Performance Limits of Delay Lines Based on "Slow" Light

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Motivation: Maximum Slow-Light Time Delay

"Slow light": group velocities < 10^{-6} c !

Proposed applications: controllable optical delay lines optical buffers, true time delay for synthetic aperture radar.

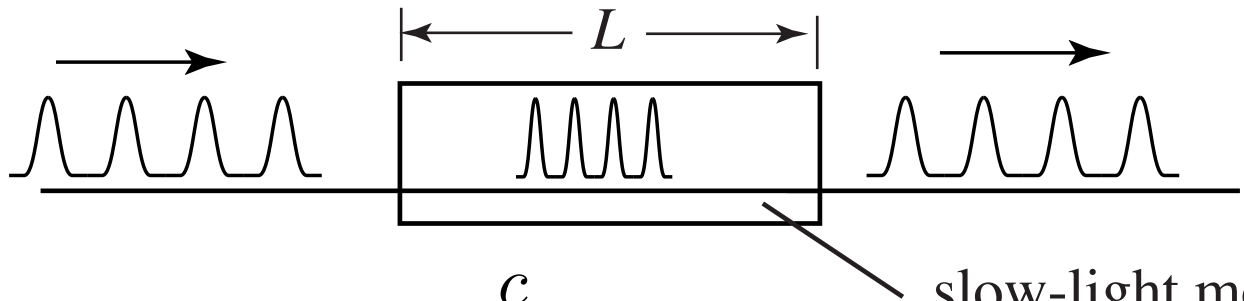
Key figure of merit:
normalized time delay = total time delay / input pulse duration
$\approx$ information storage capacity of medium

Best result to date: delay by 4 pulse lengths (Kasapi et al. 1995)

But data packets used in telecommunications contain $\approx 10^3$ bits

What are the prospects for obtaining slow-light delay lines with 10^3 bits capacity?

Review of Slow-Light Fundamentals



group velocity: $$v_g = \frac{c}{n_g}$$

group index: $$n_g = n + \omega \frac{dn}{d\omega}$$

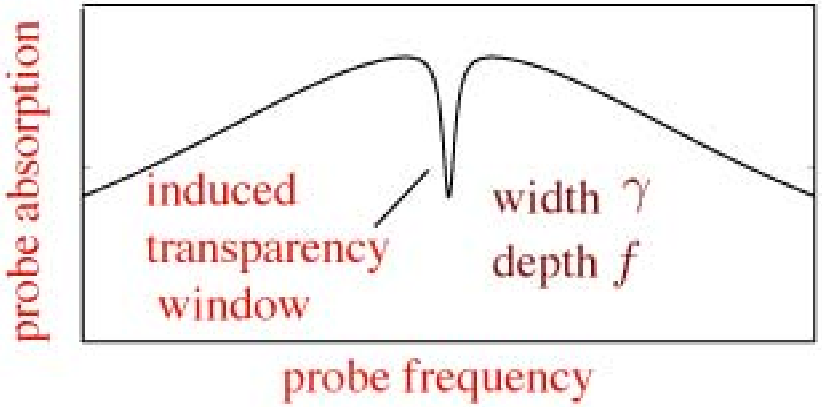
group delay: $$T_g = \frac{L}{v_g} = \frac{L n_g}{c}$$

controllable delay: $$T_{\text{del}} = T_g - L/c = \frac{L}{c}(n_g - 1)$$

To make controllable delay as large as possible:

- make L as large as possible (reduce residual absorption)
- maximize the group index

Generic Model of EIT and CPO Slow-Light Systems



probe absorption

$$\alpha(\delta) = \alpha_0 \left(1 - \frac{f}{1 + \delta^2/\gamma^2}\right) \approx \alpha_0 \left[(1-f) - f\frac{\delta^2}{\gamma^2}\right] \quad \text{where} \quad \delta = \omega - \omega_0$$

probe refractive index (by Kramers Kronig)

$$n(\delta) = n_0 + f\left(\frac{\alpha_0 \lambda}{4\pi}\right) \frac{\delta/\gamma}{1 + \delta^2/\gamma^2} \approx n_0 + f\left(\frac{\alpha_0 \lambda}{4\pi}\right) \frac{\delta}{\gamma}\left(1 - \frac{\delta^2}{\gamma^2}\right)$$

probe group index

$$n_g \approx f\left(\frac{\alpha_0 \lambda}{4\pi}\right) \frac{\omega}{\gamma}\left(1 - \frac{3\delta^2}{\gamma^2}\right).$$

induced delay

$$T_{\mathrm{del}} \approx \frac{f\alpha_0 L}{2\gamma}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

normalized induced delay (T_0 = pulse width)

$$\frac{T_{\mathrm{del}}}{T_0} \approx \frac{f\alpha_0 L}{2\gamma T_0}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

Limitations to Time Delay

Normalized induced delay $$\frac{T_{\rm del}}{T_0} \approx \frac{f\alpha_0 L}{2\gamma T_0}\left(1-\frac{3\delta^2}{\gamma^2}\right)$$

Limitation 1: Residual absorption limits L; Solution: Eliminate residual absorption

Limitation 2: Group velocity dispersion

A short pulse will have a broad spectrum and thus a range of values of δ
There will thus be a range of time delays, leading to a range of delays and pulse spreading
Insist that pulse not spread by more than a factor of 2. Thus

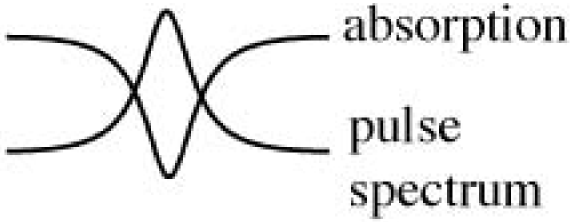
$$L_{\rm max} = 2\gamma^3 T_0^3/3f\alpha_0 \quad \text{and} \quad \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{1}{3}\gamma^2 T_0^2.$$

Limitation 3: Spectral reshaping of pulse (more restrictive than limitation 2)

Pulse will narrow in frequency and spread in time
from T_0 to T where $T^2 = T_0^2 + f\alpha_0 L/\gamma^2$.

Thus

$$L_{\rm max} = 3T_0^2\gamma^2/(2f\alpha_0) \quad \text{and} \quad \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{3}{2}\gamma T_0.$$



Note that γT_0 can be arbitrarily large!

Summary: Fundamental Limitations to Time Delay

- If one can eliminate residual absorption, the maximum relative time delay is

$$\left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{3}{2}\gamma T_0,$$

which has no upper bound.

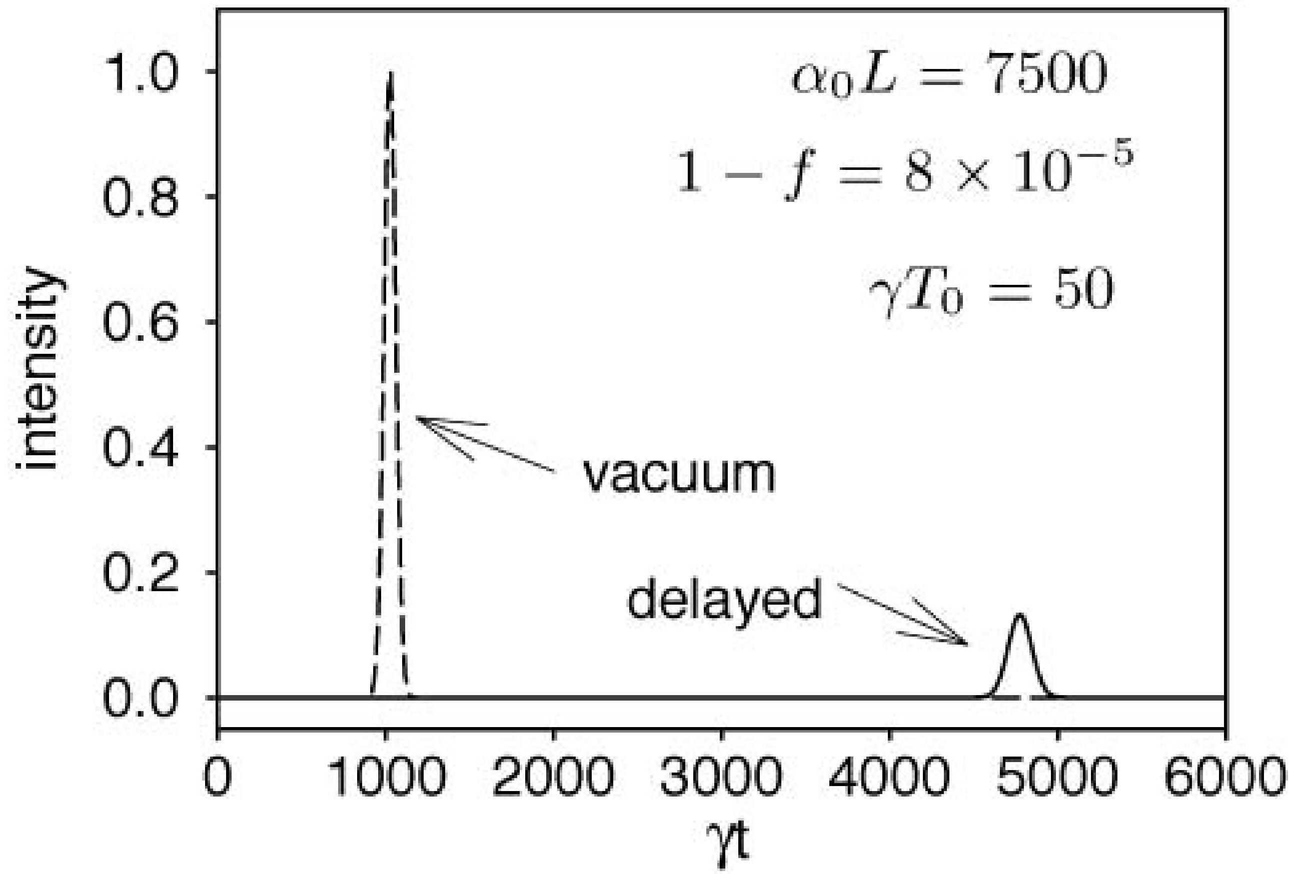
- But to achieve this time delay, one needs a large initial (before saturation) optical depth given by

