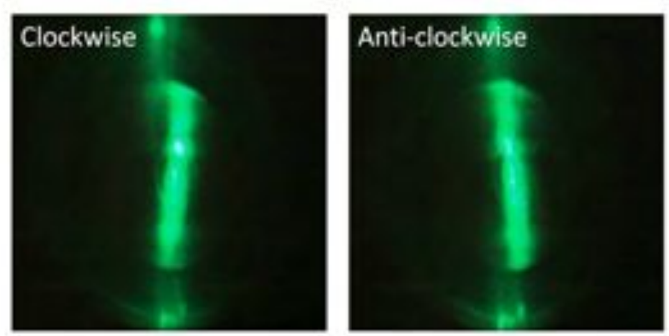
(Laser-excited ruby has a group index of 10^6.)

Experimental setup



rotating, 10-cm-long ruby rod

Effect clearly visible by eye!



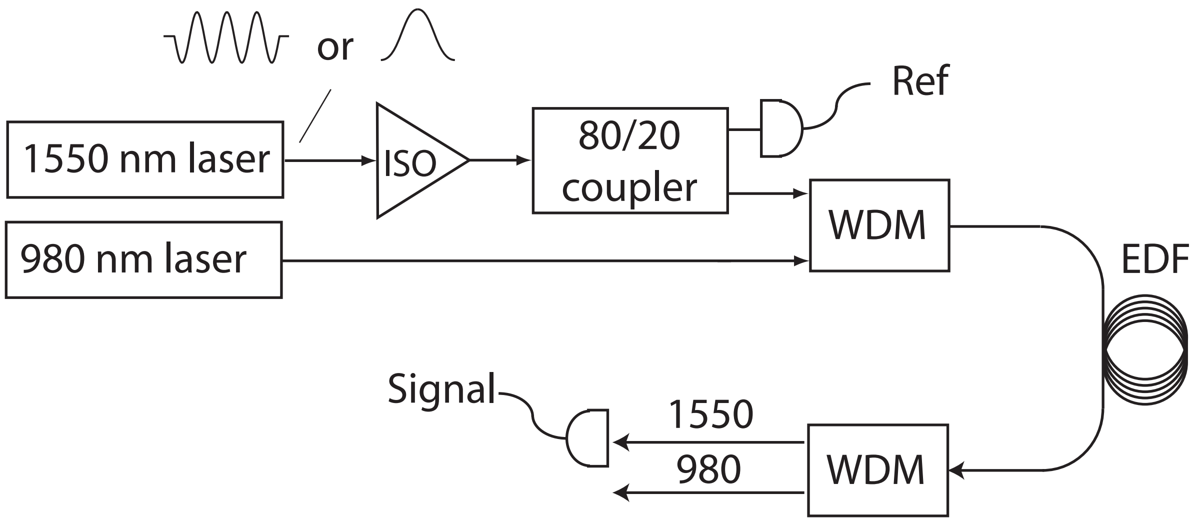
Franke-Arnold, Gibson, Boyd and Padget, Science, 2011

(See also the earlier work of Leach et al., 2008.)

Fun Physics with Slow and Fast Light

Topic 2: “Backwards” Propagation and Negative Group Velocities

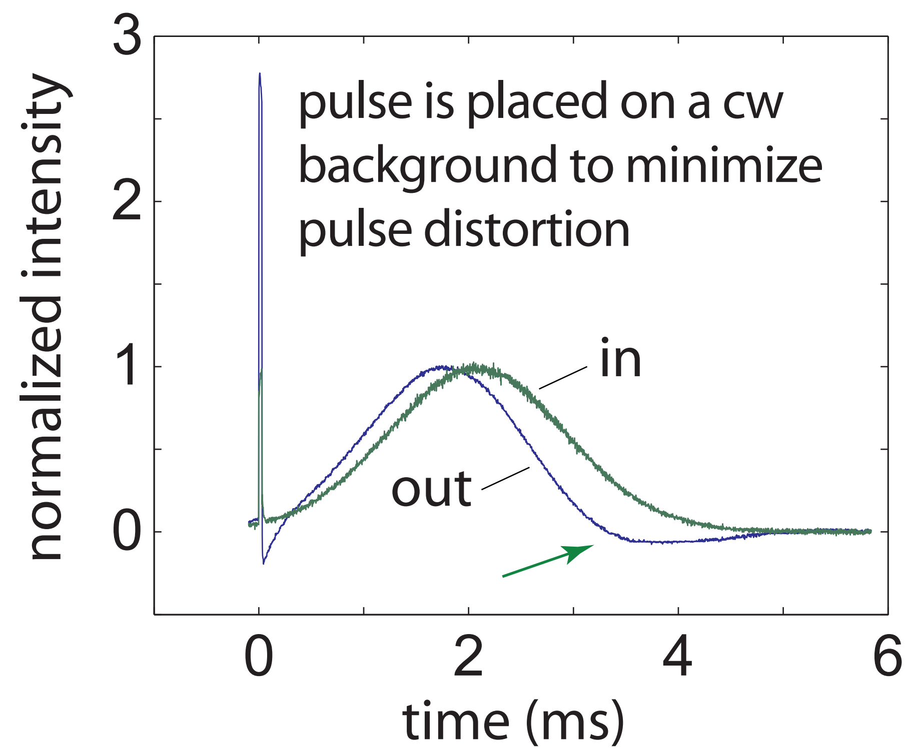
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



