Applications of Slow Light

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with special thanks to George M. Gehring, Andreas Liapis, Aaron Schweinsberg, Zhimin Shi, and Joseph E. Vornehm, Jr.

Presented at Photonics West, January 27, 2009.

Overview of Presentation: Applications of Slow Light

– Light can be made to go:

slow: $v_g << c$
fast: $v_g > c$
backwards: v_g negative

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

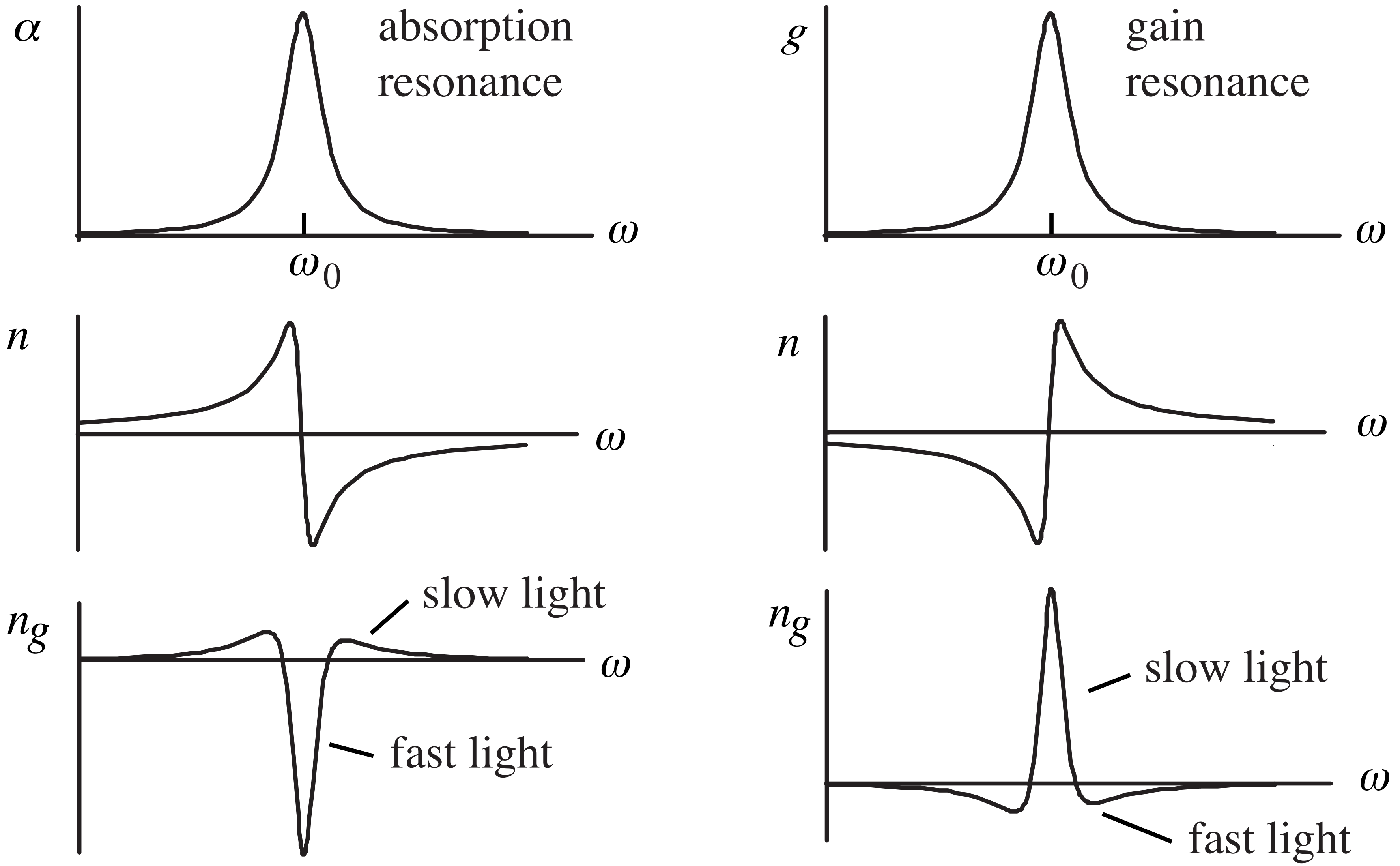
– Controllable light velocity leads to many applications

buffers / regenerators for optical telecommunications
interferometers with novel properties
phased and synchronized arrays for beam steering

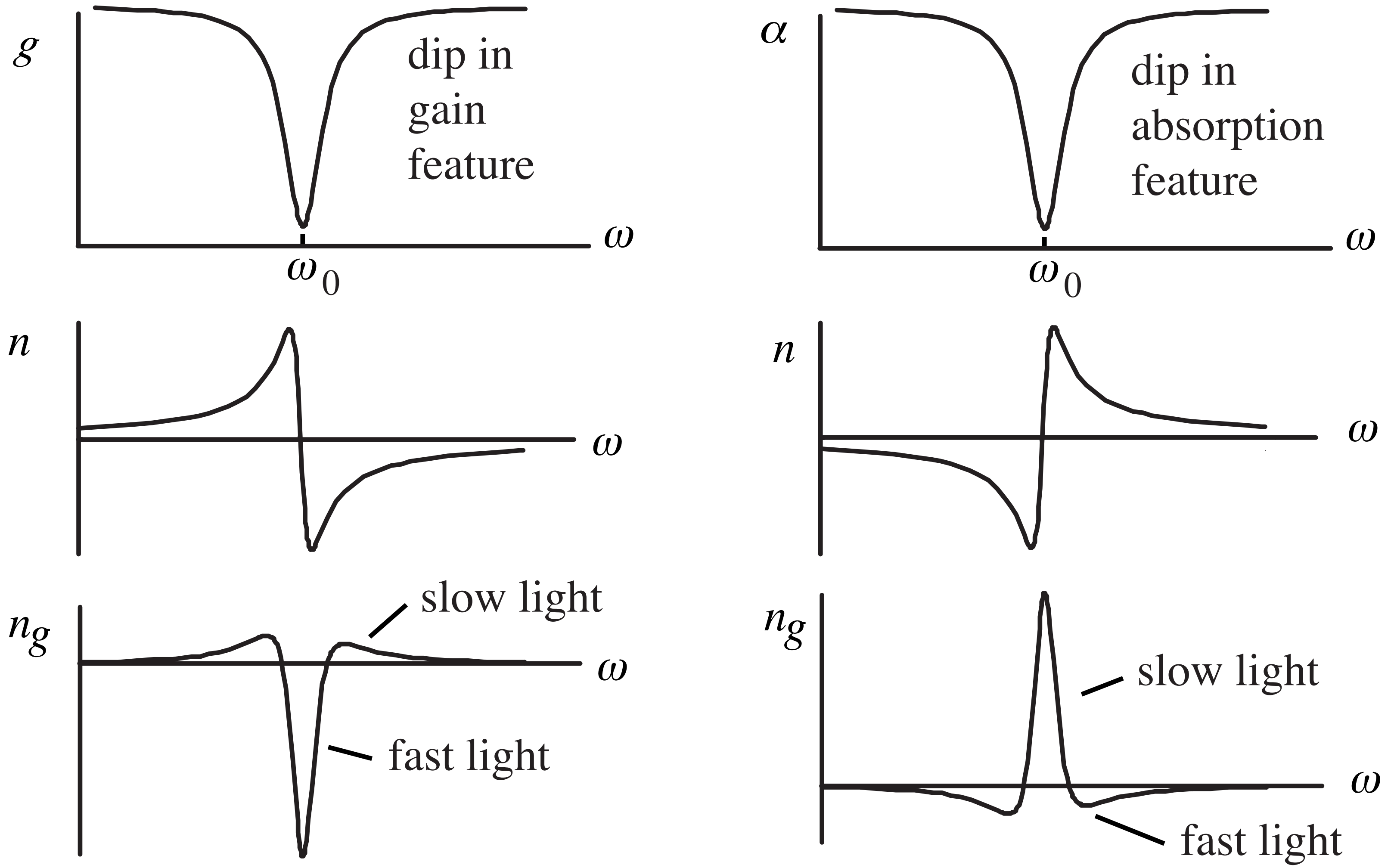
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

Slow Light Fundamentals: How to Create Slow and Fast Light I

Use Isolated Gain or Absorption Resonance



How to Create Slow and Fast Light (Better) – Use a Dip in a Gain or Absorption Feature



Narrow dips in gain and absorption lines can be created by various nonlinear optical effects, such as electromagnetically induced transparency (EIT), coherent population oscillations (CPO), and conventional saturation.