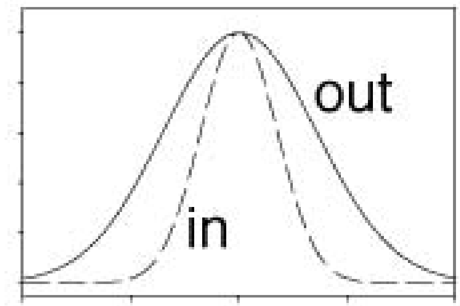
$$\alpha_0 L = (4/3)(T_{\rm del}/T_0)^2_{\rm max}.$$

- For typical telecommunications protocols, the bit rate B is approximately T_0^{-1} and the required transparency linewidth must exceed the bit rate by the relative delay

$$\gamma = \frac{2}{3} B \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max}$$

Numerical Example Showing Large Relative Delay

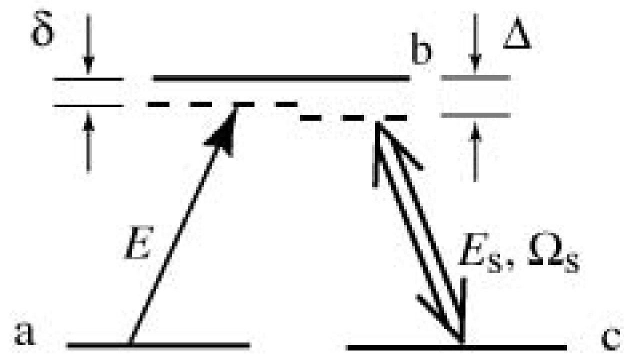




Factor-of-two pulse spreading

Relative time delay $T_{\mathrm{del}}/T_0 = 75$.

Specific Example: Electromagnetically Induced Transparency



- The reponse to the probe field in the presence of the strong coupling field is given by

$$\chi^{(1)} = -\frac{\alpha_0 c}{\omega} \frac{[i(\delta - \Delta) - \gamma_{ca}]}{(i\delta - \gamma_{ba})[i(\delta - \Delta) - \gamma_{ca}] + |\Omega_s/2|^2}$$

- The width of the transparency window displays power broadening: $\gamma = \frac{|\Omega_s/2|^2}{\gamma_{ba}}$

- The residual absorption can be rendered arbitrarily small $(f \rightarrow 1)$ through use of an intense coupling field.

$$f = \frac{|\Omega_s/2|^2}{\gamma_{ca}\gamma_{ba} + |\Omega_s/2|^2}$$

- For $(f \rightarrow 1)$ the normalized delay can be arbitrarily large

$$\left(\frac{T_{del}}{T_o}\right)_{\max} = \frac{3}{2} \frac{|\Omega_s/2|^2 T_o}{\gamma_{ba}}.$$

Modeling of Slow-Light Systems

We conclude that there are no *fundamental* limitations to the maximum fractional pulse delay [1]. Our model includes gvd and spectral reshaping of pulses.

However, there are serious *practical* limitations, primarily associated with residual absorption.

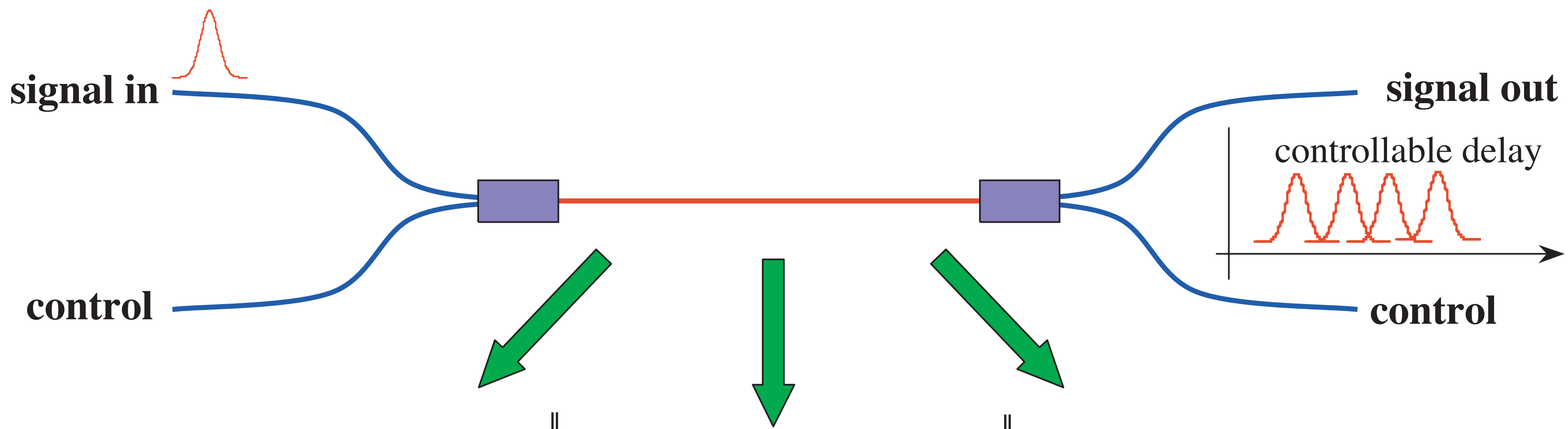
Another recent study [2] reaches a more pessimistic (although entirely mathematically consistent) conclusion by stressing the severity of residual absorption, especially in the presence of Doppler broadening.

Our challenge is to minimize residual absorption.

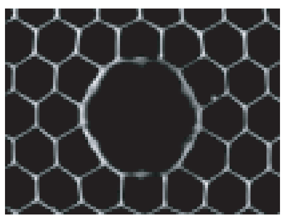
[1] Boyd, Gauthier, Gaeta, and Willner, Phys. Rev. A 71, 023801, 2005.

[2] Matsko, Strekalov, and Maleki, Opt. Express 13, 2210, 2005.

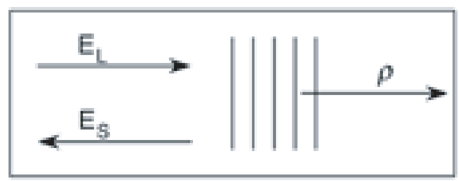
DARPA/DSO Project on Applications of Slow Light in Optical Fibers



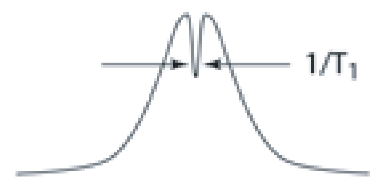
3 Approaches:



Photonic Crystal Fiber
- Utilize EIT effects in gas-filled fiber.



Stimulated Scattering
- Raman/Brillouin effect produces gain/delay.



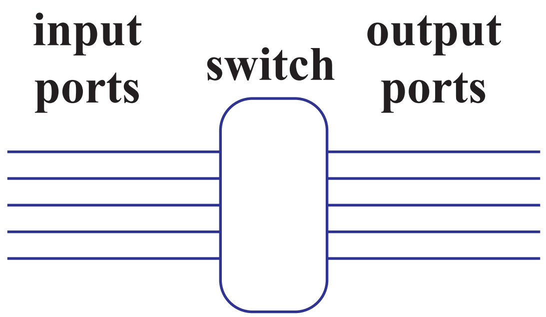
Population Oscillations
- Pumped Er-doped fiber with control beam to provide gain/delay.