We time-resolve the propagation of the pulse as a function of position along the erbium-doped fiber.

Procedure

- cutback method
- couplers embedded in fiber

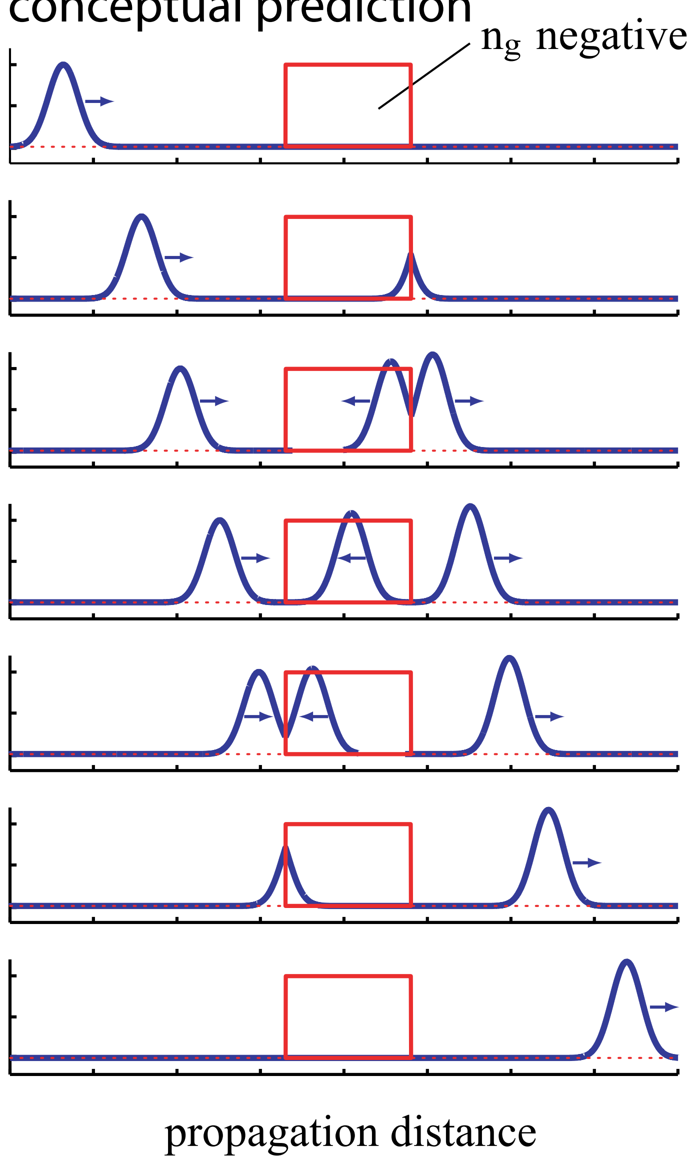


G. M. Gehring, A. Schweinsberg, C. Barsi, N. Kostinski, R. W. Boyd, Science 312, 985 2006.

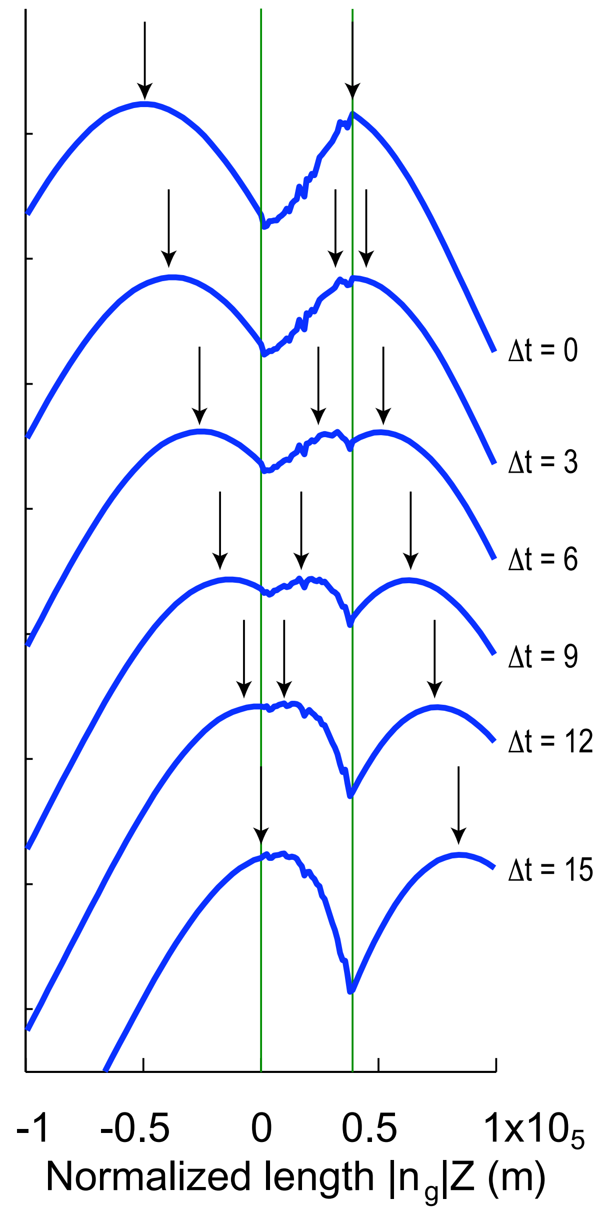