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

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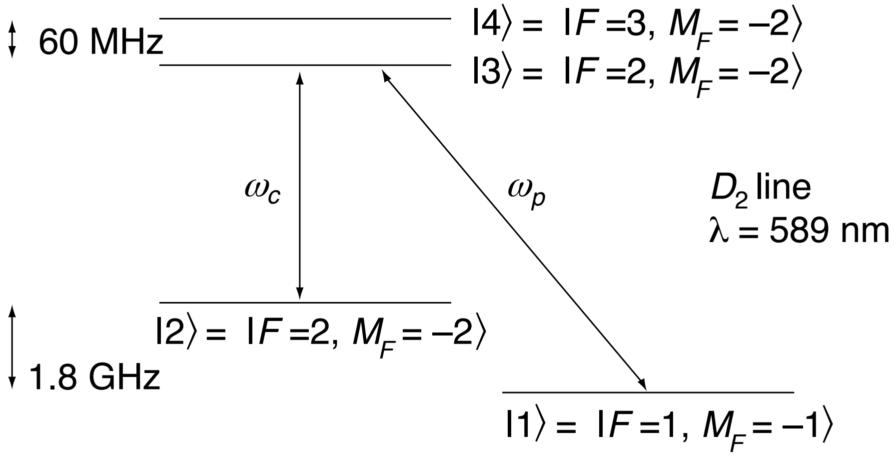
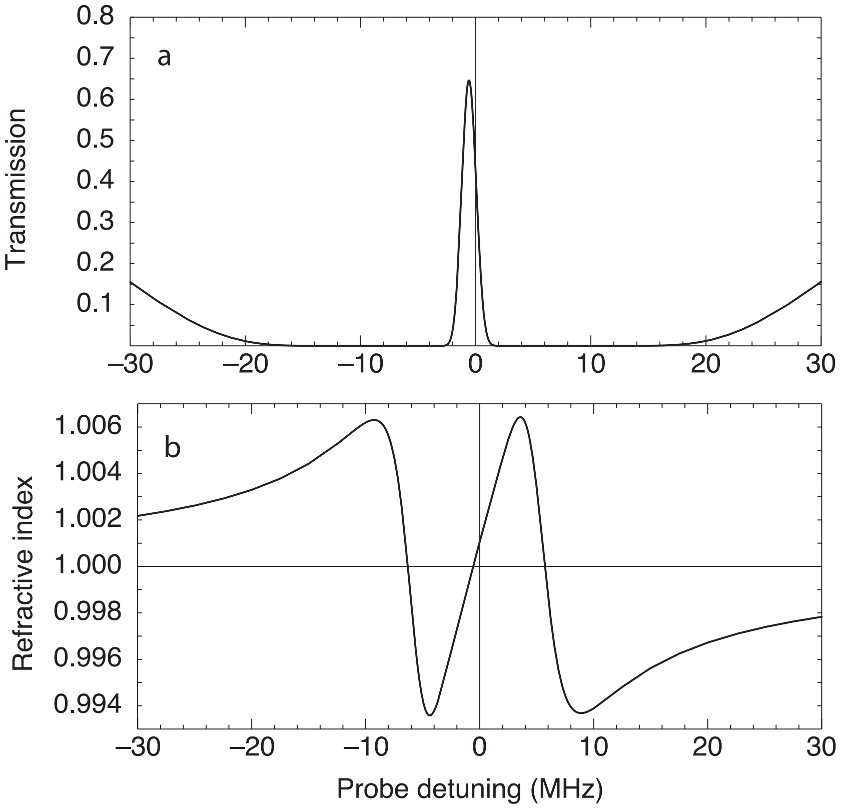
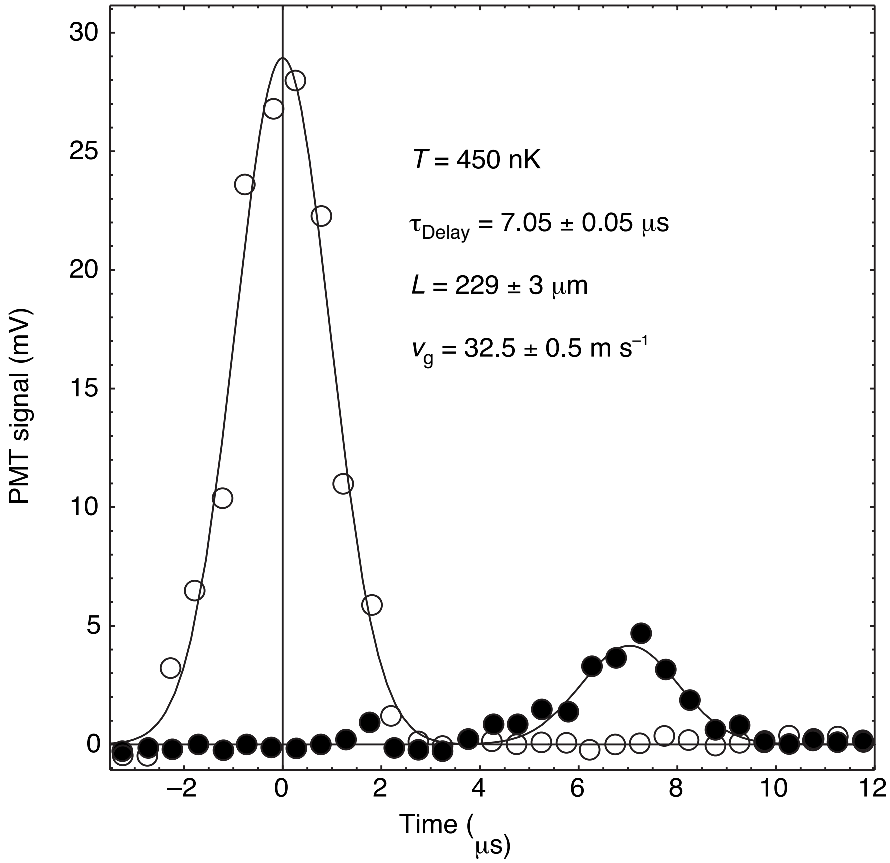
NATURE | VOL 397 | 18 FEBRUARY 1999 |www.nature.com







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 three preferred methods for producing slow light

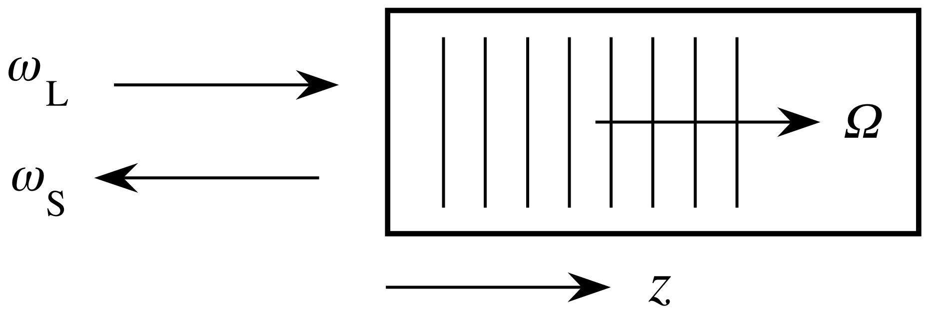
(1) Slow light *via* stimulated Brillouin scattering (SBS)

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

(3) Dispersive slow light (conversion/dispersion) (C/D)

Slow Light by Stimulated Brillouin Scattering (SBS)

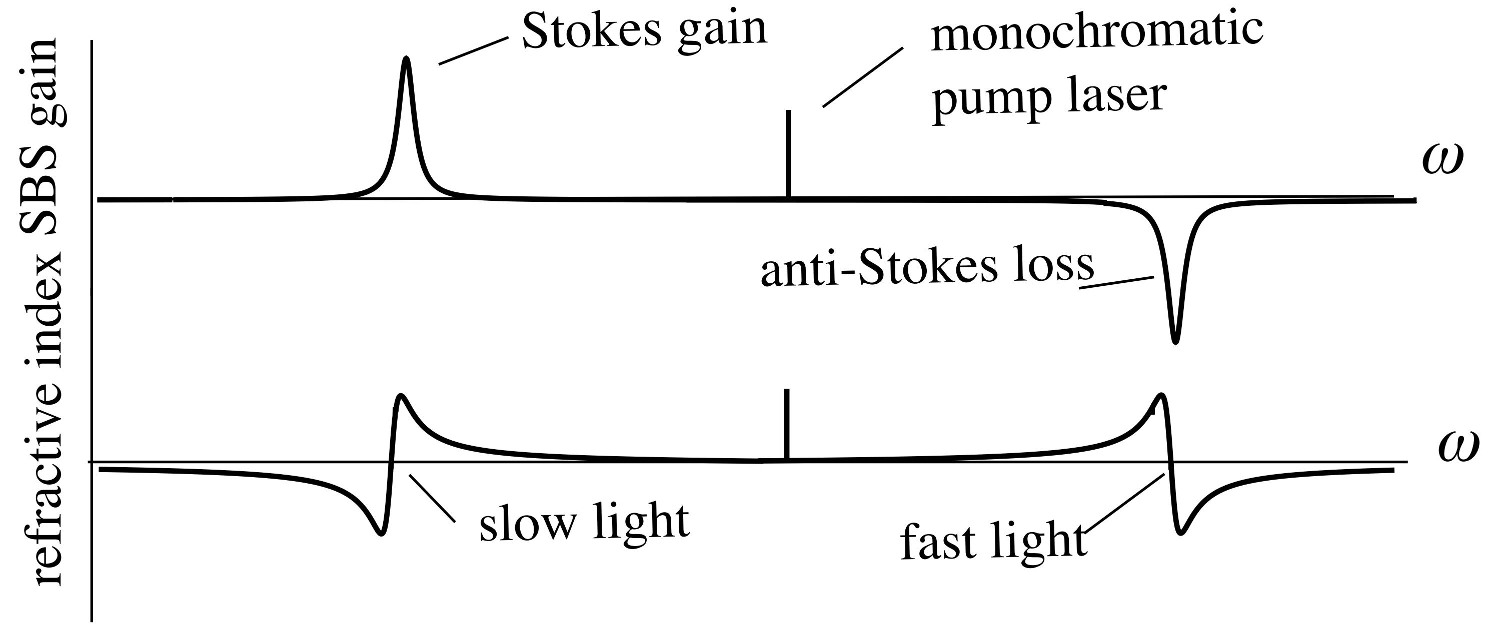
$$\omega_S = \omega_L - \Omega$$



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

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

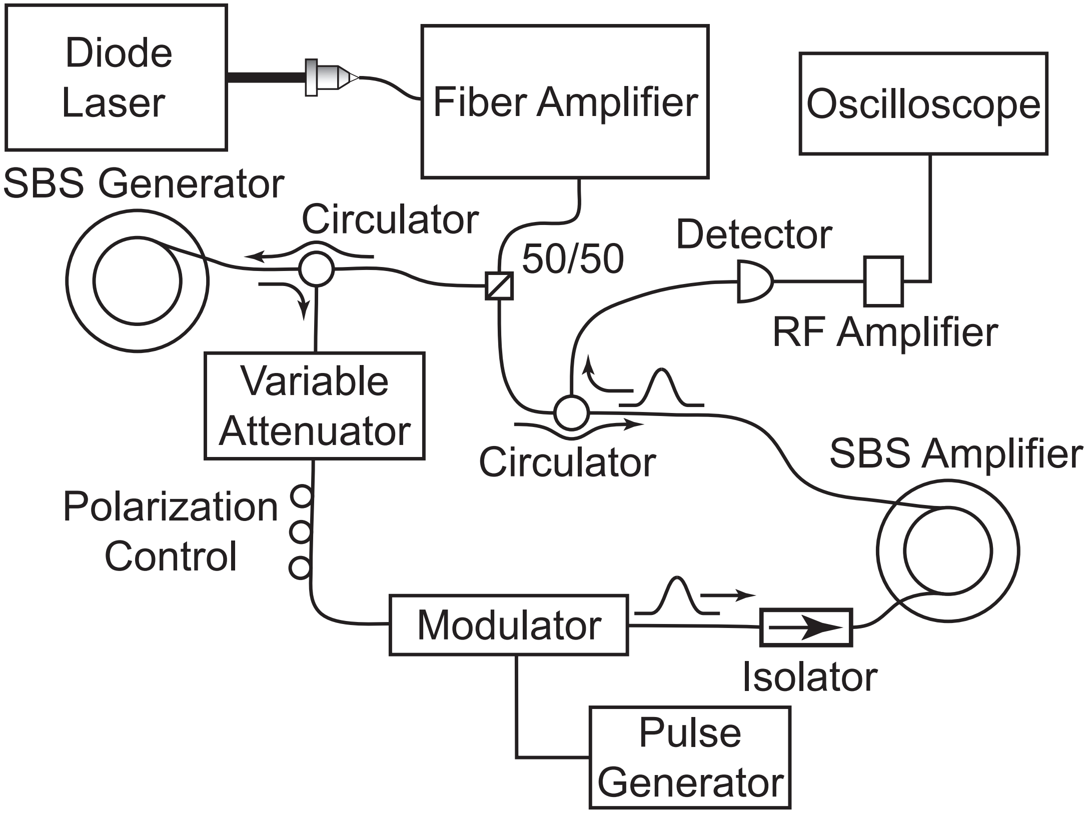
We often think of SBS as a pure gain process, but it also leads to a change in refractive index