Our Team:

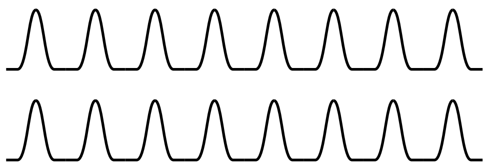
Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester

Slow Light and Optical Buffers

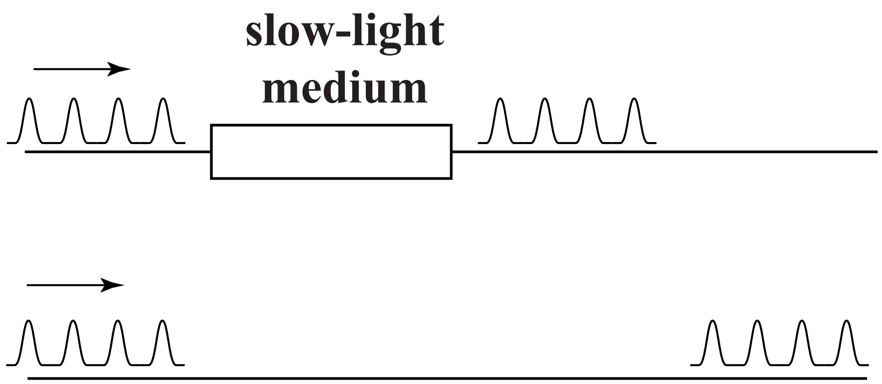
All-Optical Switch



But what happens if two data packets arrive simultaneously?



Use of Optical Buffer for Contention Resolution



Controllable slow light for optical buffering can dramatically increase system performance.

Challenge/Goal

Slow light in a room-temperature solid-state material.

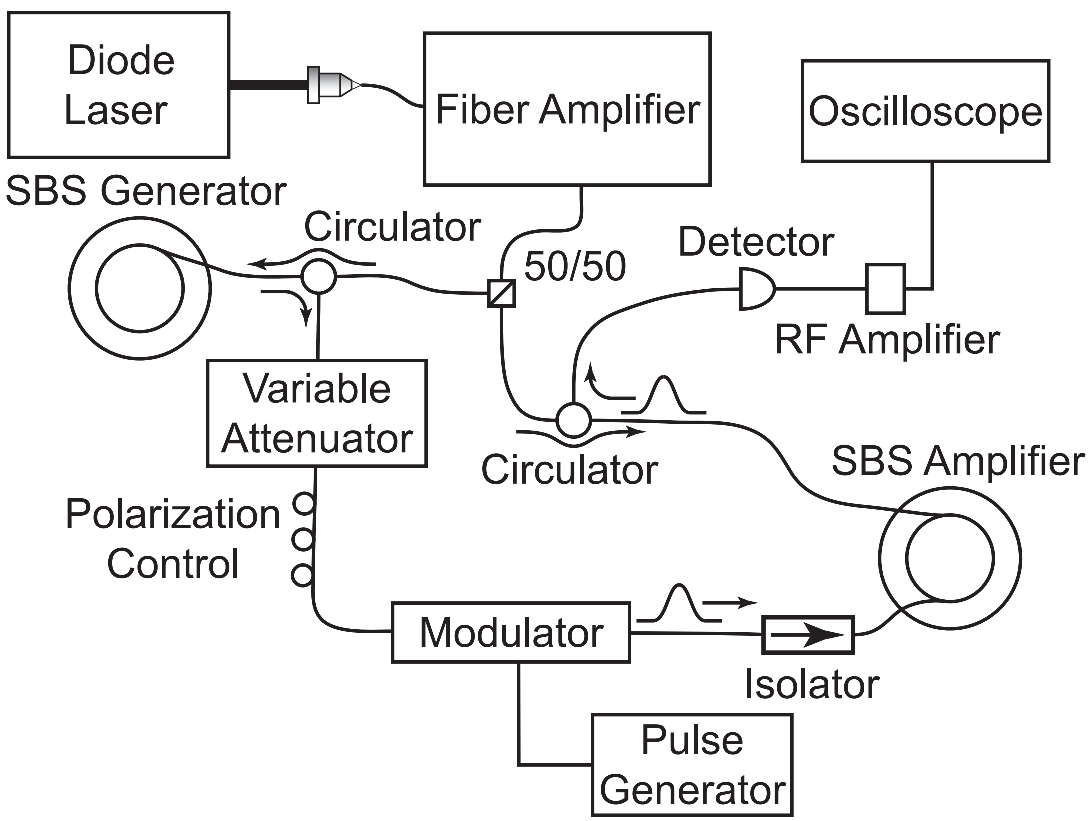
Our approaches:

1. Stimulated Brillouin Scattering
2. Stimulated Raman Scattering
3. Wavelength Conversion and Dispersion
4. Coherent Population Oscillations
    a. Ruby and alexandrite
    b. Semiconductor quantum dots (PbS)
    c. Semiconductor optical amplifier
    d. Erbium-doped fiber amplifier

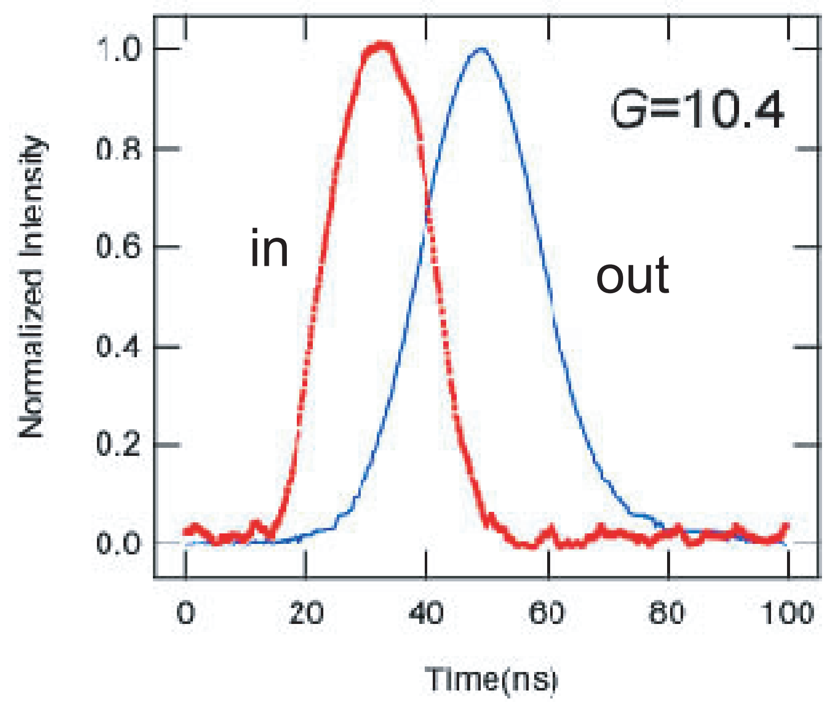
Also: application of slow-light to low-light-level switching

Slow-Light via Stimulated Brillouin Scattering

- Rapid spectral variation of the refractive response associated with SBS gain leads to slow light propagation
- Supports bandwidth of 100 MHz, large group delays
- Even faster modulation for SRS



