Limits on the Time Delay Induced by Slow-Light Propagation

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See also Phys. Rev. A 71, 023801 (2005)

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.

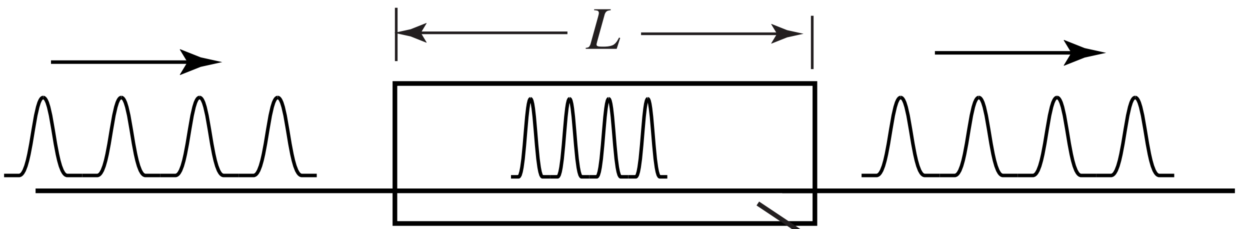
Key figure of merit:
normalized time delay = total time delay / input pulse duration
≈ information storage capacity of medium

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

But data packets used in telecommunications contain ≈ 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: $$n_g = n + \omega \frac{dn}{d\omega}$$

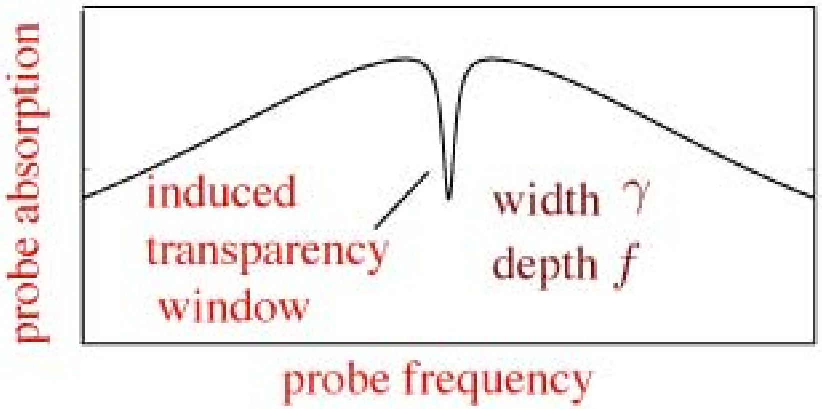
group delay: $$T_g = \frac{L}{v_g} = \frac{L n_g}{c}$$

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

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

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

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

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

normalized induced delay (T_0 = pulse width)

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

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

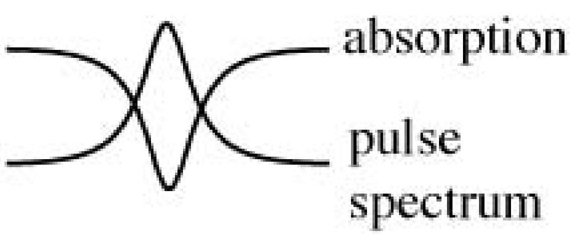
$$L_{\rm max} = 2\gamma^3 T_0^3 / 3f\alpha_0 \qquad \text{and} \qquad \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{1}{3}\gamma^2 T_0^2.$$

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

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

which has no upper bound.