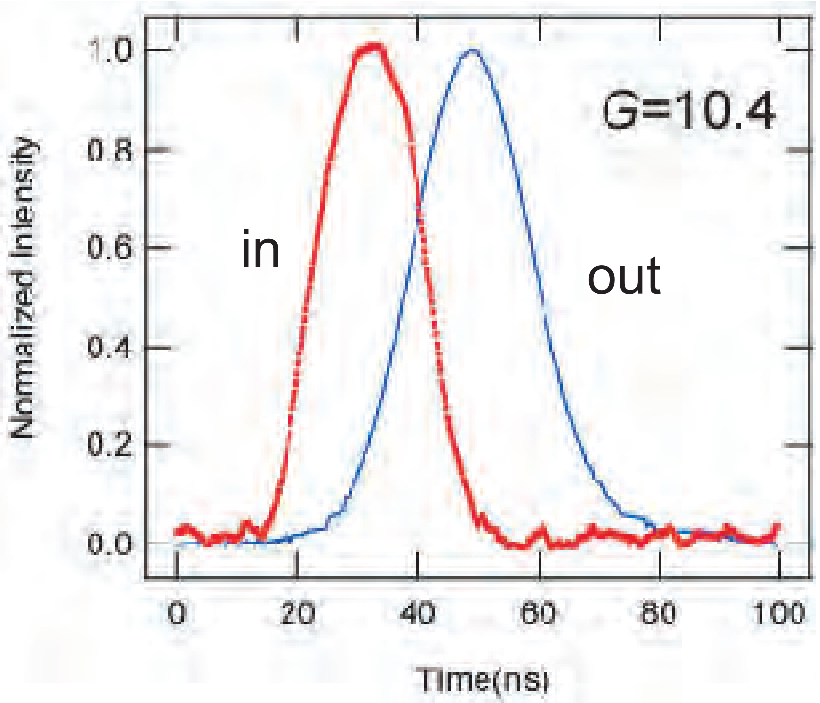
The induced time delay is $\Delta T_\mathrm{d} \approx \dfrac{G}{\Gamma_\mathrm{B}}$ where $G = g\,I_\mathrm{p}\,L$ and Γ_B is the Brillouin linewidth

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 30 – 100 MHz, large group delays



typical data

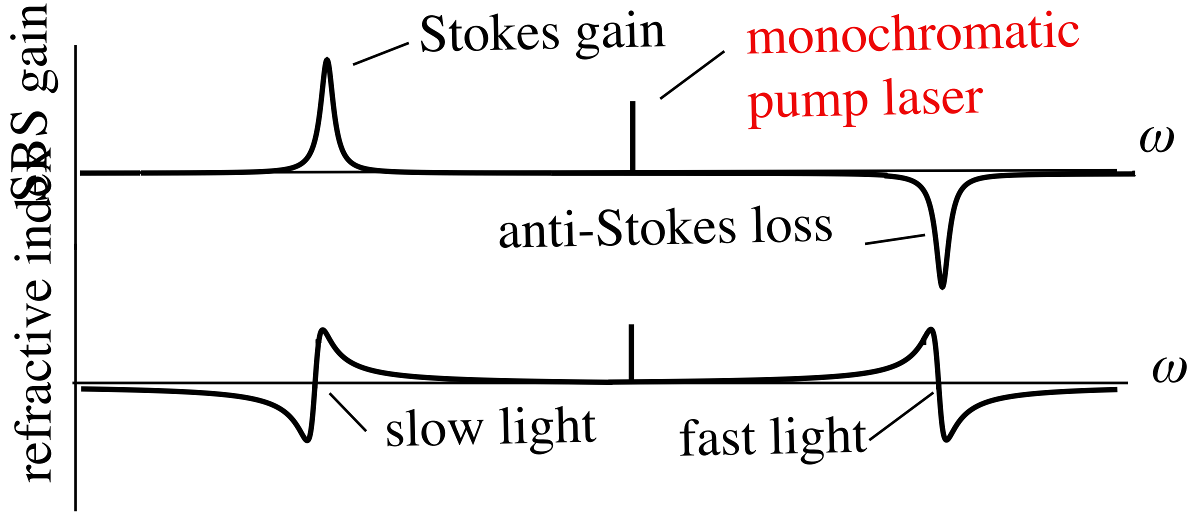


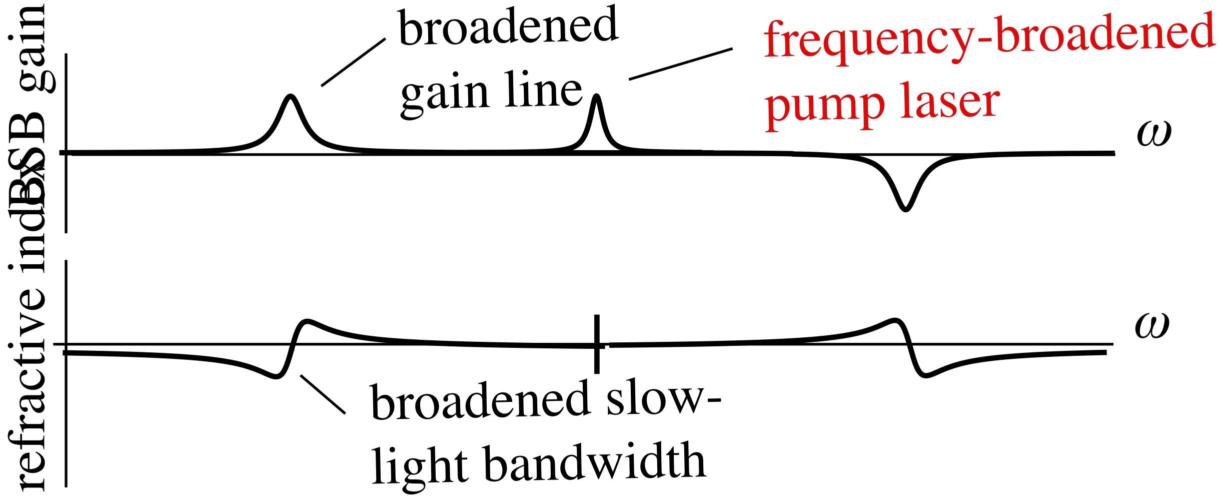
Okawachi, Bigelow, Sharping, Zhu, Schweinsberg, Gauthier, Boyd, and Gaeta Phys. Rev. Lett. 94, 153902 (2005).
Related results reported by Song, González Herráez and Thévenaz, Optics Express 13, 83 (2005).

Broadening the SBS Line Width

Problem: SBS linewidth $\Gamma_B/2\pi$ is only 30 MHz (typical value at 1550 nm)
This line width is too small to support the Gb/s data rates of telecom

Solution: Frequency-broaden the punp laser, which broadens the SBS gain line.
This solution works remarkably well, giving linewidths of many GHz





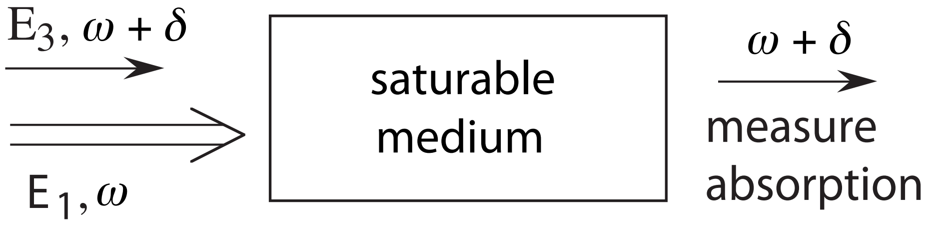
Slow Light by Coherent Population Oscillations in Ruby

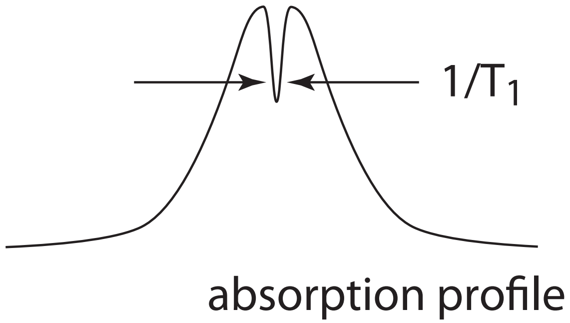
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

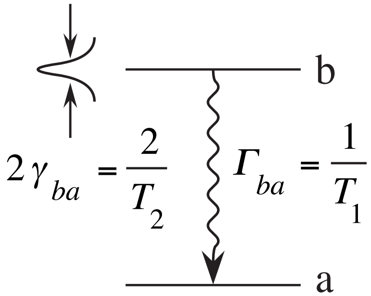
Kramers-Kronig relations:
Want a very narrow feature in absorption line.

Well-known "trick" for doing so:
Make use of spectral holes due to population oscillations.

Hole-burning in a homogeneously broadened line; requires $T_2 \ll T_1$.