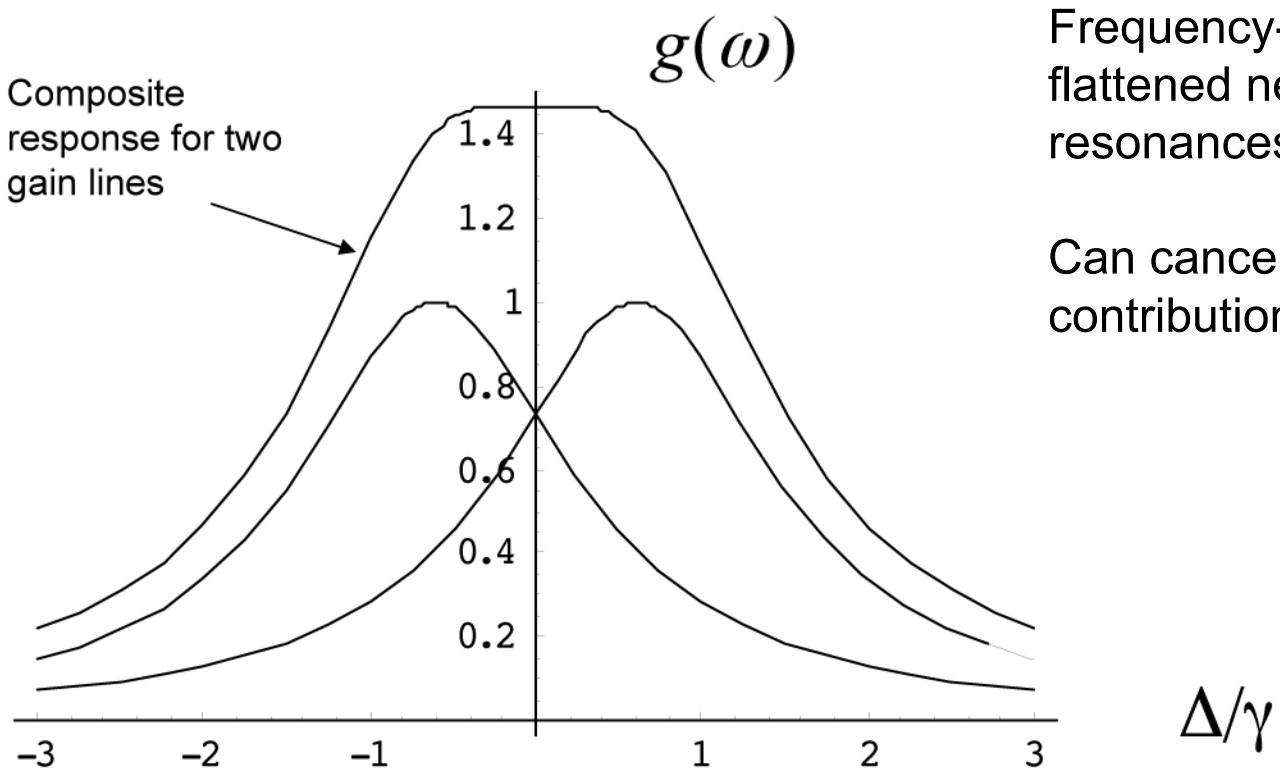
typical data



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).

Increasing the Bandwidth of a Slow Light Medium

Approach: Use two nearby Brillouin gain lines to flatten the response



Frequency-dependent gain flattened near center of resonances

Can cancel lowest-order contribution to pulse distortion

Generalized distortion definition

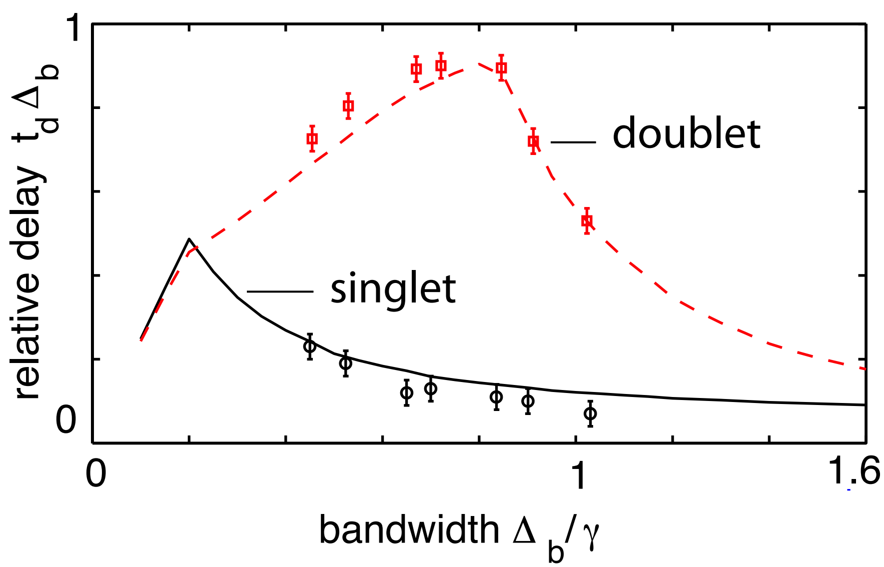
$$|t(\omega)| = A \times [1 + d_A(\omega)]$$

$$\arg t(\omega) = \phi_0 \times (\omega - \omega_0) \times [1 + d_\phi(\omega)]$$

Theoretical and Experimental Results

Constraints: maximum distortion < 0.05, peak gain of a single gain line: $g_0L<5$

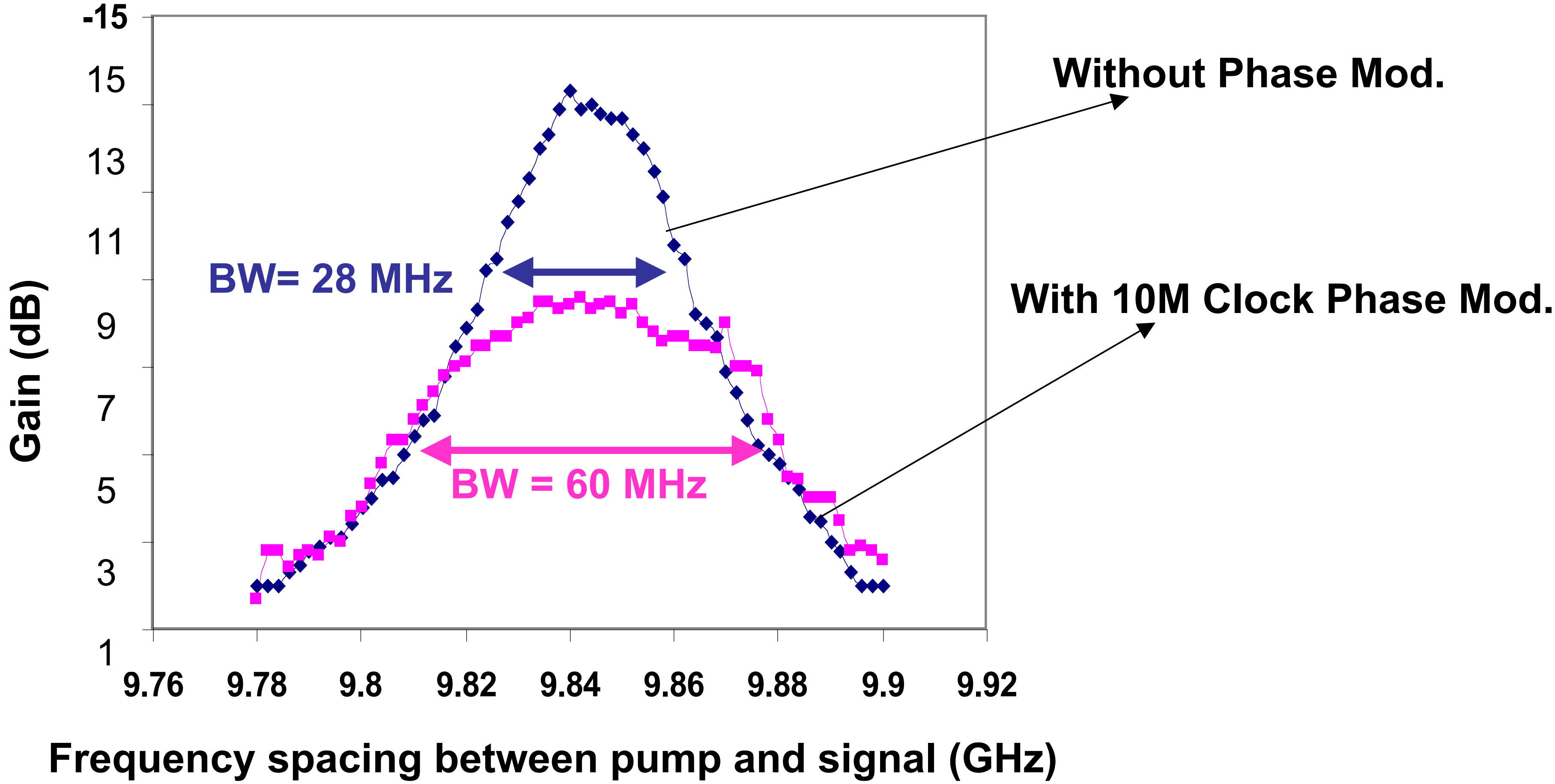
Comparison of compensated and uncompensated delay



- Maximum relative pulse delay of 0.53 at a distortion of 0.05.
- 9-fold improvement in relative pulse delay using two gain lines rather than one for a given distortion criterion.
- Delay accuracy at maximum delay: +/- 2% (corrected for detection system noise)
- Delay-Bandwidth Product of 0.23 at a distortion of 0.05
- 9-fold increase in Delay-Bandwidth product
- Bit rate at maximum delay: ~28 Mbits/s (assuming time slot is twice the FWHM pulse width)