Observation of Superluminal and "Backwards" Pulse Propagation

- 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.

- conceptual prediction



- laboratory results

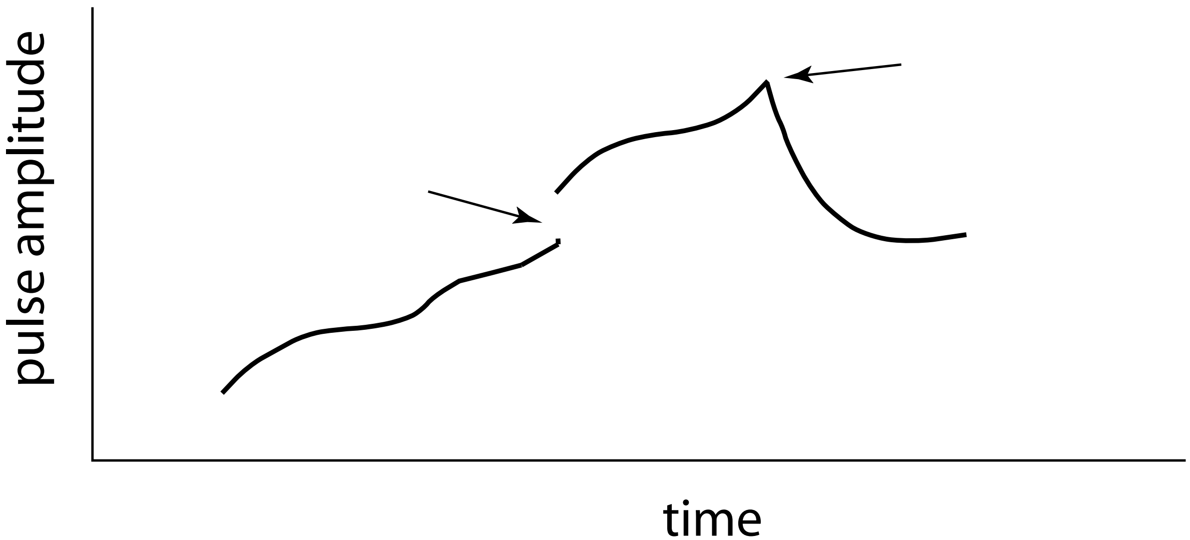


Causality?

- Superluminal (v_g>c) and backwards (v_g negative) propagation may seem counterintuitive but are fully compatible with causality.