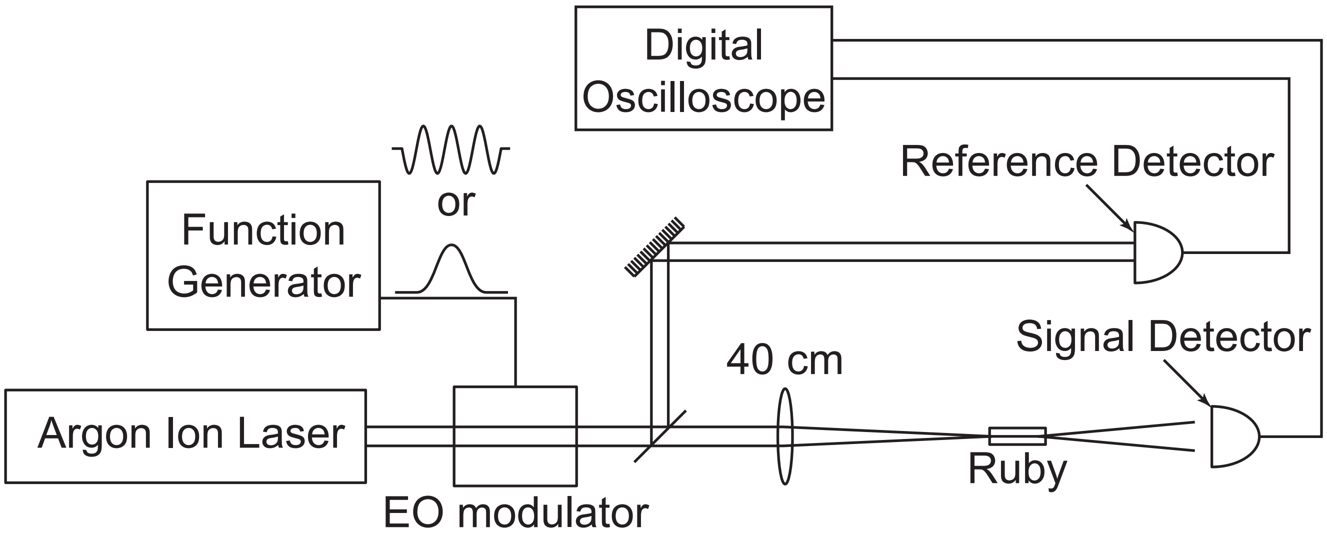




PRL 90,113903 (2003).

Observation of Slow Light Propagation in Ruby

Experimental setup

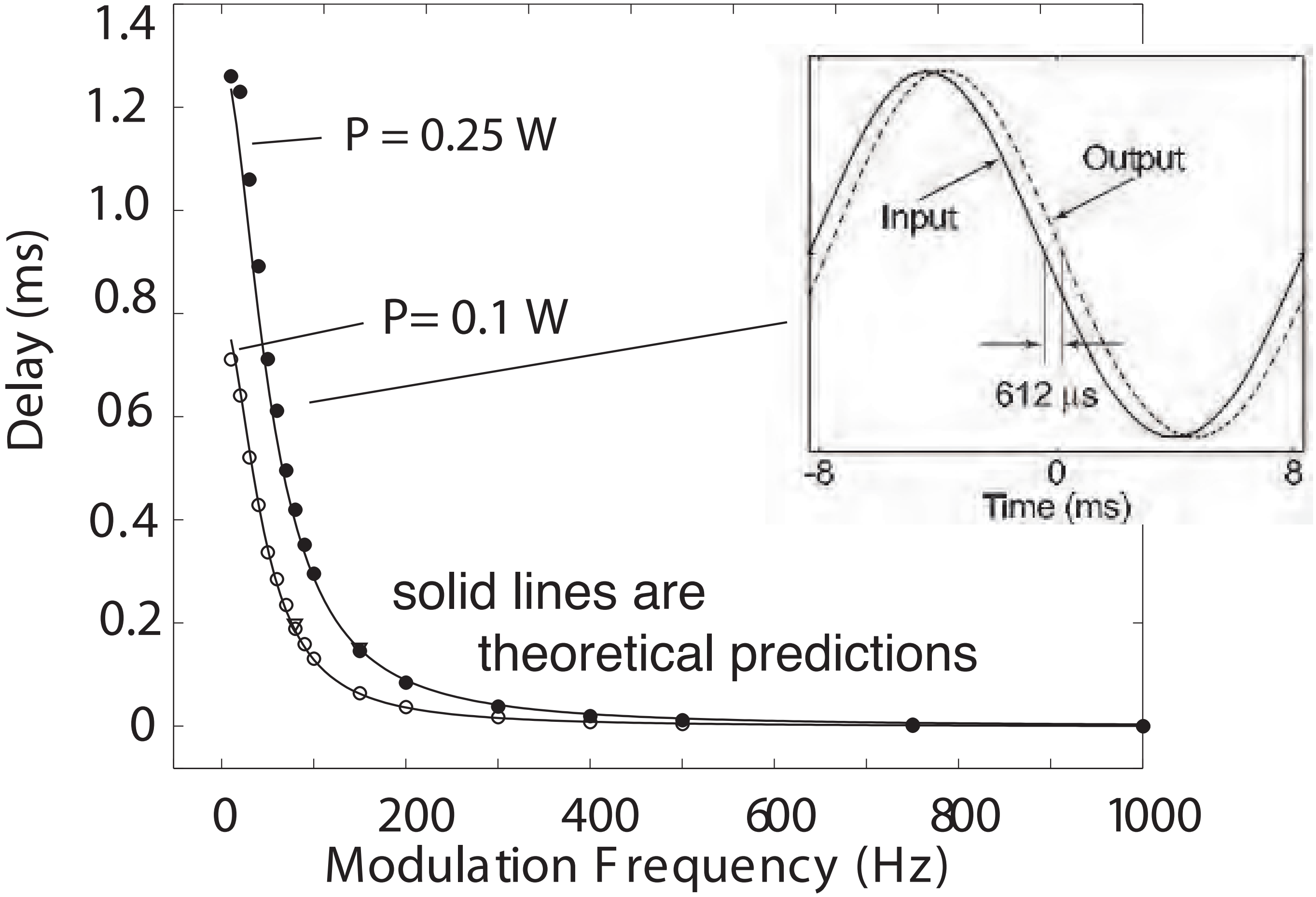


Measurement results:

For a 1.2 ms delay,

$v_g = 60$ m/s

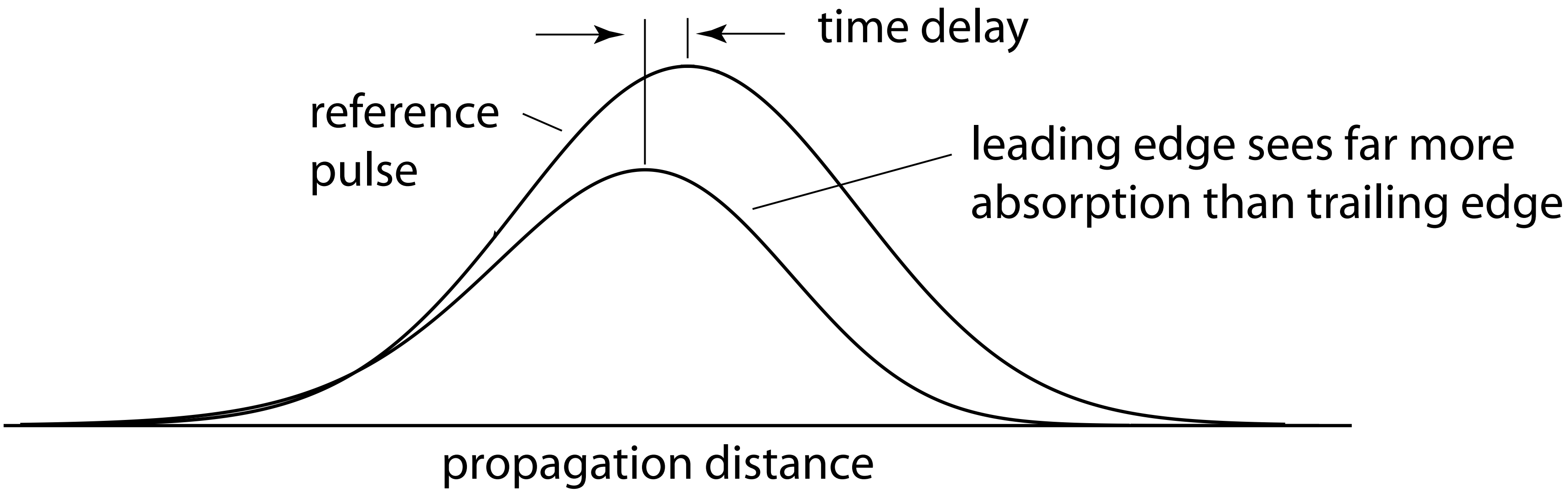
$n_g = 5\text{x}10^6$

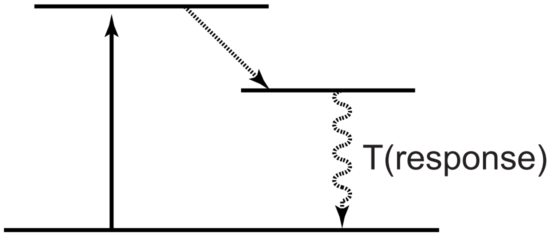


solid lines are theoretical predictions

Time-Domain Explanation of CPO

- Assume that $T_{pulse} \ll T_1$ = time scale for saturation changes
- Then absorption decreases with time during pulse due to saturation



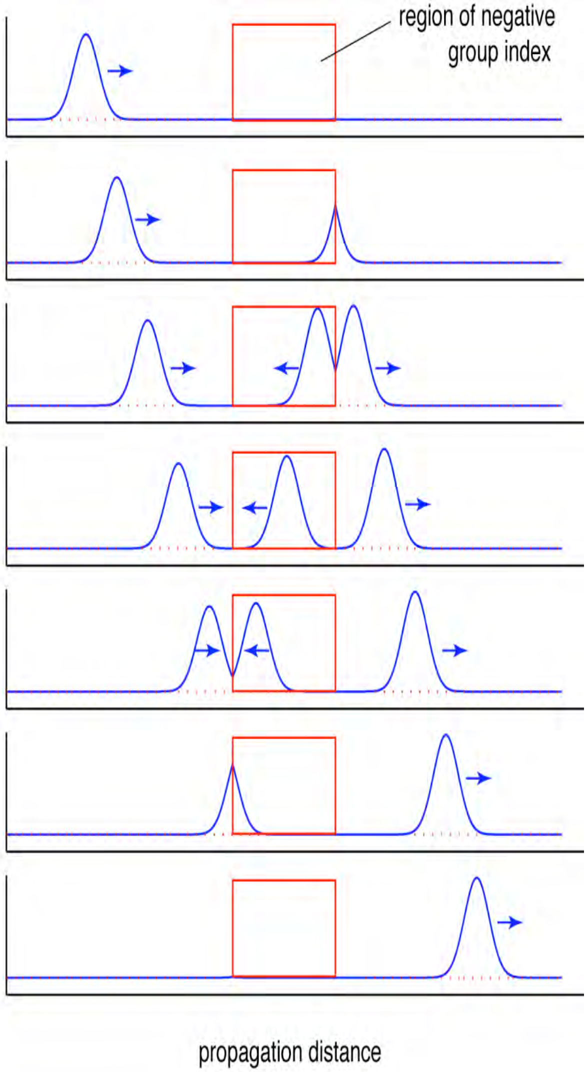


- Proposed by Basov many years ago
- Entirely equivalent to frequency-domain explanation, but probably less useful for making simple calculations of the group delay