Study of SBS Gain Spectrum Broadening

Expand the BW by phase modulating the pump

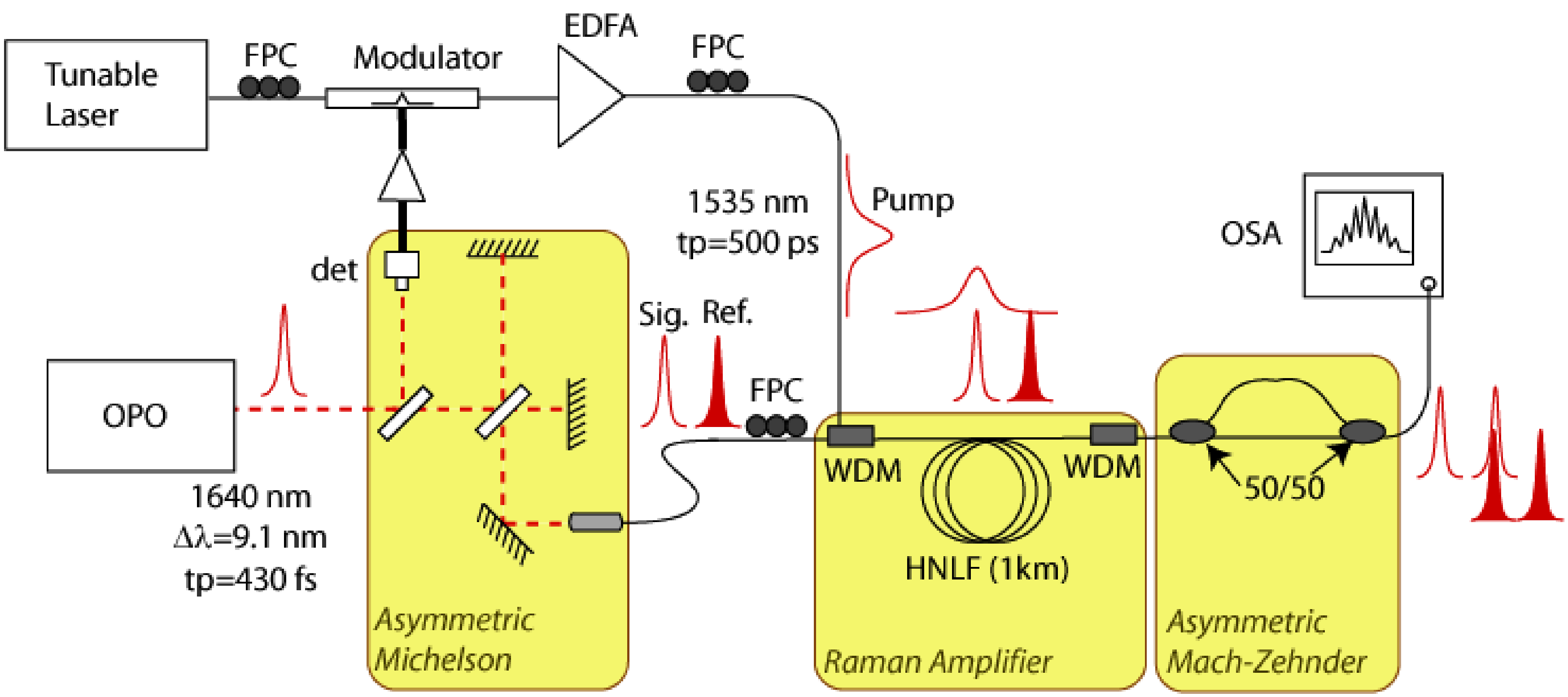


10 MHz clock phase modulating the pump

- Gain BW: 28 MHz → 60 MHz

Slow-Light by Stimulated Raman Scattering

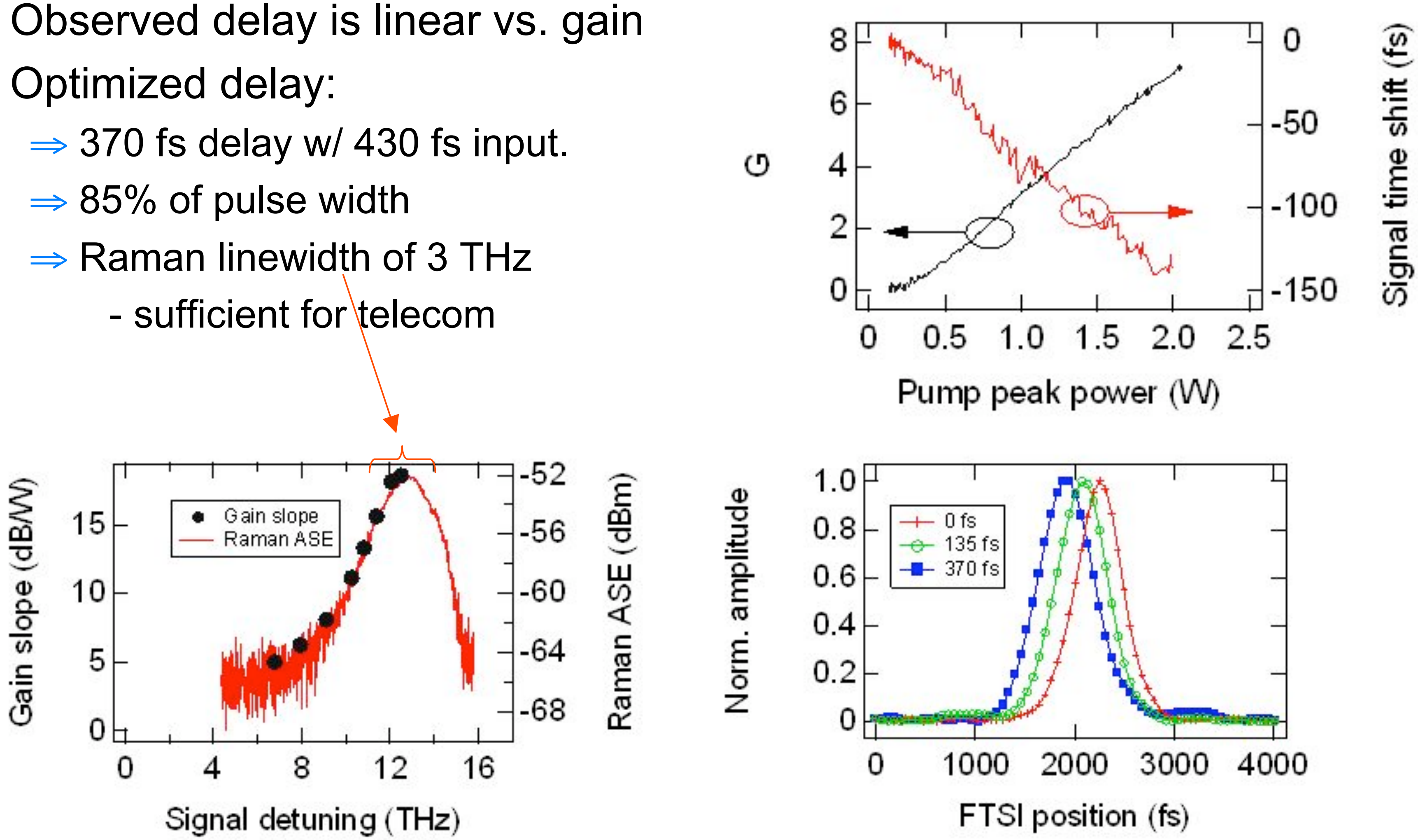
- The Raman linewidth (~3 THz) is much greater than that of Brillouin.
- Co- or counter-propagating configurations can be used.
- Spectral interferometry between test and reference pulses is used (10 fs delay resolution at low peak power) to measure delays.



Alex Gaeta, Cornell

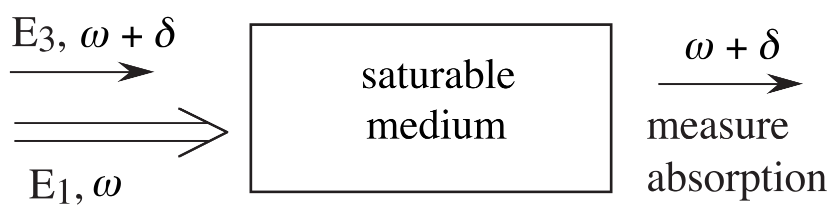
SRS Delay Results

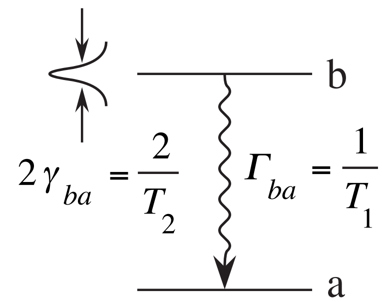
- Observed delay is linear vs. gain
- Optimized delay:
  - ⇒ 370 fs delay w/ 430 fs input.
  - ⇒ 85% of pulse width
  - ⇒ Raman linewidth of 3 THz
    - sufficient for telecom

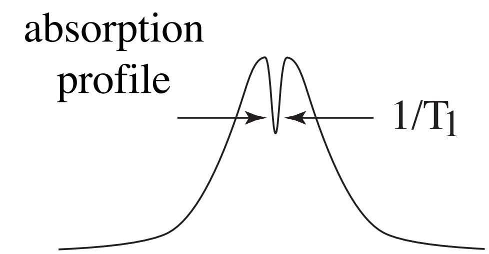


J. E. Sharping, Y. Okawachi, and A. L. Gaeta, "Wide bandwidth slow light using a Raman fiber amplifier," *Opt. Express* **13**, 6092 (2005).