- The group velocity is the velocity at which peak of pulse moves; it is not the "information velocity."

- It is believed that information is carried by points of nonalyticity of a waveform



- broad spectral content at points of discontinuity
- disturbance moves at vacuum speed of light

see, for instance, R. Y. Chiao

Applications of Slow and Fast Light
(where the action is now!)

Buffers and regenerators for telecom

Slow/fast light for interferometery

Phased- and synchronized-array laser radar

Construction of quantum memories

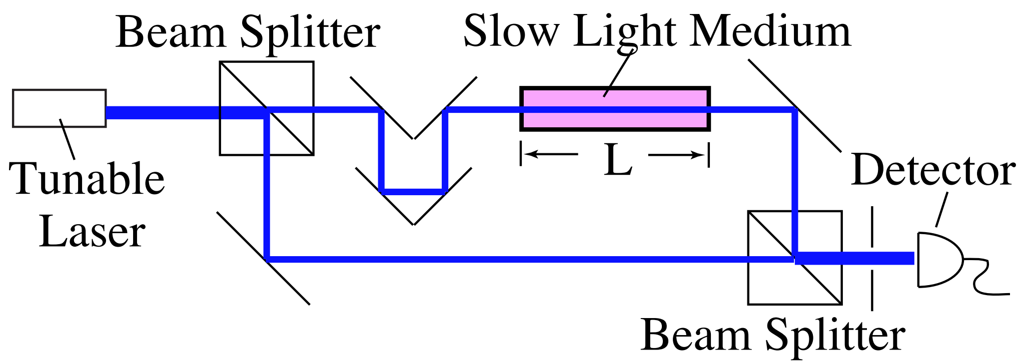
Interferometry and Slow Light

- 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 spectromters

- Here is why it works:

Slow-light interferometer:

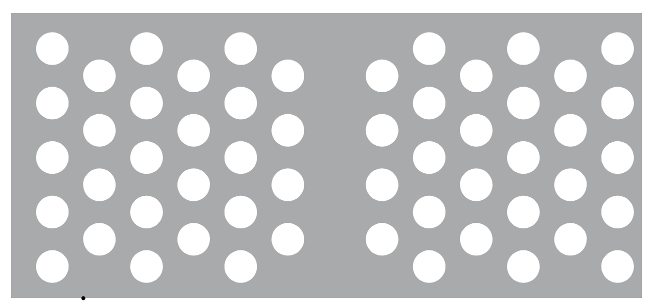


Simple analysis

$$\frac{d\,\Delta\phi}{d\omega} = \frac{d}{d\omega}\frac{\omega n L}{c} = \frac{L}{c}\left(n + \omega\frac{dn}{d\omega}\right) = \frac{L n_g}{c}$$

- 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).

See also the group of Shahriar on fast-light and interferometry

Regeneration of Pulse Timing

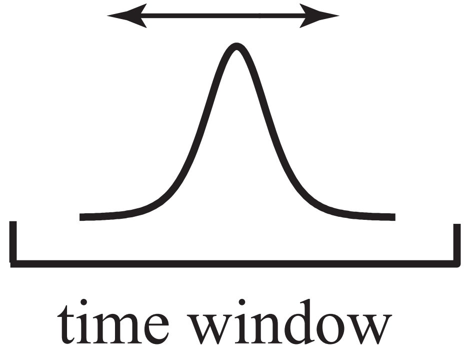
Need to recenter each pulse in its time window

