Slow and Fast Light Propagation in Erbium-Doped Optical Fibers

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Background

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- Slow light: $n_g > 10^6$ Fast light: $n_g > c$ or negative
- Applications of slow light: controllable delay lines, buffering for telecommunication, etc.
- Room temperature solids desirable for applications
- Coherent population oscillations (CPO) leads to slow light in room temperature solids.
- Slow light by CPO demonstrated in ruby and alexandrite.
- Present work: slow and fast light in erbium-doped fibers

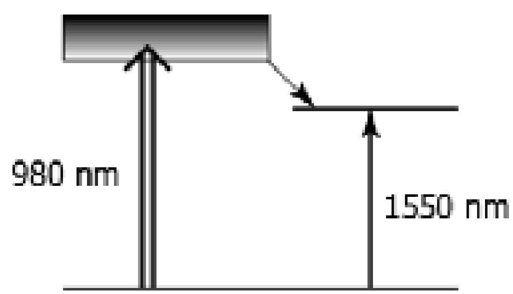
Advantages of the EDF system

Coherent Population Oscillations

- Room temperature
- Works in a solid
- Pulses can be self-delayed

Specific to Erbium doped fiber

- Long interaction lengths
- Makes use of existing technologies at 1550 nm
- Pulses can still be self-delayed, but separate pump allows for independent tuning of delay and for negative group velocities



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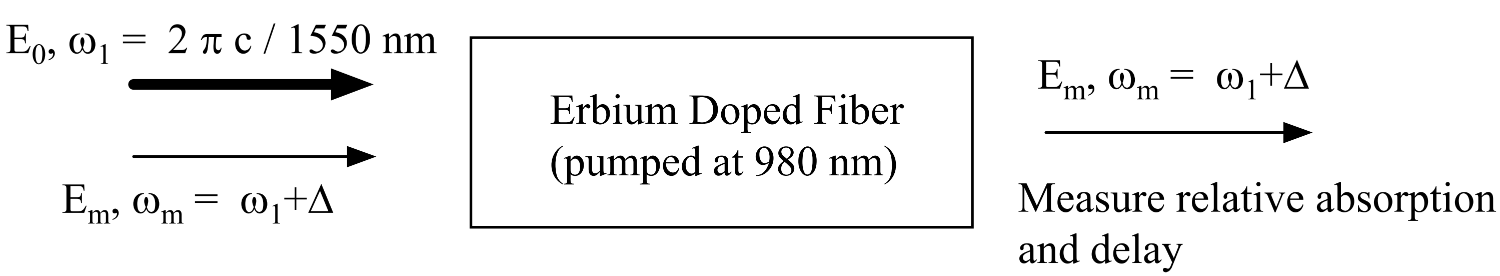
Theory

- Coherent Population Oscillations: ground state population of a medium oscillates at the beat frequency between two applied optical fields.
  - The resulting narrow hole in the medium's gain or absorption spectrum produces a region of high dispersion and anomalous group velocities.
  - $$\nu_g = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}}$$



Theory (EDF)

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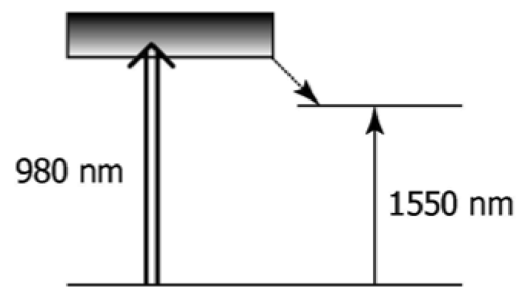
Assuming a fast decay from the pump-absorption level, the EDF can be analyzed in terms of rate equations for a two level system. The equation for the ground state population is given by

$$\frac{\partial n}{\partial t} = \frac{\rho - n}{\tau} + \left(1 - \frac{n}{\rho}\right) \beta_s I_s - \frac{n}{\rho}\ \alpha_s I_s - \frac{n}{\rho}\ \alpha_p I_p$$

where n is the ground state population density, ρ is the Er ion density, τ is the metastable level lifetime (~10.5 ms), I_p is the pump intensity I_s is the signal intensity, β_s is the signal gain coefficient and α_p, α_s are the pump and signal absorption coefficients [1]



[1] S. Novak and A. Moesle, J. Lightwave Technology IEEE, **20**, 975 (2002)

Theory (cont.)