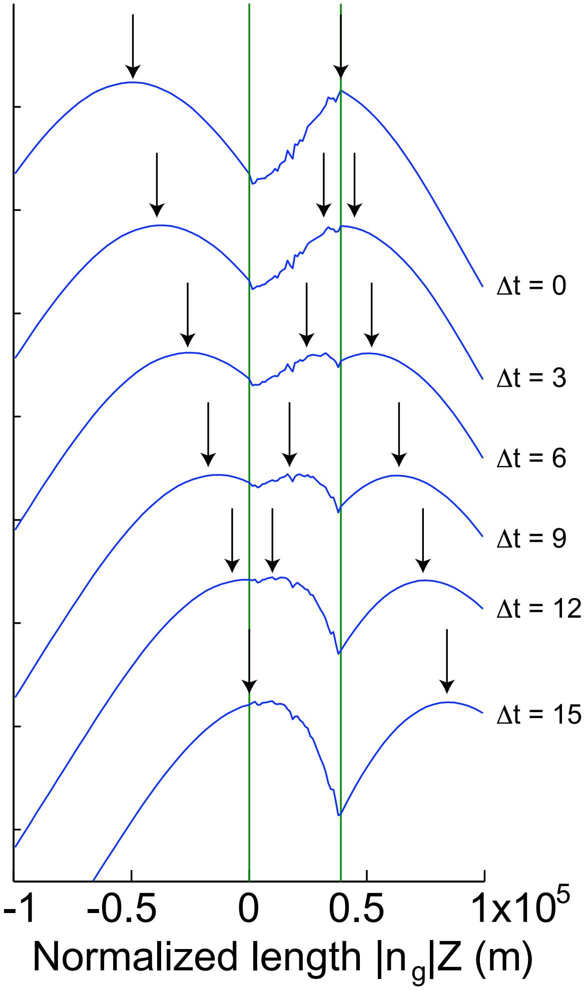
Observation of Superluminal and "Backwards" Pulse Propagation

- A strongly counterintuitive phenomenon
- But entirely consistent with established physics
- G. M. Gehring, A. Schweinsberg, C. Barsi, N. Kostinski, and R. W. Boyd, Science 312, 985 2006.

- conceptual prediction



- laboratory results



Applications of Slow and Fast Light

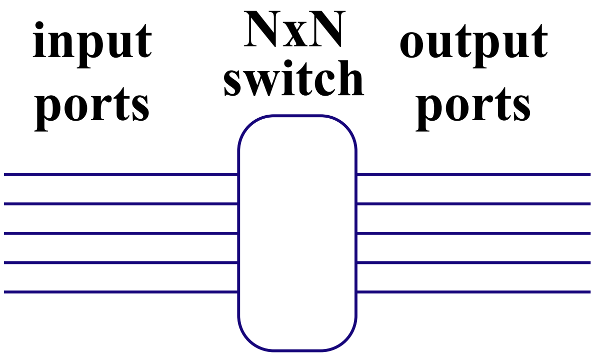
Buffers and regenerators for telecom

Slow/fast light for interferometery

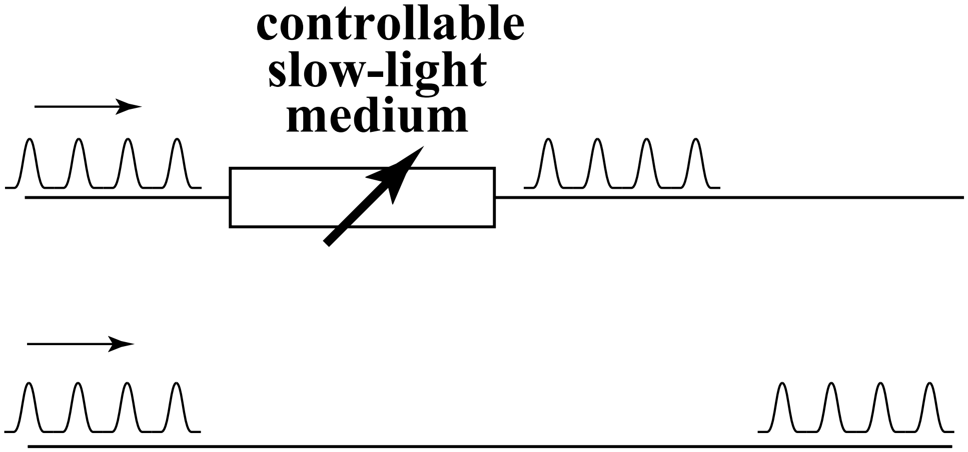
Phased- and synchronized-array laser radar

Slow Light and Optical Buffers

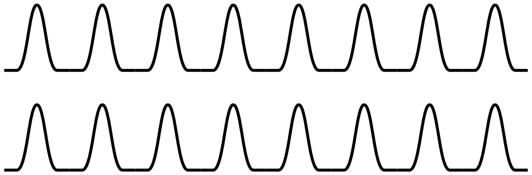
All-Optical Switch



Use Optical Buffering to Resolve Data-Packet Contention



But what happens if two data packets arrive simultaneously?



Buffering can lead to dramatic increase in system performance.

But requires many pulse lengths of controllable delay.

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

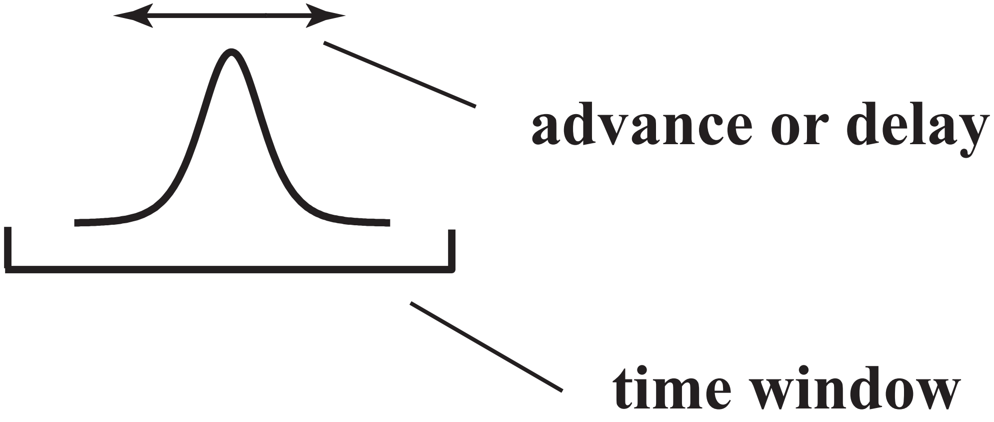
Regeneration of Pulse Timing

Need to recenter each pulse in its time window

Crucial for many situations in telecom

Removes timing jitter caused by NL and environment effects in fiber

Most conveniently done by access to both slow and fast light

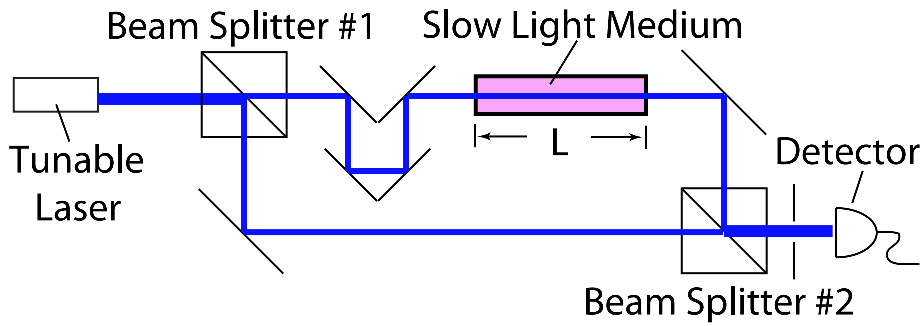


Need only approximately ±1 pulse width of delay!

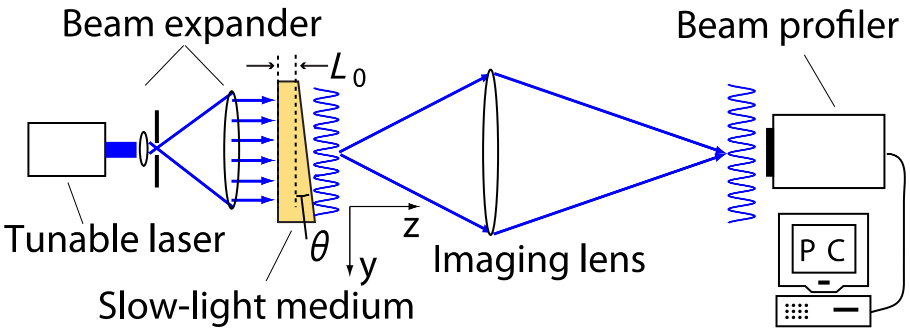
Interferometry and Slow Light

- Under certain (but not all) circumstances, the sensitivity of an interferomter is increased by the group index of the material within the interferometer!
- Sensitivity of a spectroscopic interferometer is increased

Typical interferometer:



We use CdS_xSe_{1-x} as our slow-light medium



Here is why it works:

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

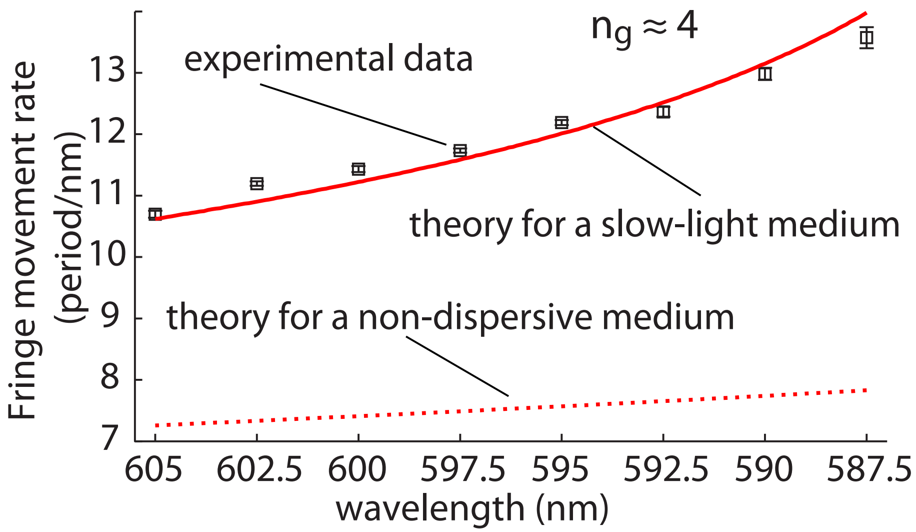
Z. Shi, R.W. Boyd, D. J. Gauthier, and C.C. Dudley, Opt. Lett. 32, 915 (2007