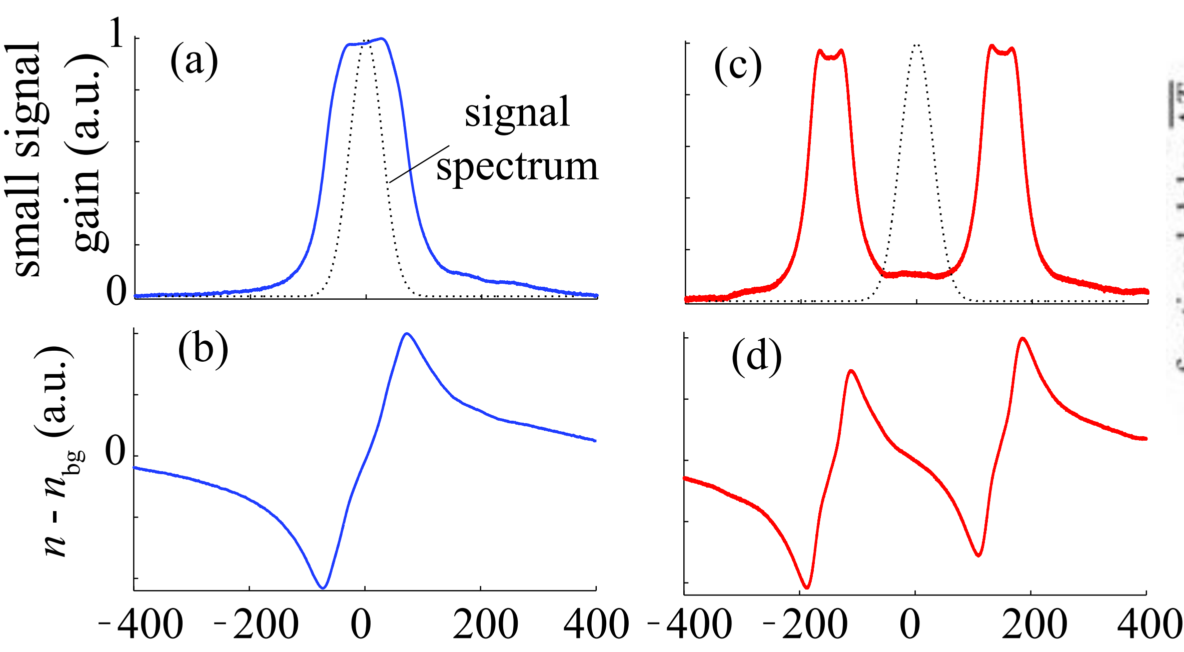
Removes timing jitter caused by NL and environment effects in fiber

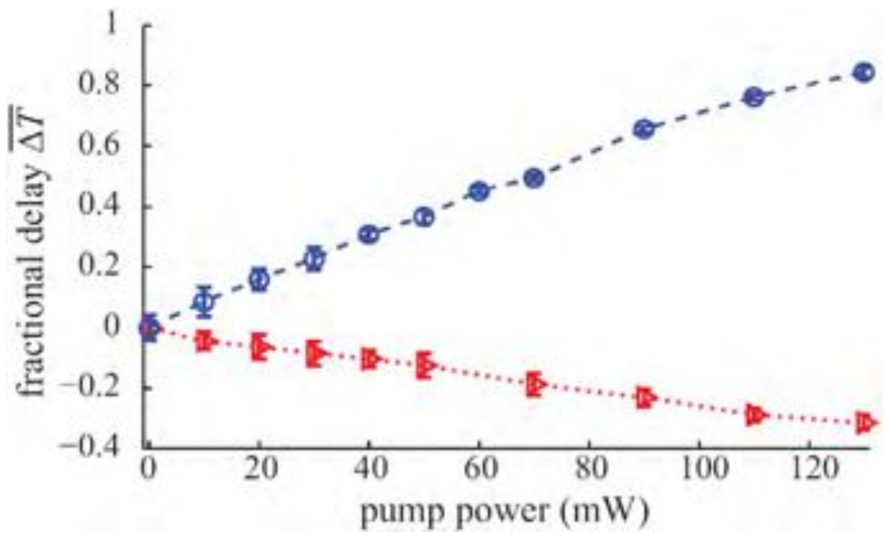
Need only approximately ±1 pulse width of delay!