If we modulate the signal intensity: $I_s = I_0 + I_m \cos(\Delta t)$

We produce oscillations in the ground state population $n(t) = n_0 + n_\delta(t)$, $n_\delta(t)$ is given by:

$$n_\delta(t) = 2 I_m G \left(\frac{\omega_c cos(\Delta t) + \Delta sin(\Delta t)}{\omega_c^2 + \Delta^2} \right)$$

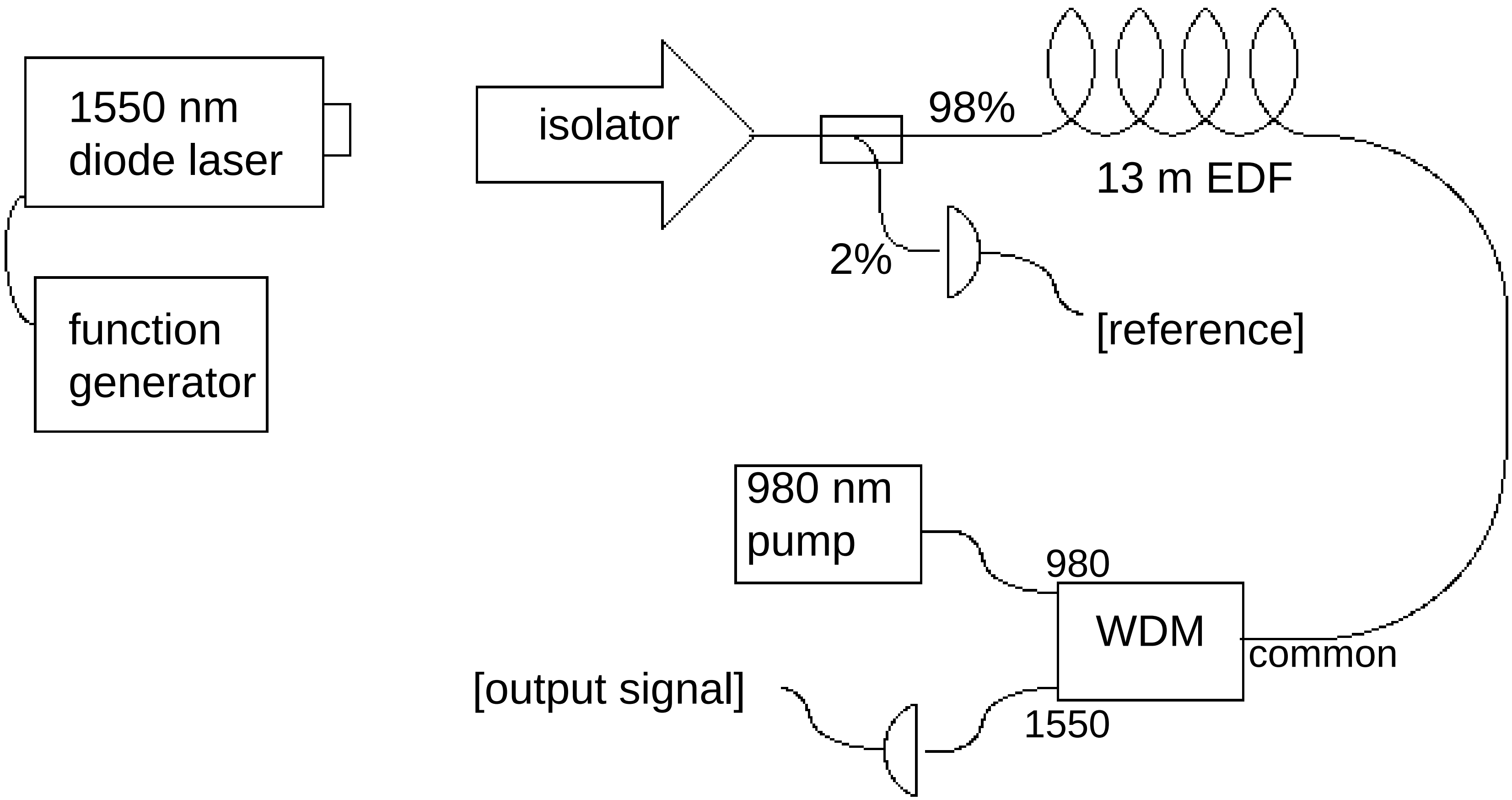
where $G = -\frac{n_0}{\rho}(\alpha_s + \beta_s) + \beta_s$, and $\omega_c = \frac{1}{\tau} + \frac{\alpha_p I_p}{\rho} + \frac{(\alpha_s + \beta_s) I_s}{\rho}$

G is a balance between the net gain and absorption in the medium and its sign determines the sign of both the modulation gain and the group velocity.