Slow Light via Coherent Population Oscillations



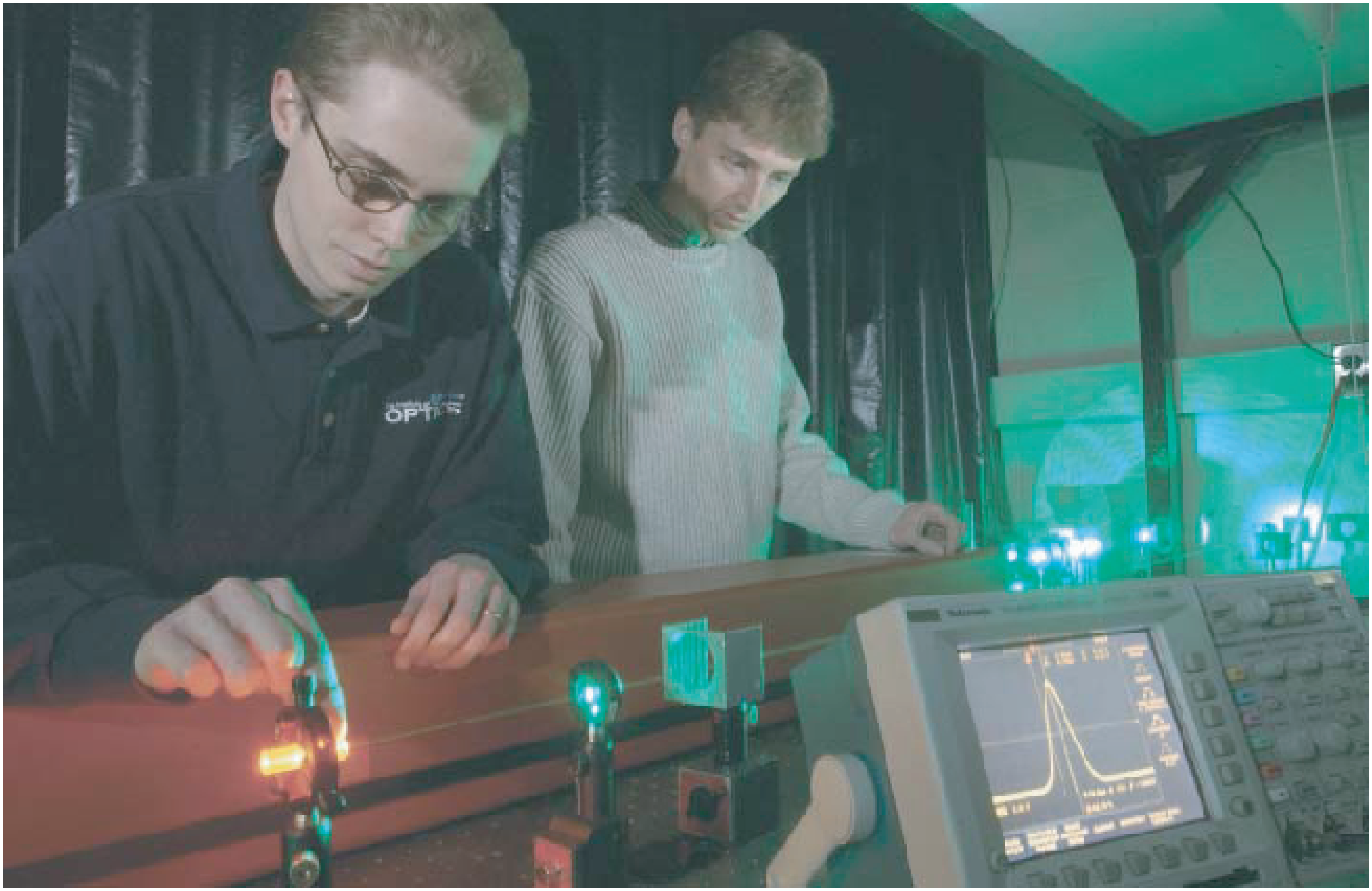




- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Rapid spectral variation of refractive index associated with spectral hole leads to large group index.
- Ultra-slow light ($n_g > 10^6$) observed in ruby and ultra-fast light ($n_g = -4 \times 10^5$) observed in alexandrite by this process.
- Slow and fast light effects occur at room temperature!

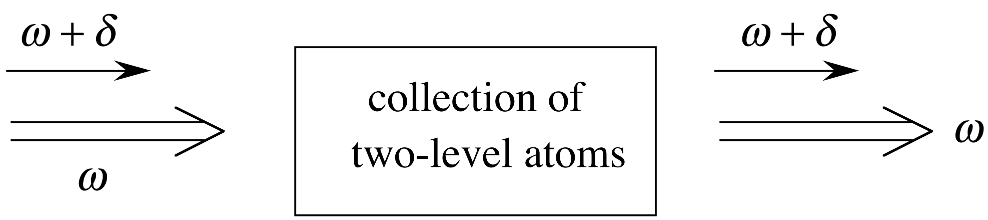
PRL 90,113903(2003); Science, 301, 200 (2003)

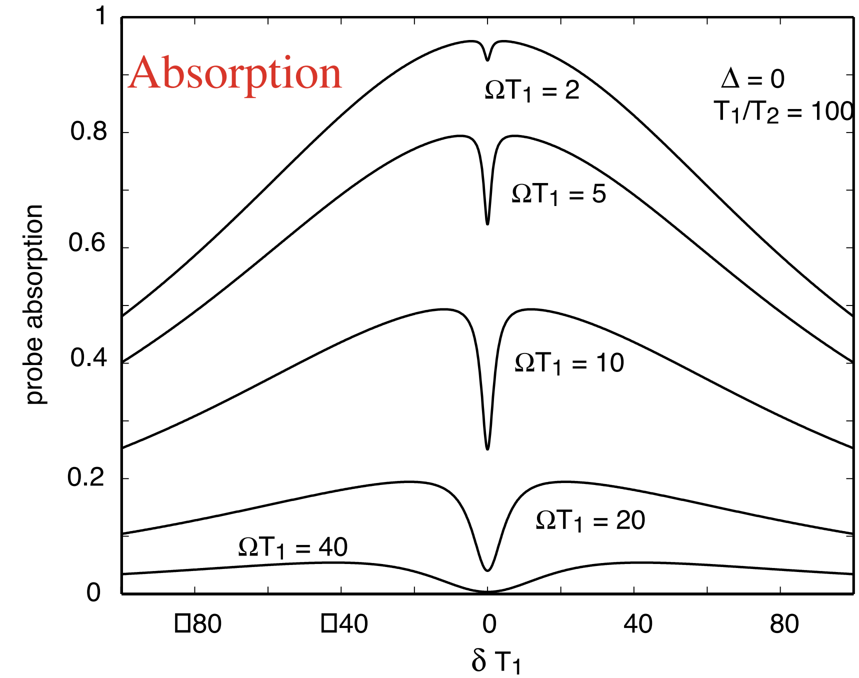
Demonstration of slow light in a room temperature solid.



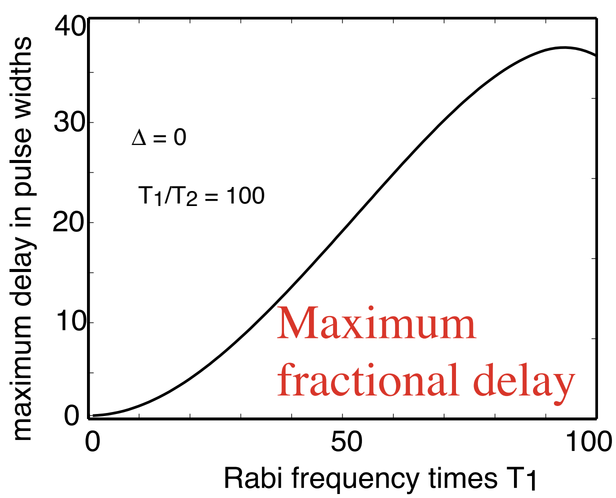
PRL 90,113903 (2003)