Z. Shi, R. W. Boyd, R. M. Camacho, P. K. Vudyasetu, and J. C. Howell, Phys, Rev. Lett. 99, 240801 (2007)

Z. Shi and R.W. Boyd, J. Opt. Soc. Am. B 25, C136 (2008).

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

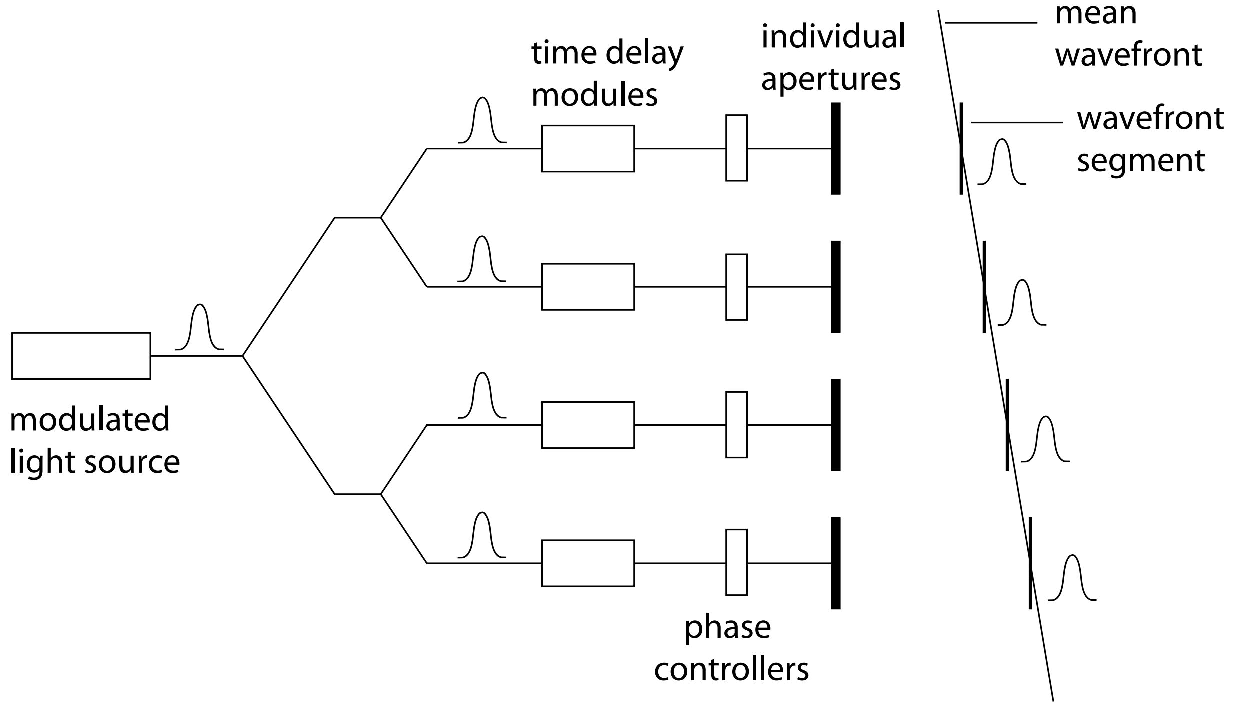
Our experimental results



SLIDAR: Slow LIght Detection and Ranging

A phased- and synchronized-array radar!

(Need to control both phase and time delay for each aperture.)

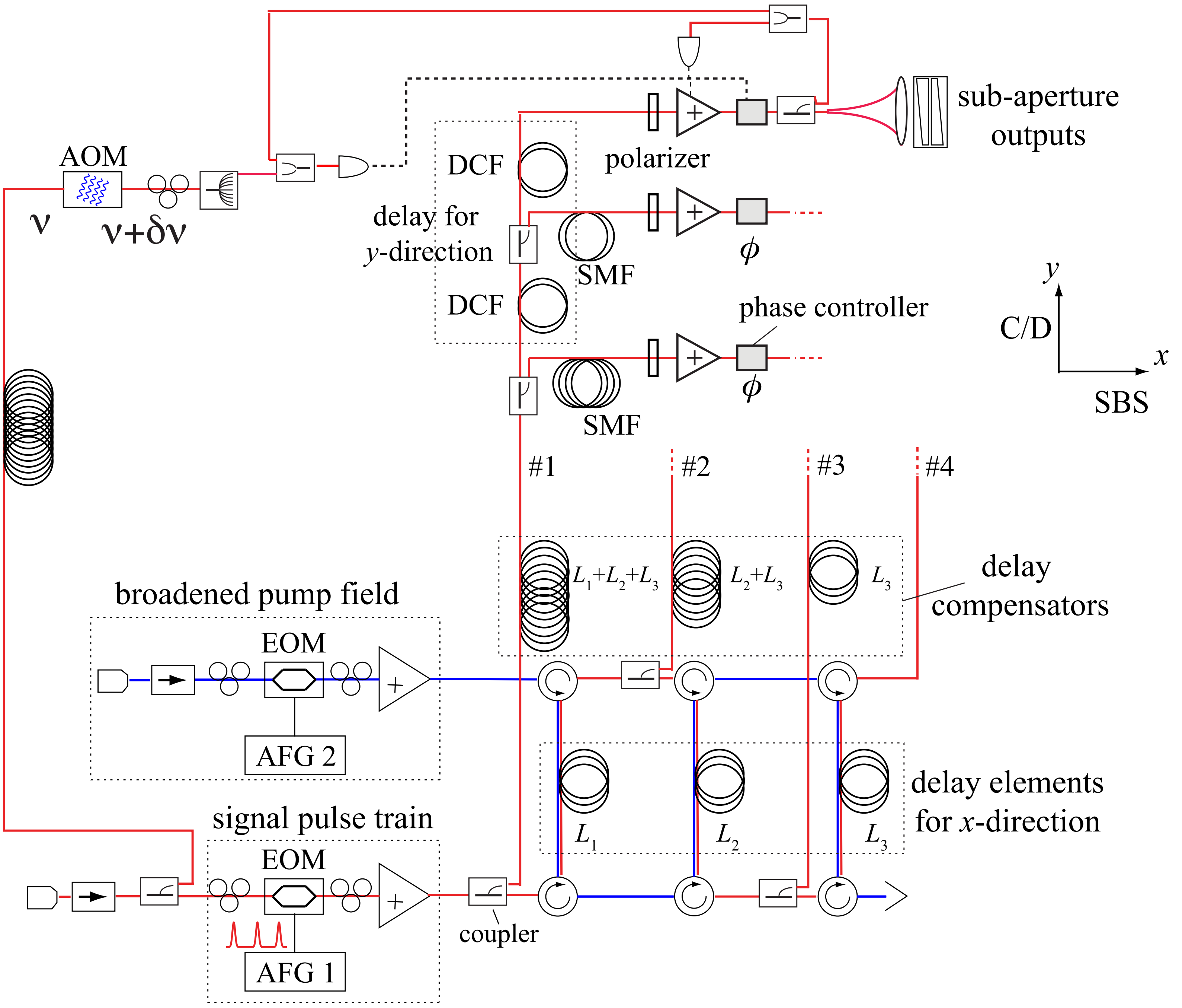


We are constructing a “sparse array”

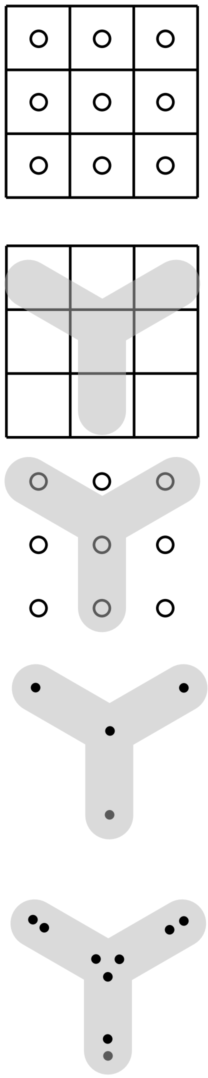
We will implement eight or nine channels with 10-cm-diameter subapertures

Total baseline approximately 1.5 m.