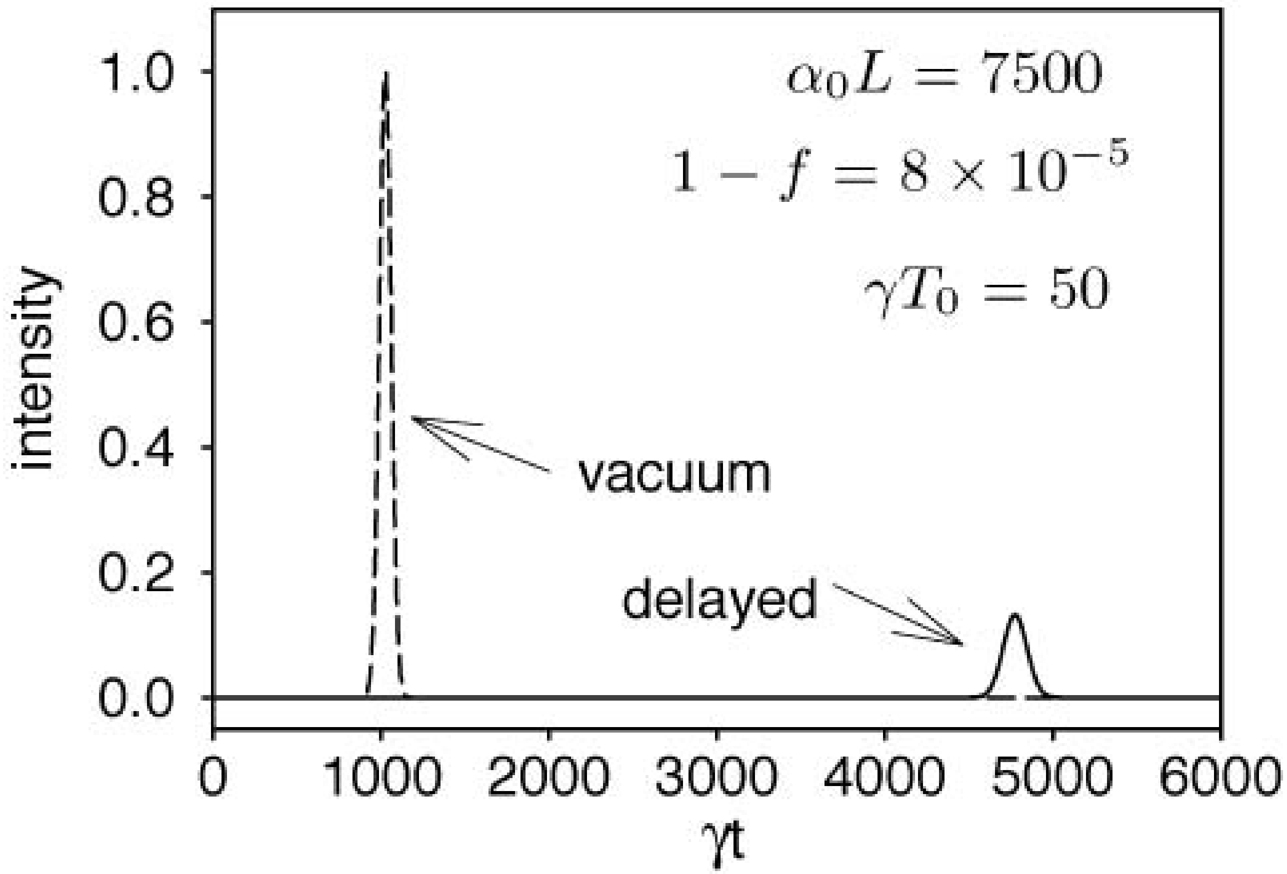
- But to achieve this time delay, one needs a large initial (before saturation) optical depth given by

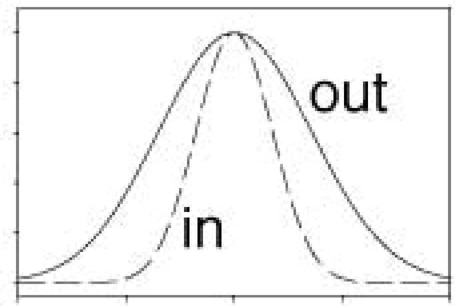
$$\alpha_0 L = (4/3)(T_{\text{del}}/T_0)^2_{\text{max}}.$$