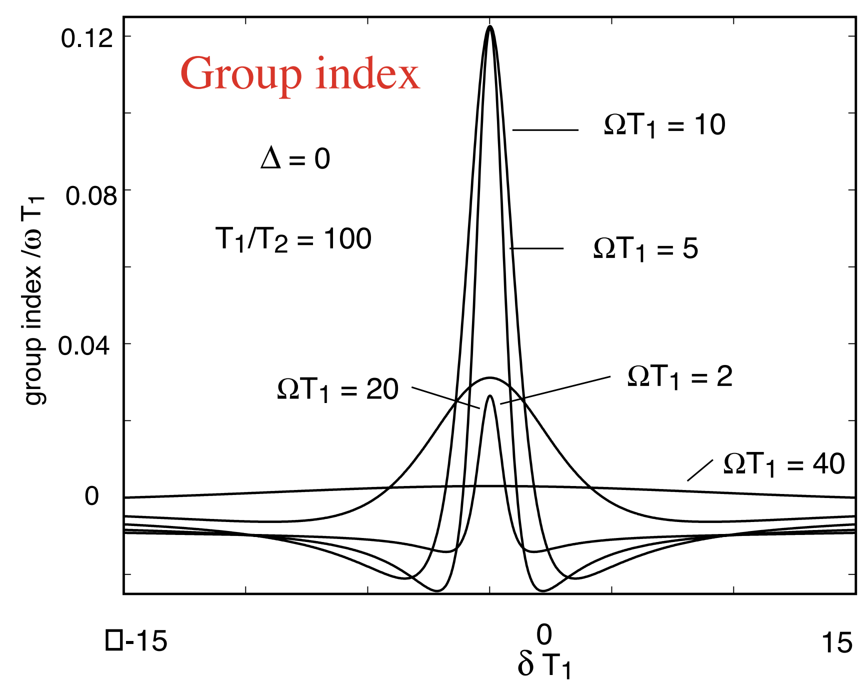
Prospects for Large Fractional Delays Using CPO





Strong pumping leads to high transparency, large bandwidth, and increased fractional delay.





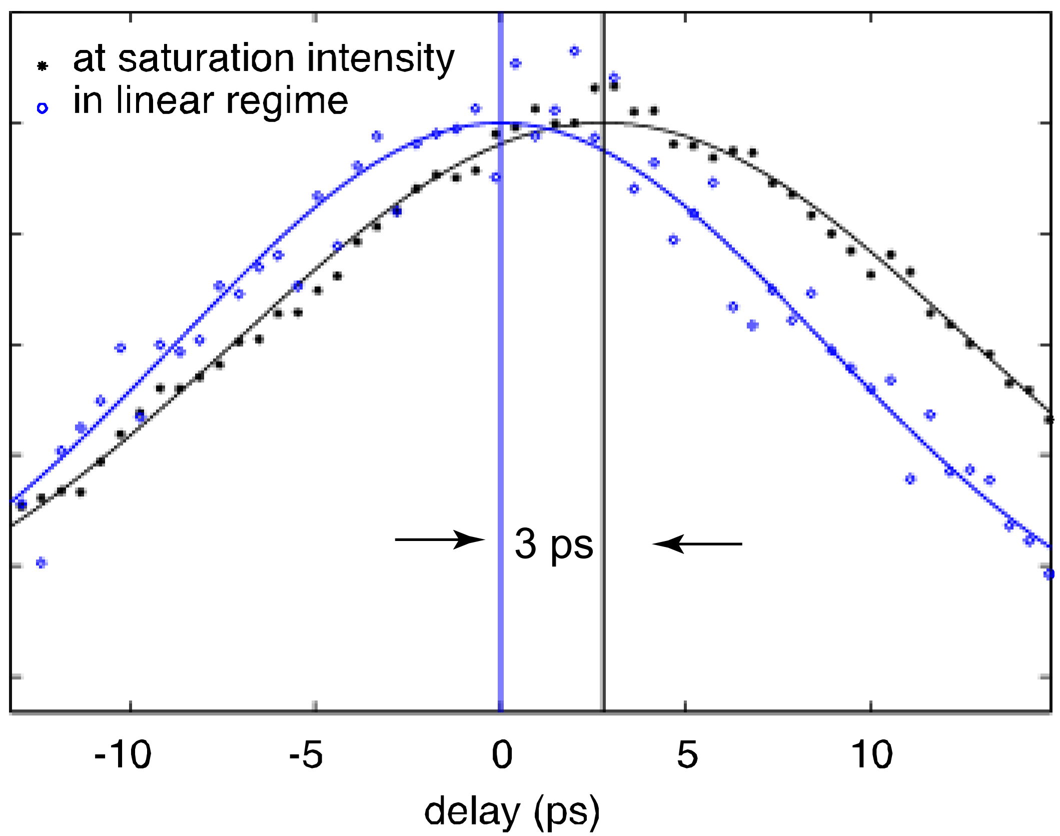
Boyd et al., Laser Physics 2005.

Slow Light in SC Quantum Dot Structures

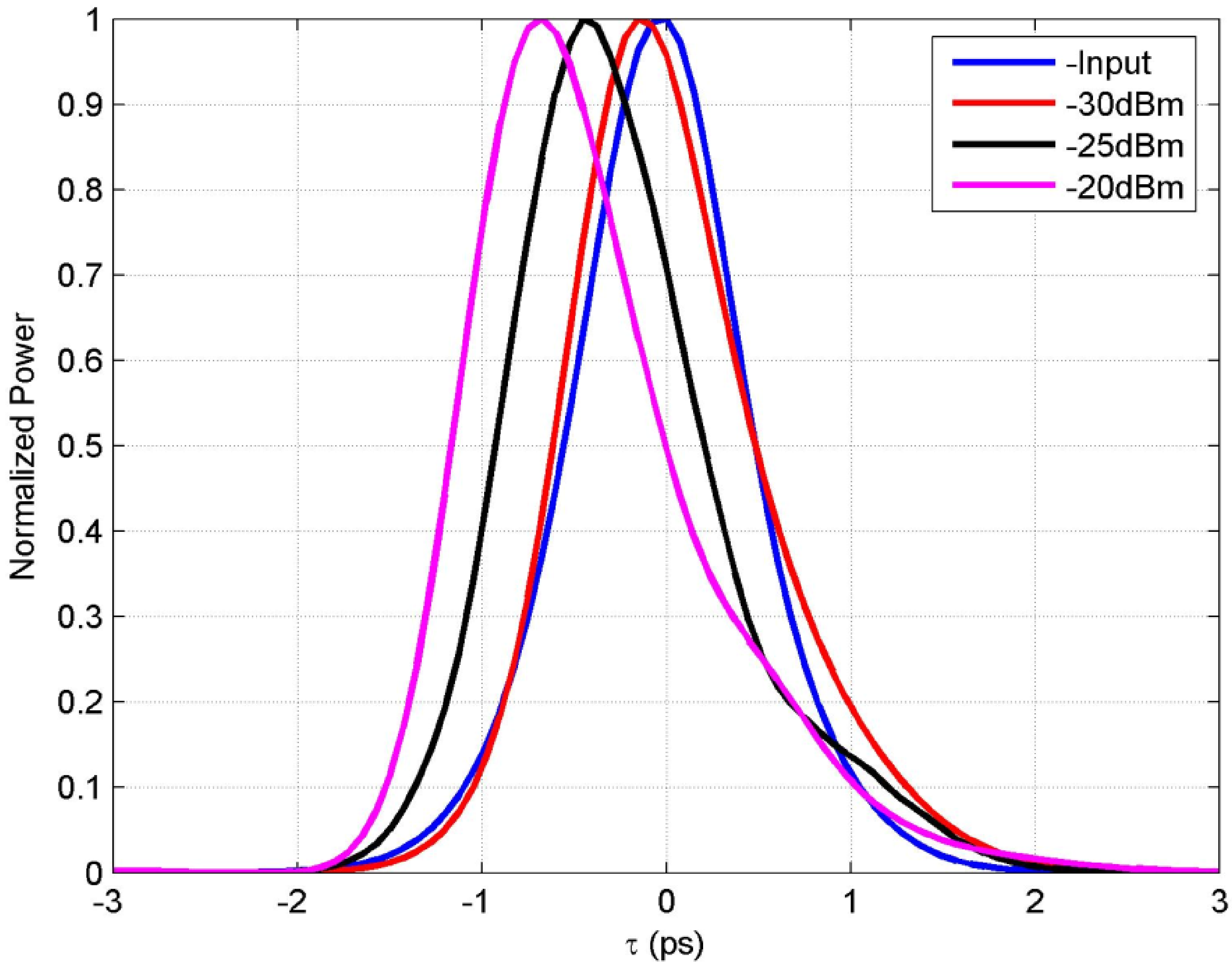
PbS Quantum Dots (2.9 nm diameter) in liquid solution

Excite with 16 ps pulses at 795 nm; observe 3 ps delay

30 ps response time (literature value)