Most conveniently done by access to both slow and fast light

Recent implementation using SBS with EO-contolled gain spectrum

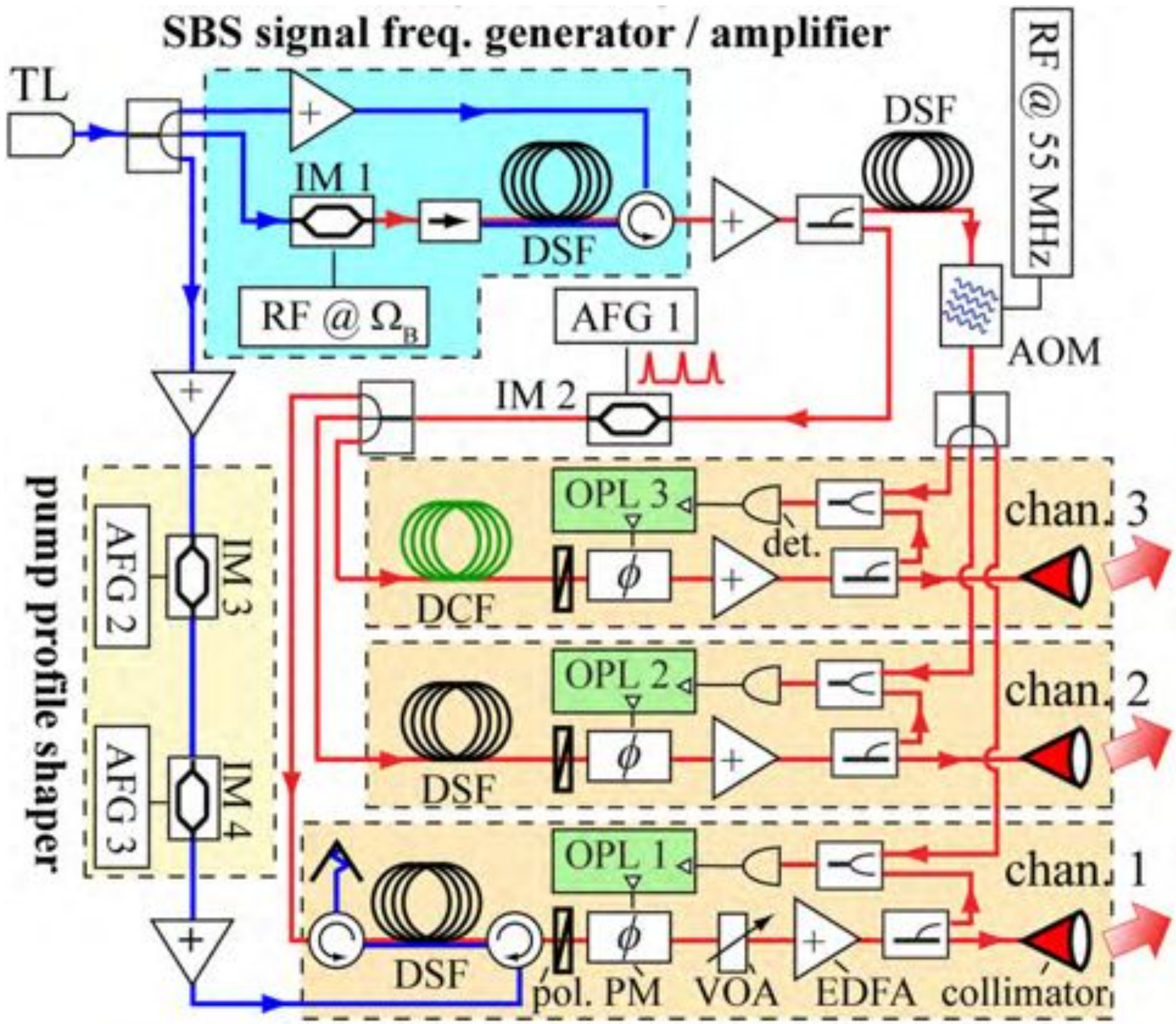






Z. Shi, A. Schweinsberg, J. E. Vornehm Jr., A. Martinez Gamez, and R. W. Boyd, Physics Letters A 374 4071–4074 (2010).

Phased-Array Laser Radar Based on Slow Light



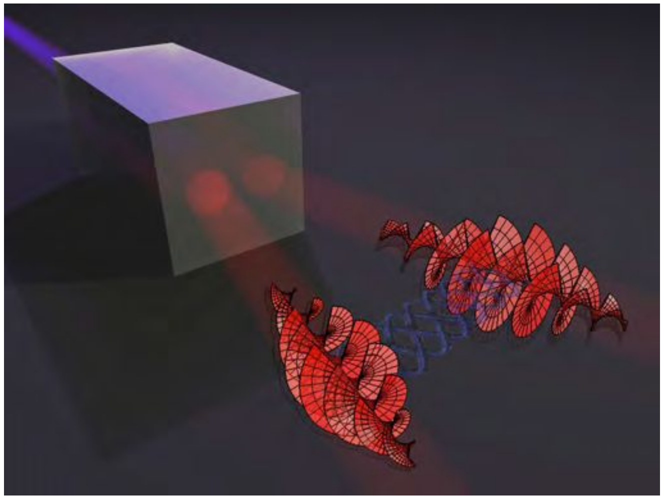
Schweinsberg et al., Optics Express 19, 15760 (2011)
Schweinsberg et al., Optics Letters, 37 329 (2012).