- 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

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

Numerical Example Showing Large Relative Delay

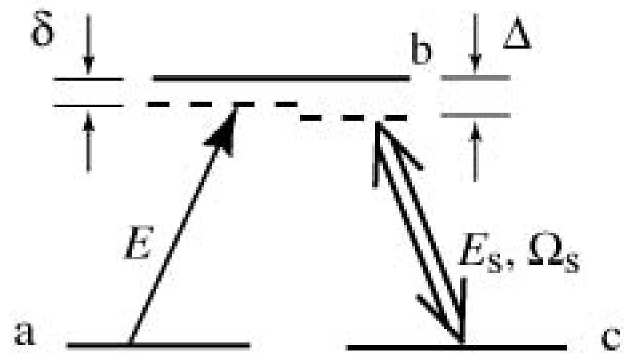




Factor-of-two pulse spreading

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

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.

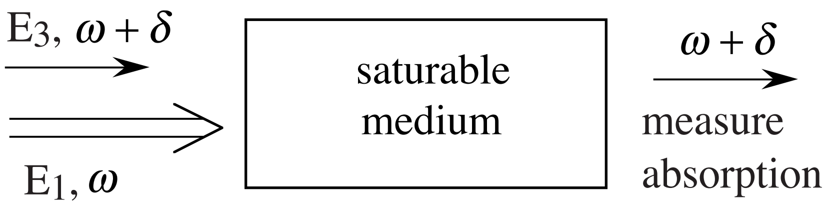
Another recent study [2] reaches a more pessimistic (although entirely mathematically consistent) conclusion by stressing the severity of residual absorption, especially in the presence of Doppler broadening.

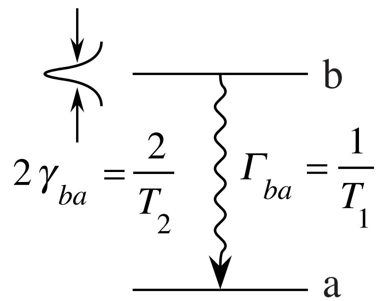
Our challenge is to minimize residual absorption.

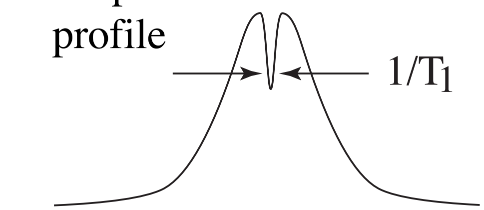
[1] Boyd, Gauthier, Gaeta, and Willner, Phys. Rev. A 71, 023801, 2005.