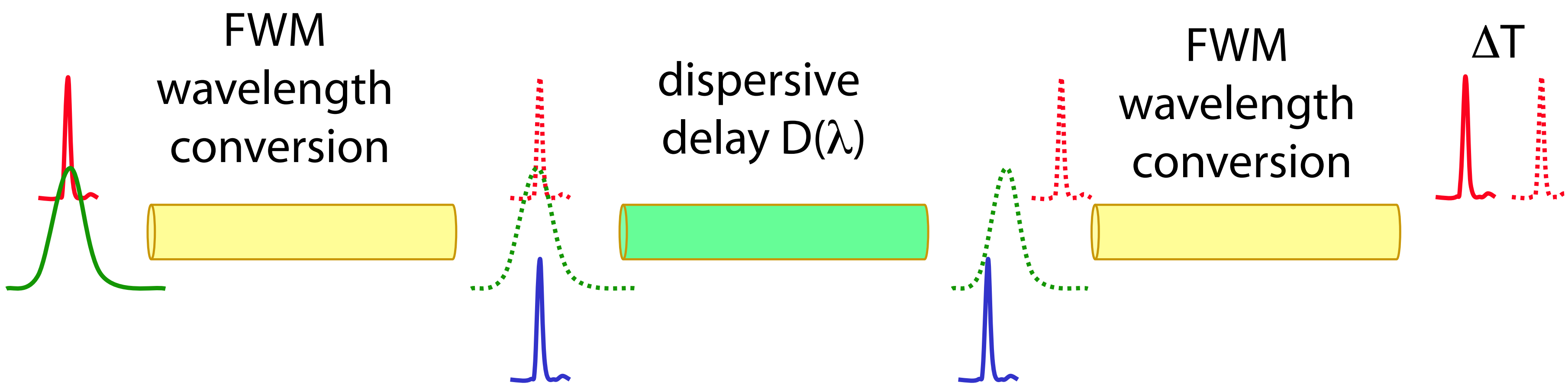


Pulse Propagation in a Semiconductor Optical Amplifier



Dan Blumenthal, UCSD

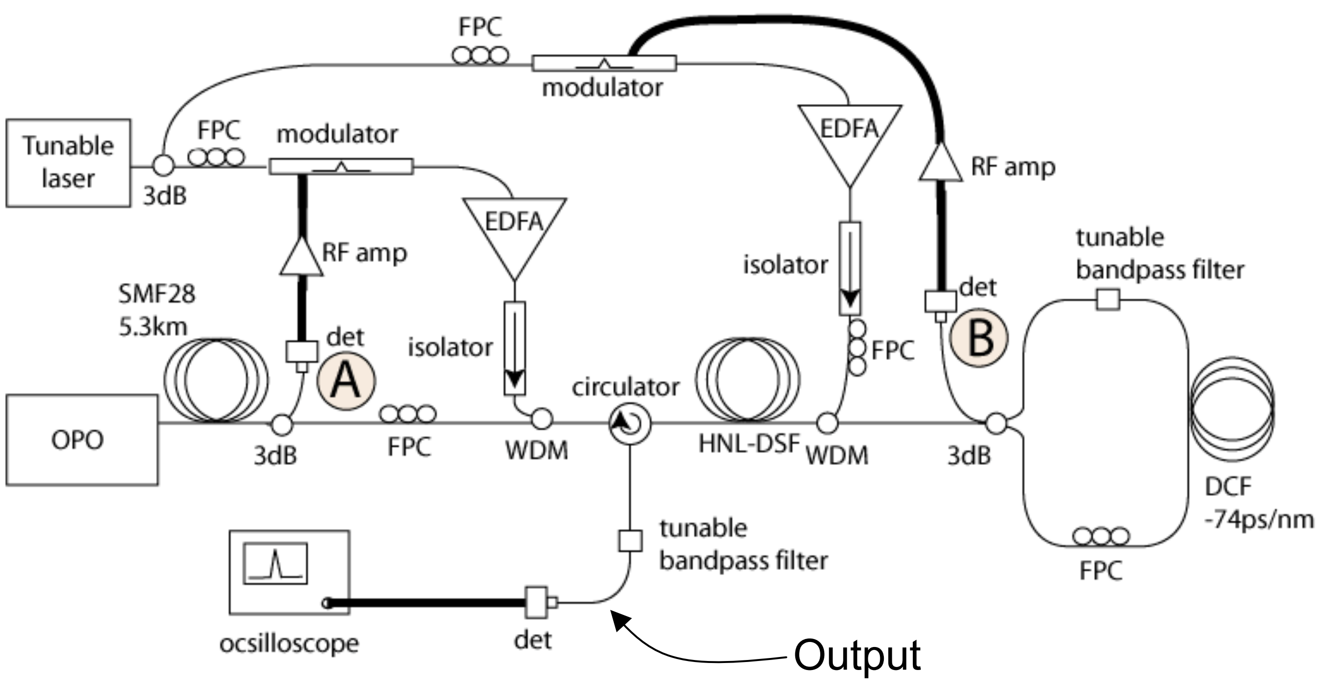
FWM-Dispersion Delay Scheme - Principle of Operation



- $\Delta T = 2\, D(\lambda)\, (\lambda_s - \lambda_p)$
- Pulsed pump ~500 ps

FWM Experiment

- Signal ~10 ps duration.
- Both pumps are derived from same CW laser.
- Dispersion pre-compensation.
- Conversion in forward direction, re-conversion in reverse.
- Delay is tuned by changing the pump wavelength.

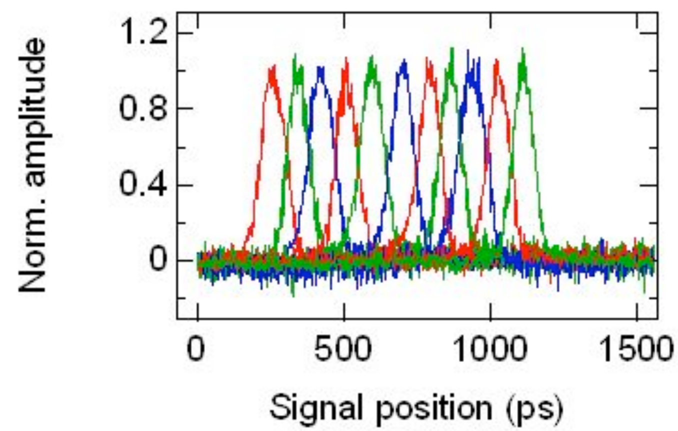


Experimental setup

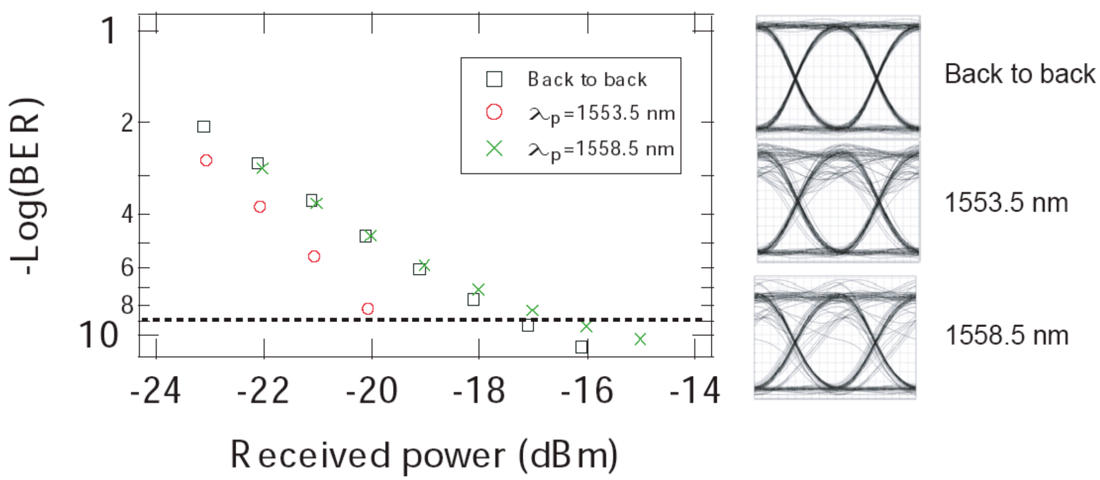
FWM-Dispersion Delay Results

- Results:
  - ⇒ 800 ps of delay
  - ⇒ Pulse quality is preserved
  - ⇒ No wavelength shift
  - ⇒ Phase information is preserved
  - ⇒ 10 Gb/s simulation implies a 3-dB received power penalty

Measured, delayed pulses



Results of 10 Gb/s simulation (w/ Willner group)



J. E. Sharping, Y. Okawachi, J. van Howe, C. Xu, Y. Wang, A. E. Willner, and A. L. Gaeta, "All-optical wavelength and bandwidth-preserving pulse delay based on parametric wavelength conversion and dispersion," submitted to *Opt. Express* (2005).

Summary

Slow-light techniques hold great promise for applications in telecom and quantum information processing

Good progress being made in devloping new slow-light techniques and applications

Different methods under development possess complementary regimes of usefullness

Thank you for your attention.

And thanks to NSF and DARPA for financial support!

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