2-D Hybrid SLIDAR System

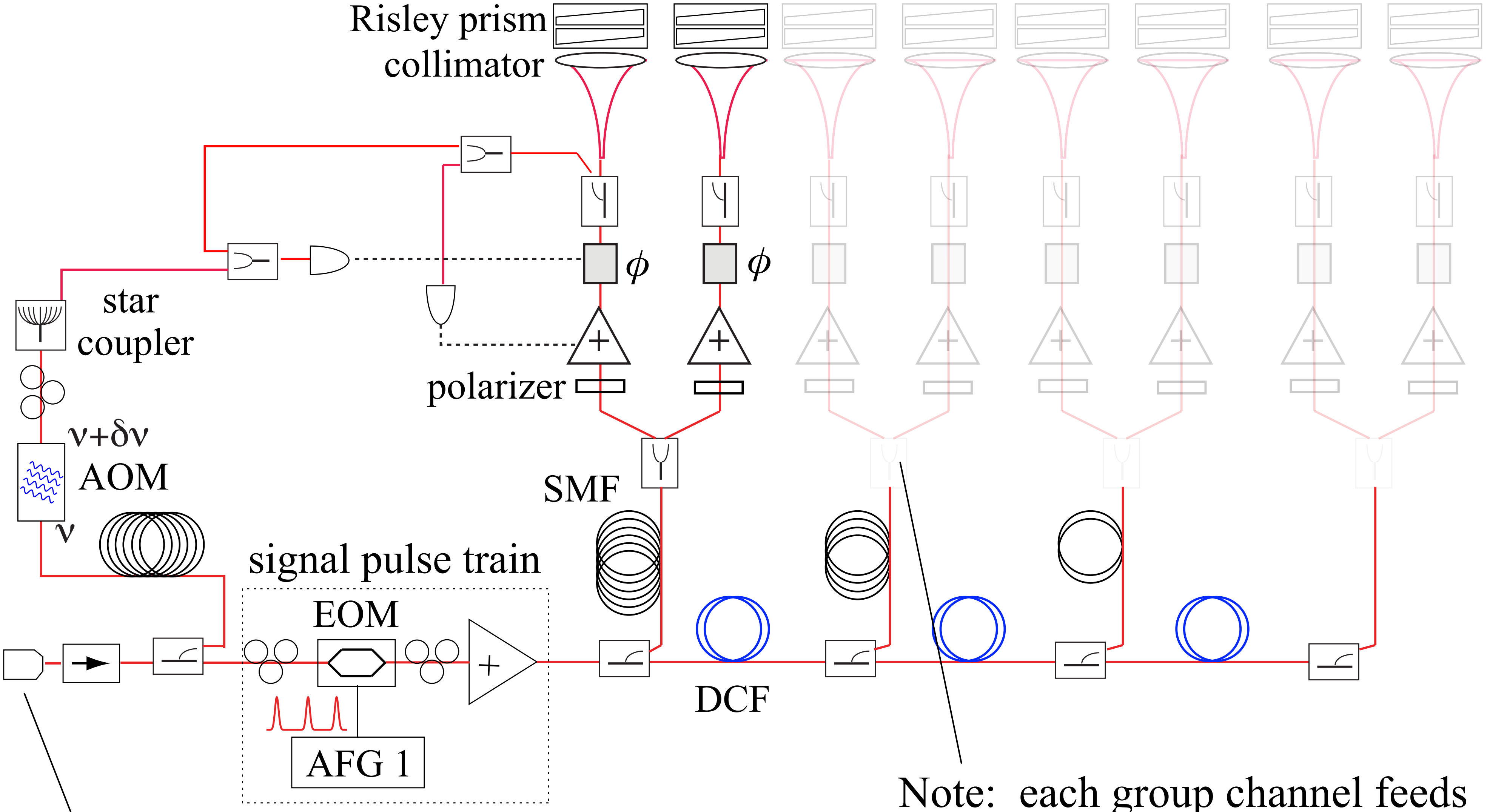


Possible array layouts



1-D Conversion/Dispersion System

or - Dispersive Slow Light



Note: each group channel feeds two phase channels

Agilent external cavity SDL; 3 mW power; tunable 1530 to 1580 nm; 100 kHz linewidth

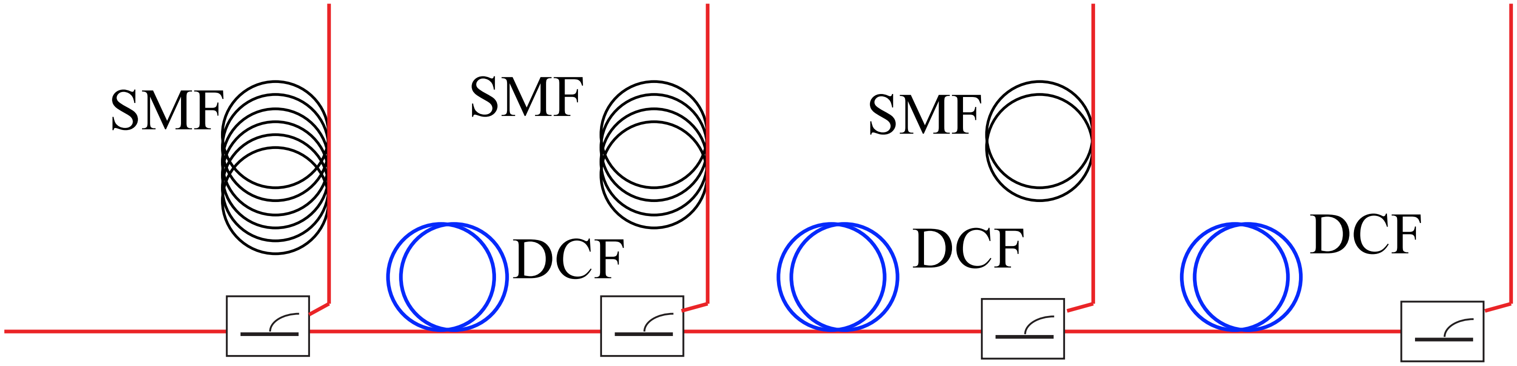
Characterization of the Dispersive Delay Unit

Finally, we have constucted a fully compensated delay unit

Channel 1: Length 3L of SMF
Channel 2: Length 2L of SMF and L of DCF
Channel 3: Length L of SMF and 2L of DCF
Channel 4: Length 3L of DCF

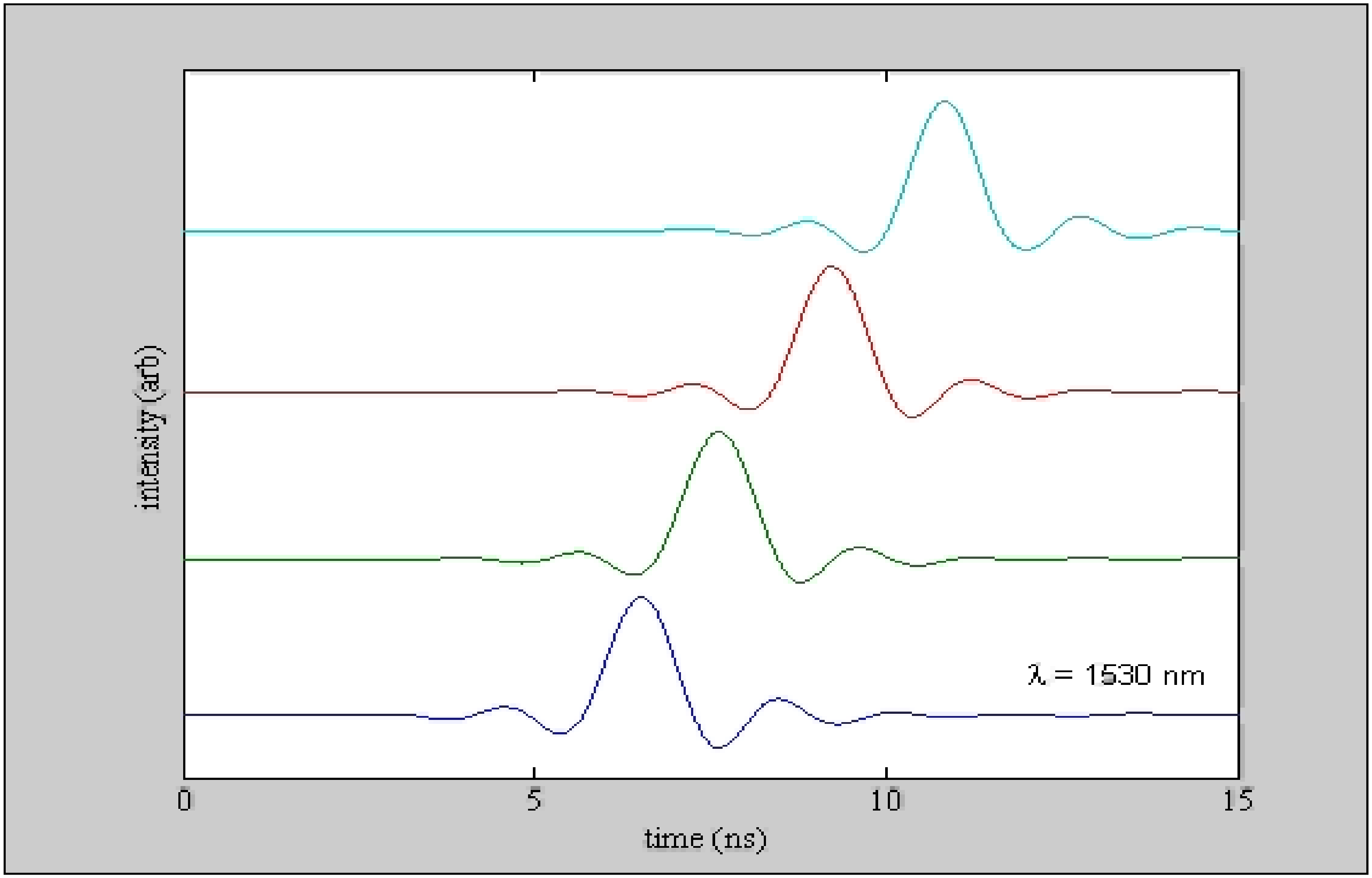
(That is, each channel has roughly the same group delay. The differential delay between channels is controlled by wavelength.)

SMF = single mode fiber
DCF = dispersion compensated fiber
L = 537 m



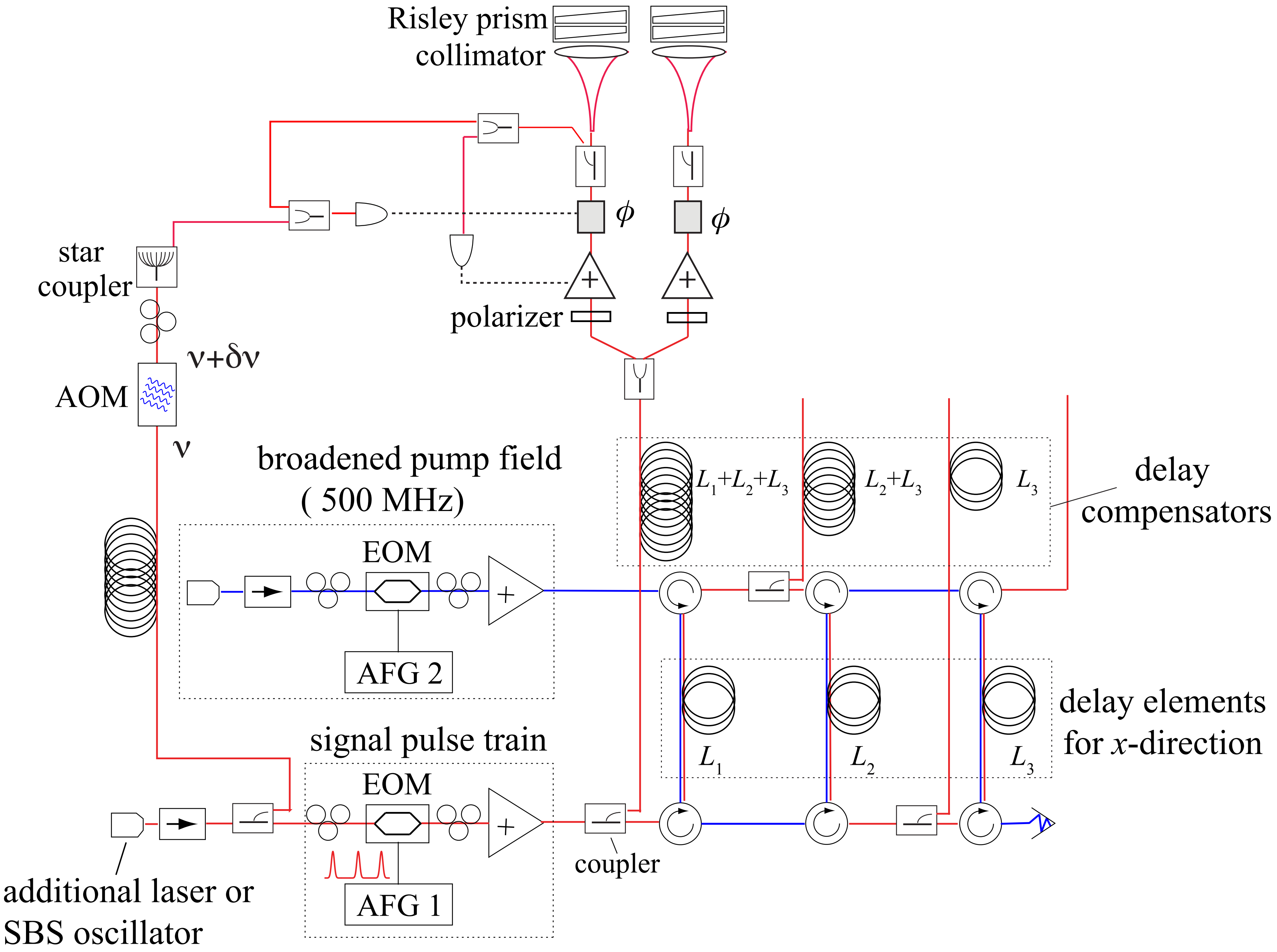
The system performance is described in the accompanying movie.