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

Slow Light via Coherent Population Oscillations



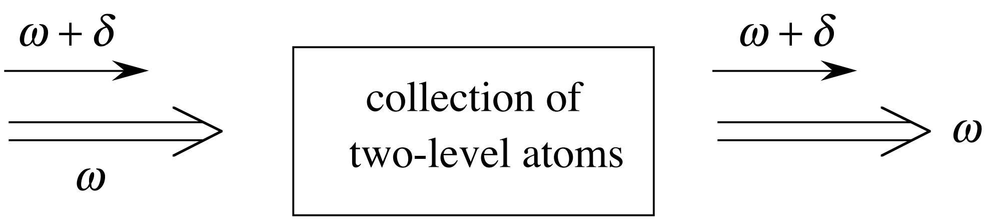


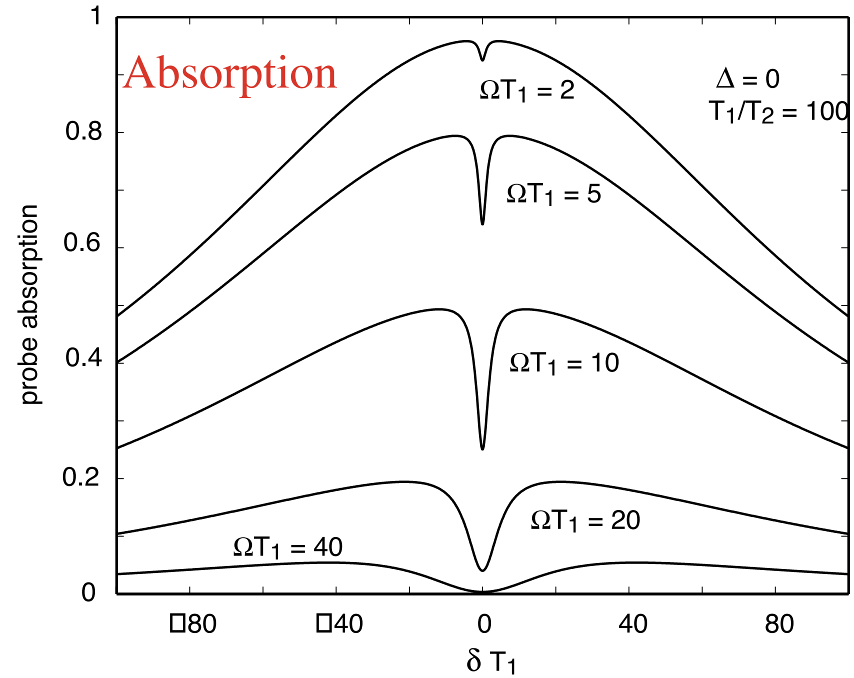


- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Rapid spectral variation of refractive index associated with spectral hole leads to large group 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!

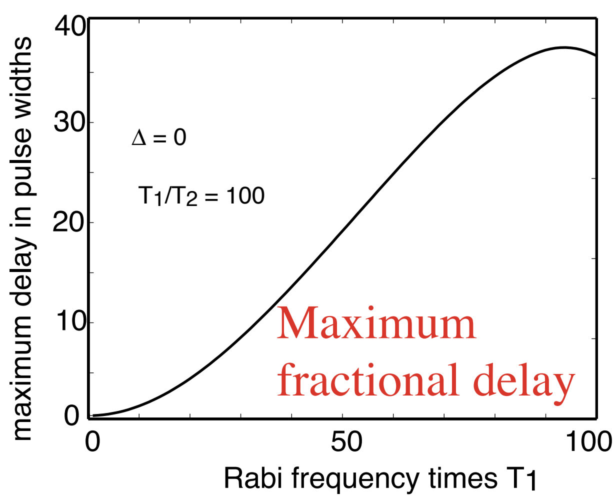
PRL 90,113903(2003); Science, 301, 200 (2003)

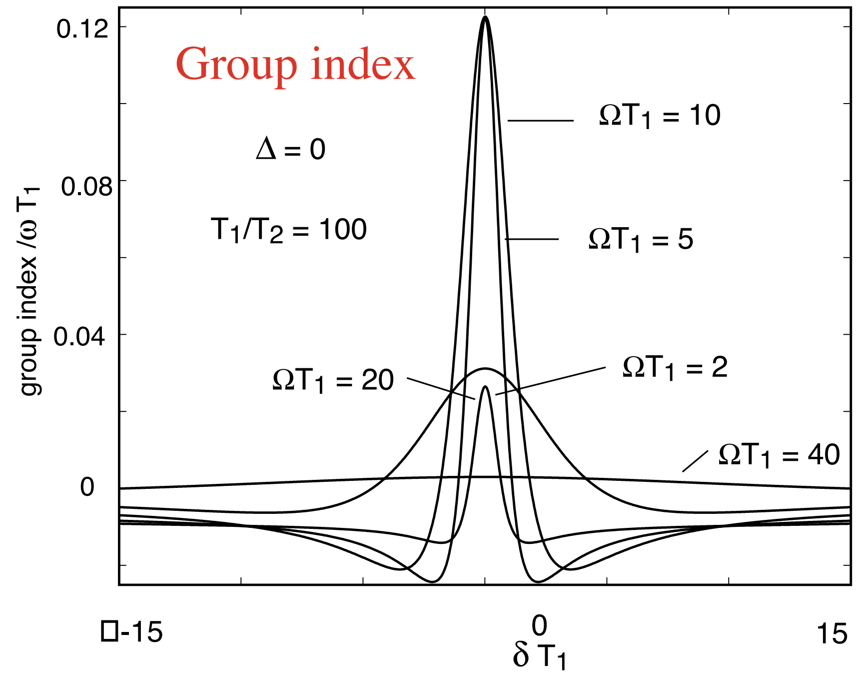
Prospects for Large Fractional Delays Using CPO