Nonlinear Optics and Quantum Information Science

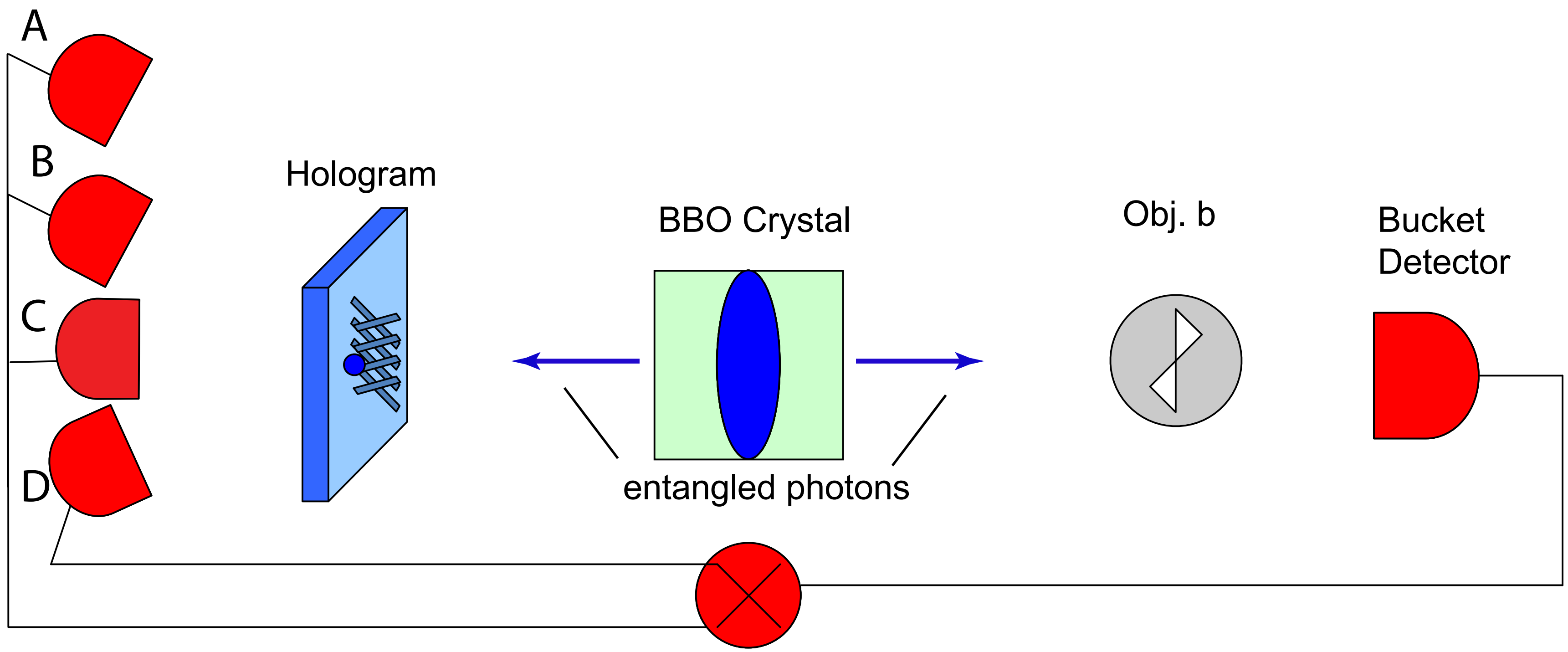
- We *use* nonlinear optics to create quantum states of light
- Some questions under investigation

  How many bits of information can one photon carry?

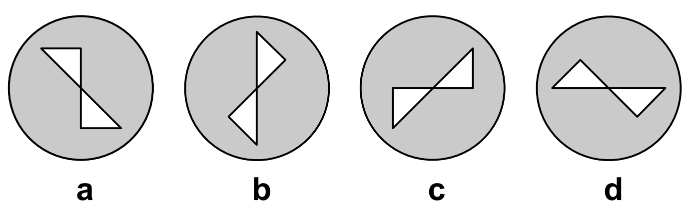
  Can we perform quantum communications with more than one bit of classical information per photon?