Demonstration of Four-Channel Dispersive Slow Light



click within frame to play movie

1-D SBS SLIDAR System



Channelization to Increase Slow-Light Delays

A key parameter in slow light systems is the delay measured in pulse width, also known as the delay-bandwidth product, $\Delta\nu\ \tau_d$.

There is no fundamental limit to $\Delta\nu\ \tau_d$, and values as large as 80 have been achieved.

Miller (PRL, 2007) showed that to achieve a given $\Delta\nu\ \tau_d$, the system must obey

$$\tau_g \Delta\nu \leqslant n_{\mathrm{avg}} L \Delta n / (\sqrt{3}\lambda_0)\,.$$

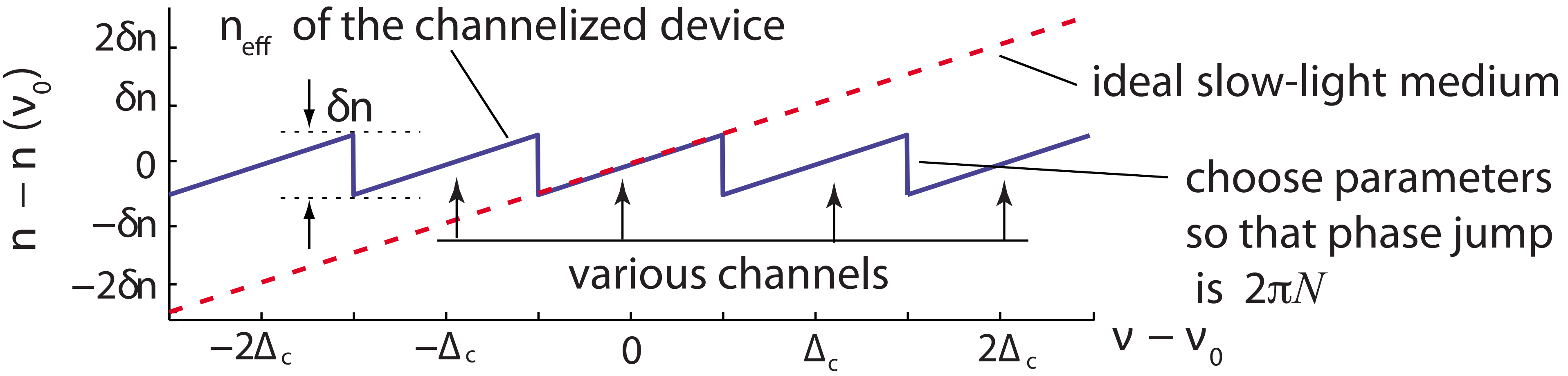
But this limit assumes the use of a single channel system. A multichannel system can overcome this limit.

Multichannel schemes have been proposed and demonstrated previously, but not in a manner that can exceed the Miller limit

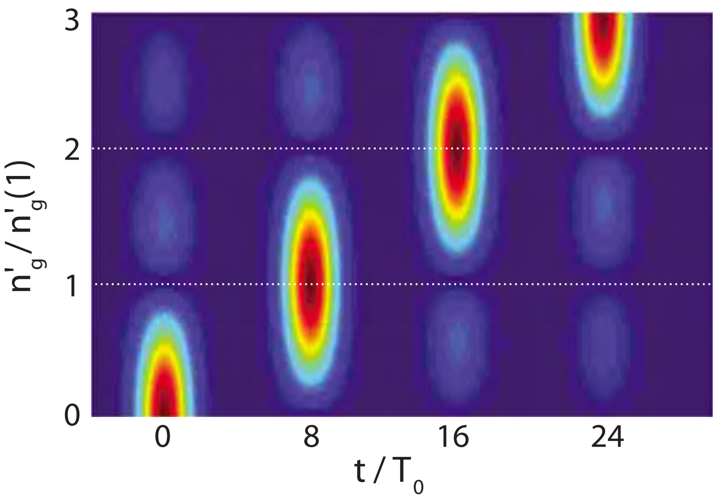
We recently (PRA, 2008) proposed a channelization architecture that can overcome this limit

Our New Channelization Architecture

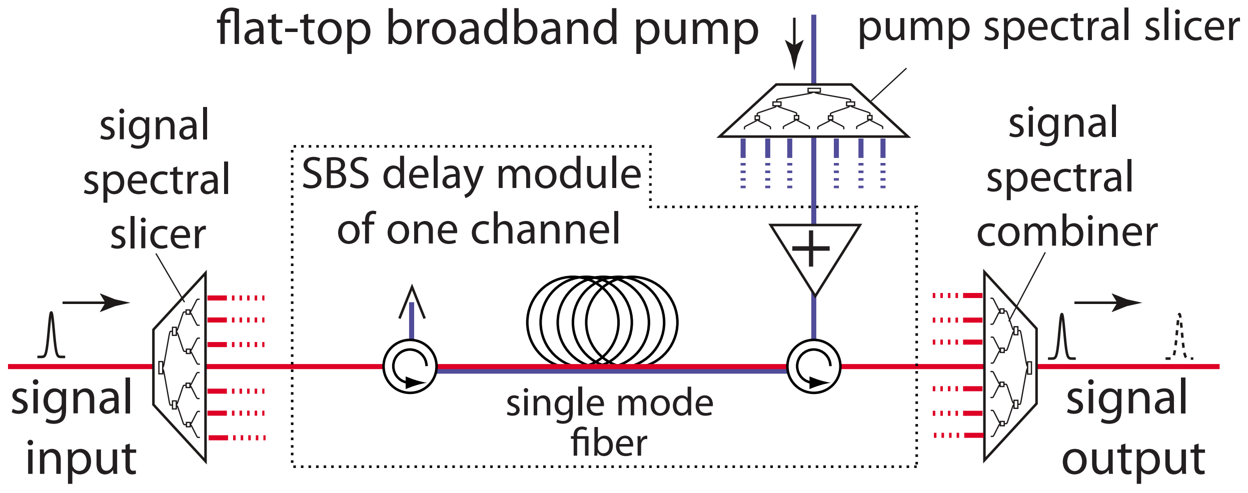
- This is the idea of our approach



- This system is discretely tunable



- This is our proposed implementation

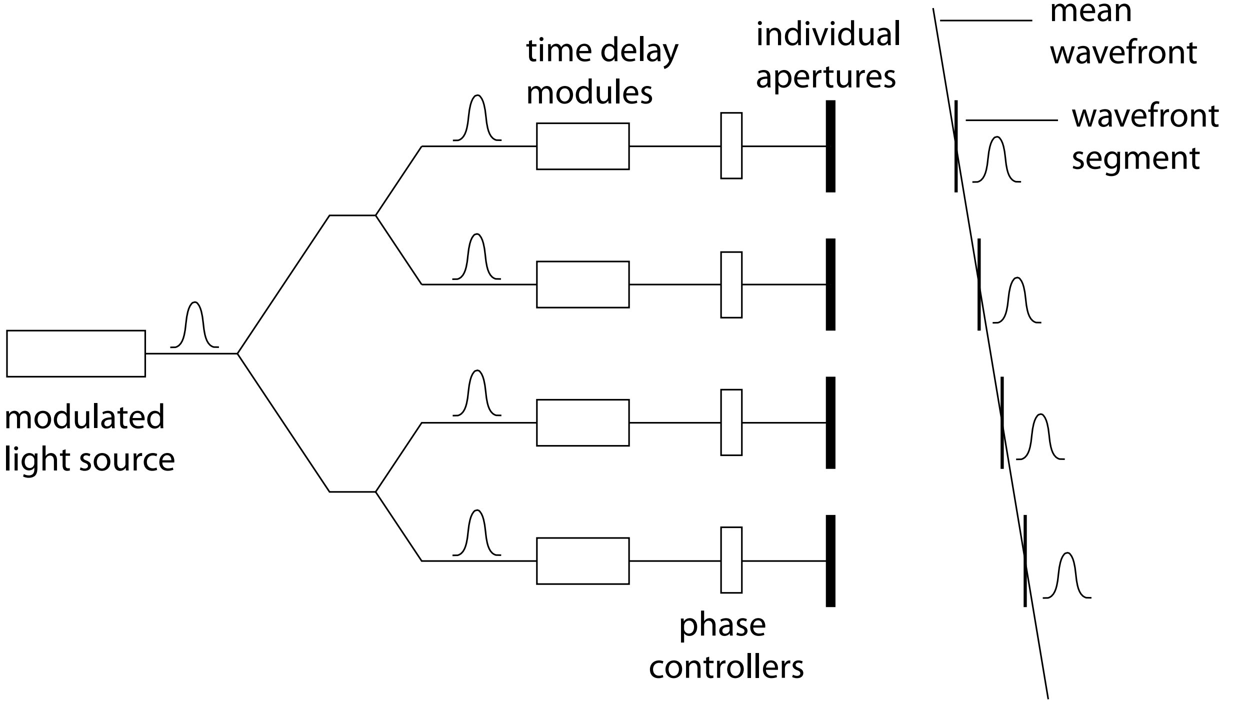


Z. Shi and RWB, PRA 78 2008.

Thank you for your attention!

SLIDAR: Slow LIght Detection and Ranging

A phased- and synchronized-array radar!



Need to control both phase and time delay for each aperture

Our Approach:

We will first construct an 8-channel, 1-D system using a tunable source and group velocity dispersion to control the group delay

We will then construct a 9-channel, 2-D system using C/D for one transverse dimension and SBS for the other