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





Boyd et al., Optics Express 2005.

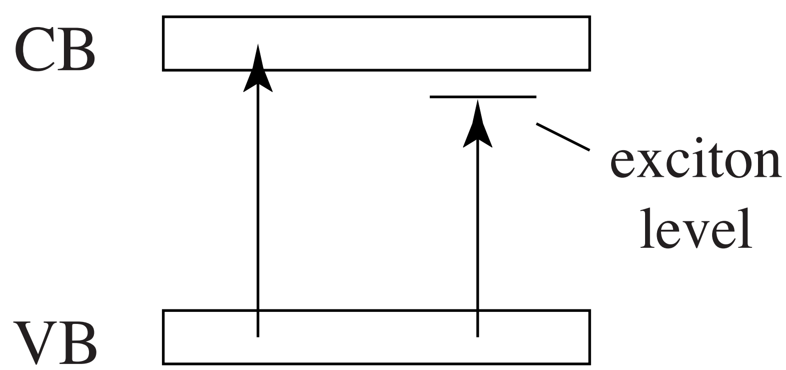
Materials for Large Fractional Delays Using CPO

Material systems under considerations:

Semiconductors (SC), SC heterostructures, dye molecules, atomic vapors.

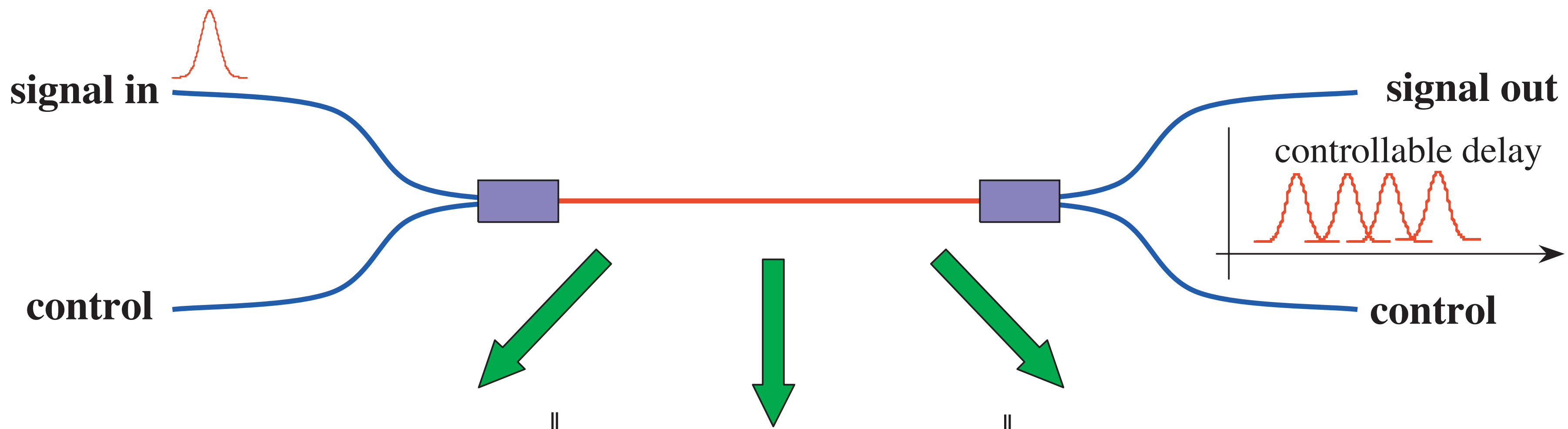
UC Berkeley group has seen slow light in SC heterostructures (but only at low temperatures) by using an excitonic transition.*

We are presently studying CPO in band-to-band transitions in a SC quantum well structure. We believe that for this system CPO and slow light will persist at room temperature.