Single-Photon Coincidence Imaging



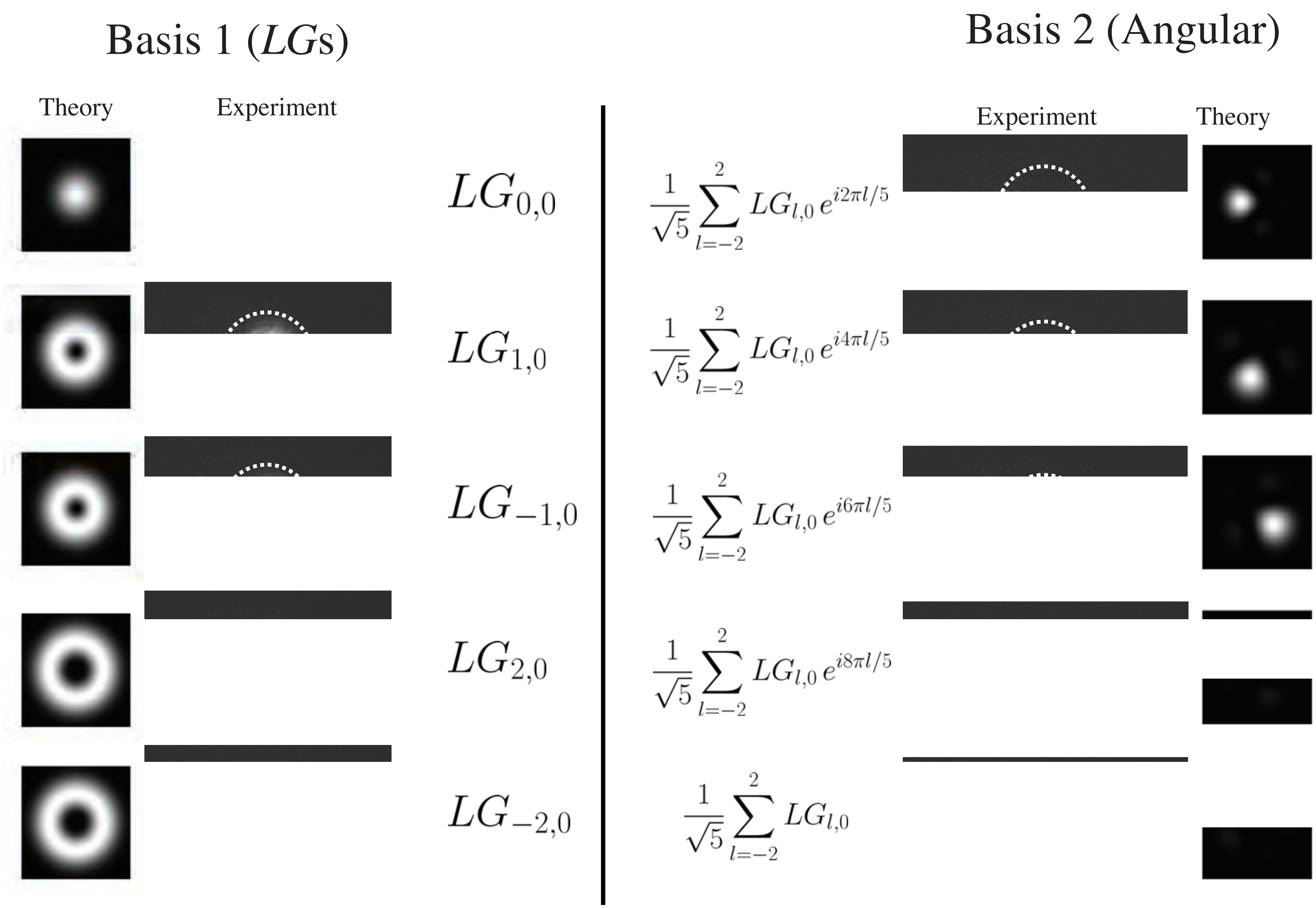
We discriminate between four orthogonal images at the single-photon level in a coincidence imaging configuration.



Malik, Shin, O'Sullivan, Zerom and Boyd, Phys. Rev. Lett 104, 163602 (2010)

Quantum Key Distribution with Many Bits Per Photon

- Offers absolutely secure communications
- Encode in a large alphabet (the Laguerre-Gauss modes)



Closing Remarks

NLO is as exciting today as it was 51 years ago
NLO has spun off many new research fields, such as
ultrafast phenomena, photonics, optical solitons, . . .
One exciting future direction is that of quantum nonlinear optics

Thank you for your attention!