ω_c is an "effective cutoff frequency" that determines the width of the spectral hole and the maximum modulation frequency where we can see slow or fast light.

cosine term of n_δ -> modulation gain, sine term -> phase advancement

Experimental Setup (modulation)



Experimental Setup (pulses)

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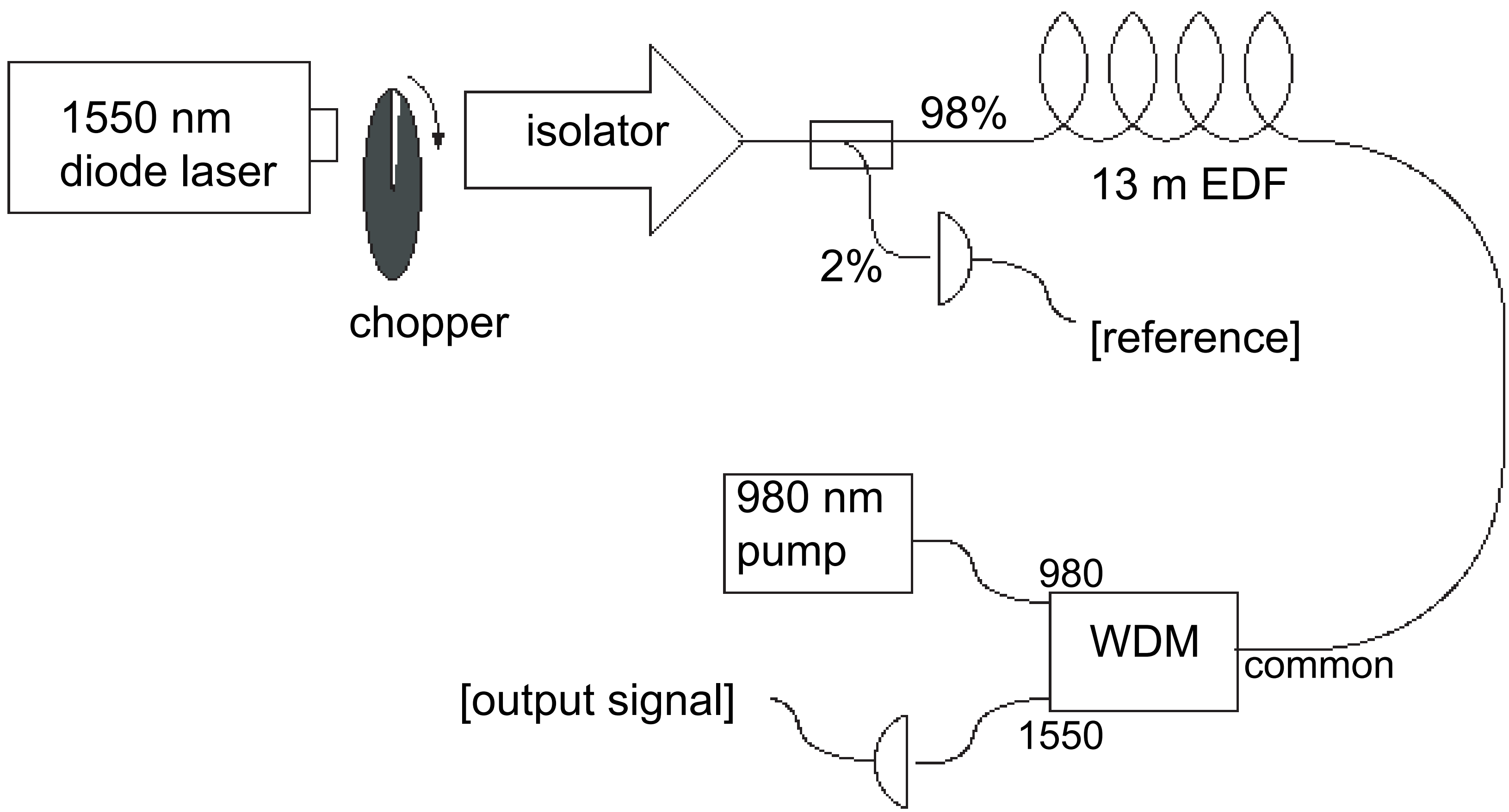
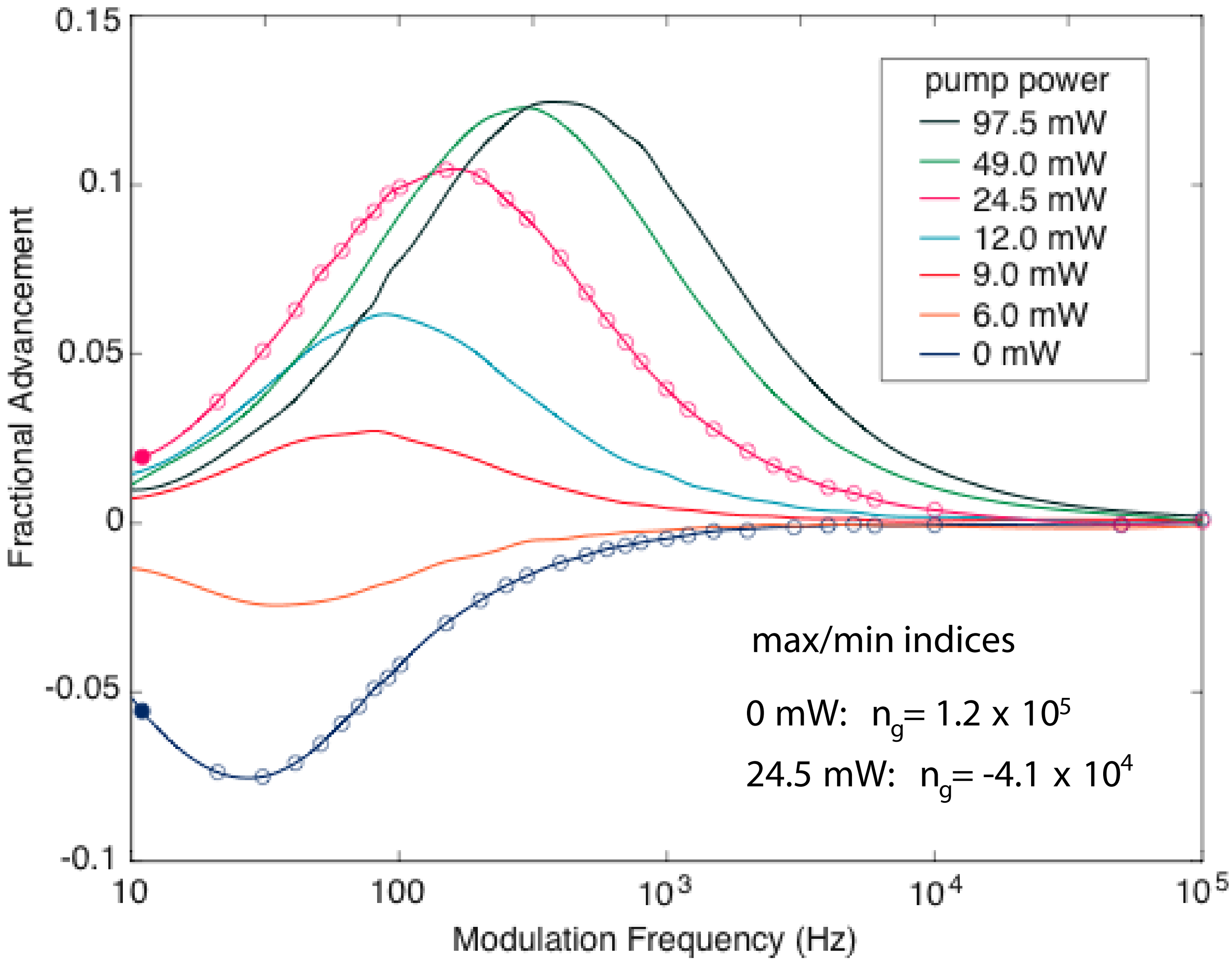
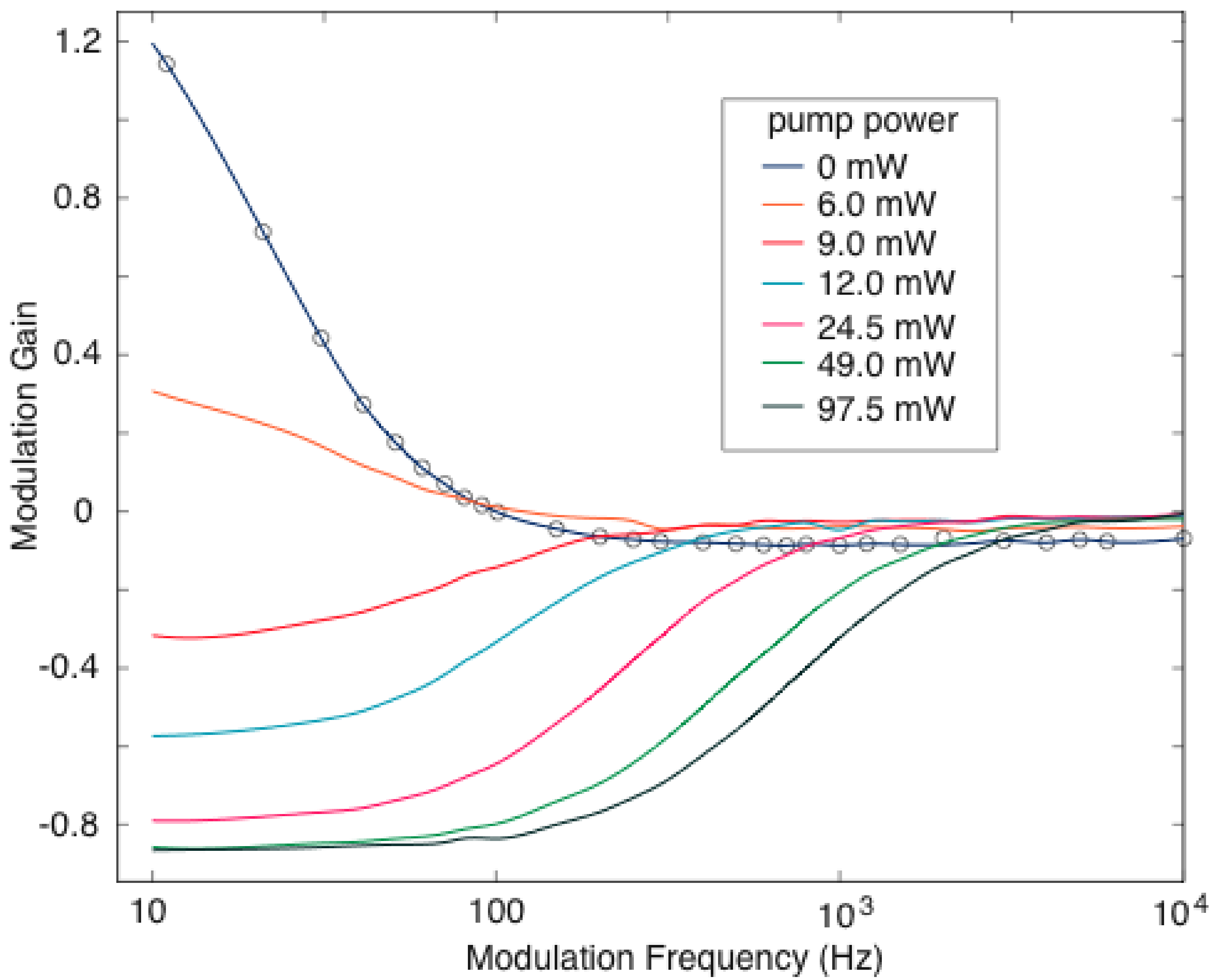