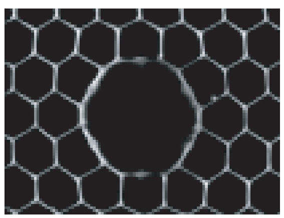


* Ku et al., Optics Letters, 29, 2291 (2004).

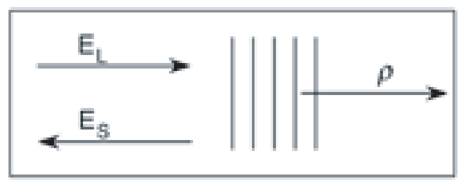
DARPA/DSO Project on Applications of Slow Light in Optical Fibers



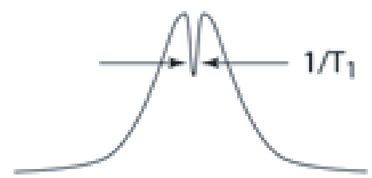
3 Approaches:



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



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



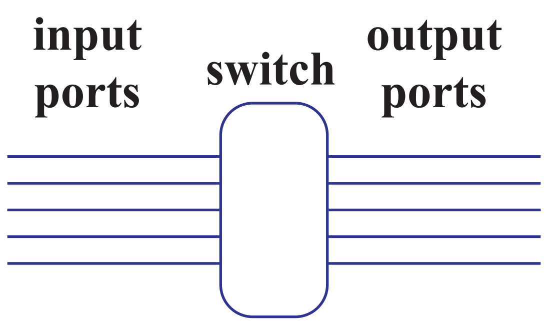
Population Oscillations
- Pumped Er-doped fiber with control beam to provide gain/delay.

Our Team:

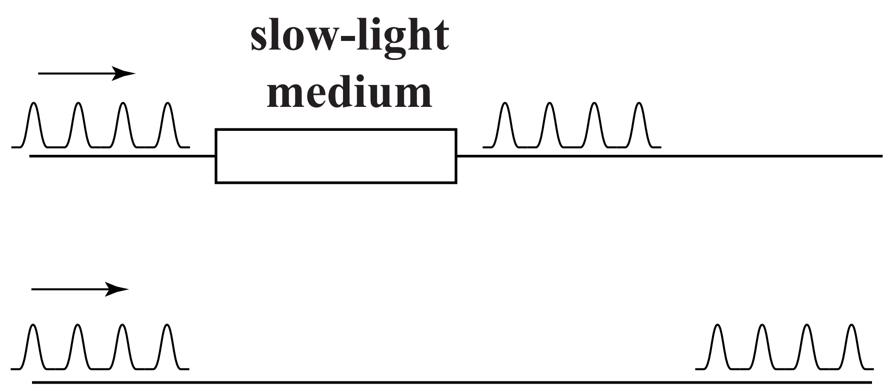
Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester

Slow Light and Optical Buffers

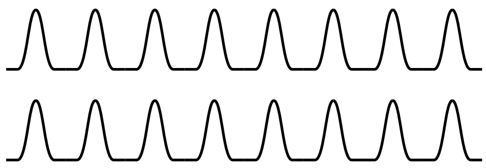
All-Optical Switch



Use of Optical Buffer for Contention Resolution



But what happens if two data packets arrive simultaneously?



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

Summary

There are no *fundamental* limitations to the maximum normalized pulse delay.

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

Exciting possibilities exist for optical buffering and other photonics applications if normalized time delays in the range of 10 – 1000 can be achieved.

Thank you for your attention.

And thanks to NSF and DARPA for financial support!