Modulation-frequency dependence of the fractional advancement in erbium-doped fiber

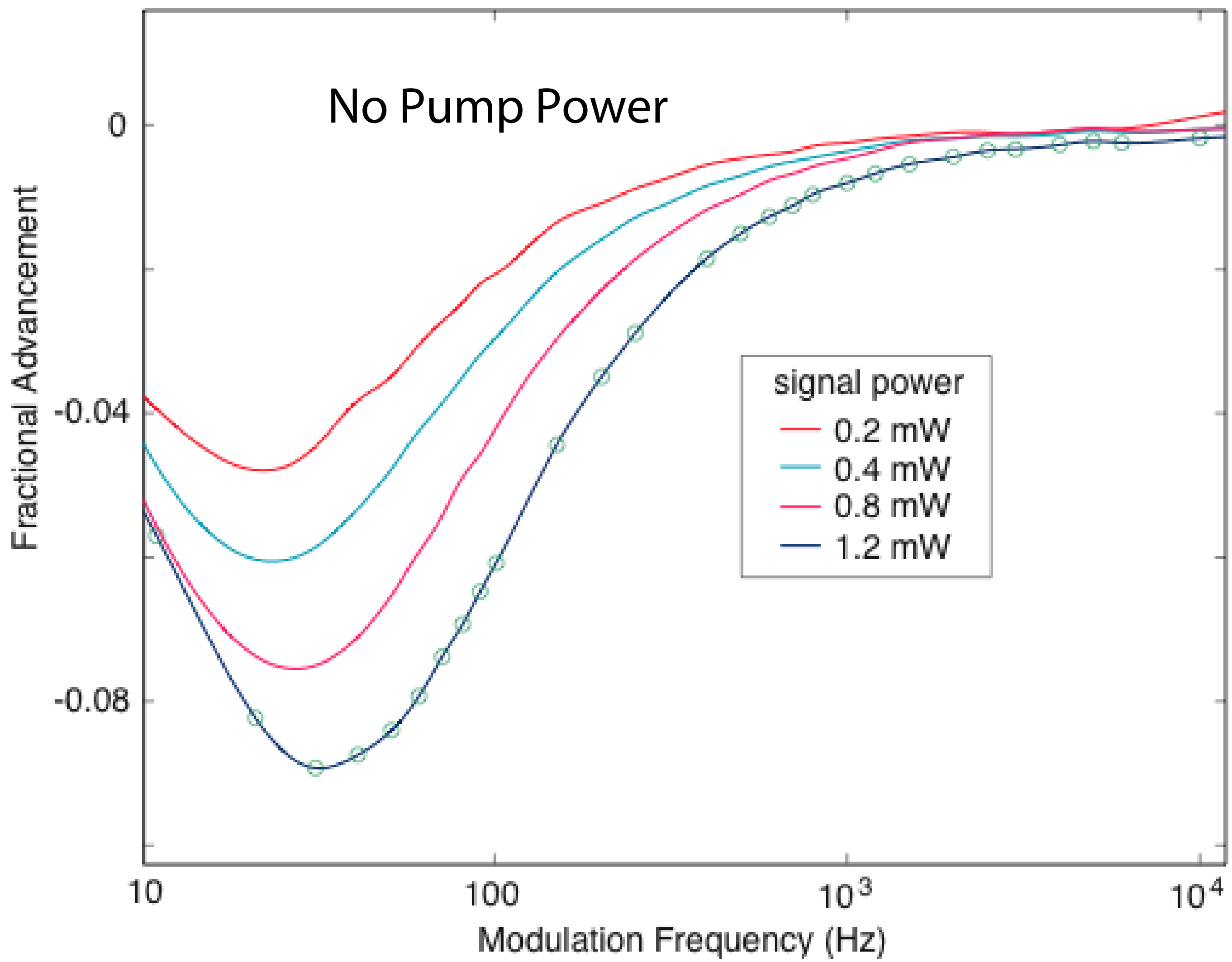


Frequency dependence of the gain of the modulated component



- Spectral hole or anti-hole is observed, depending on pump power.

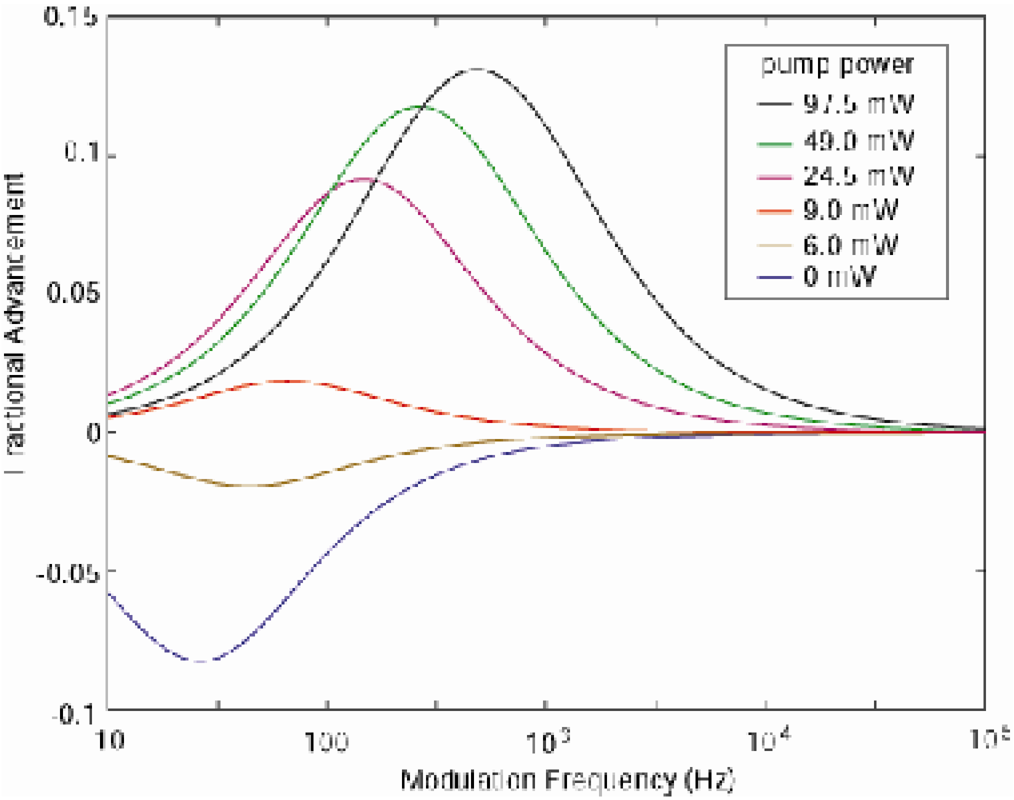
Broadening from Increased Signal Power



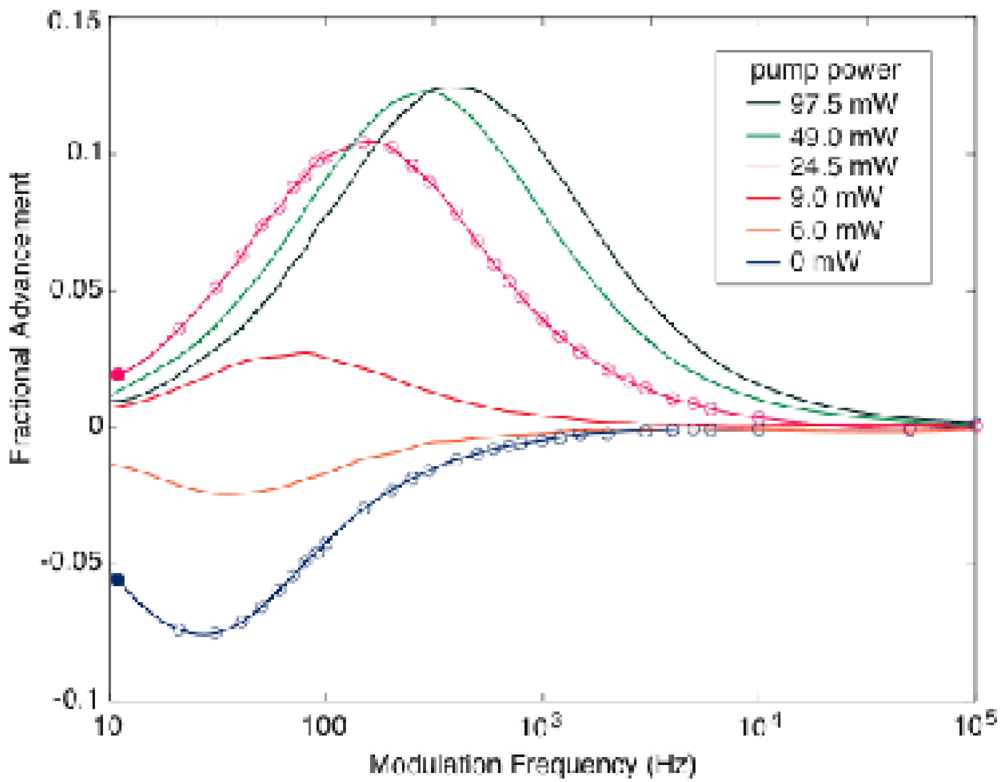
- Increasing the signal power broadens the spectral hole, increasing the fractional delay and shifting the peak to higher frequencies.

Results of Numerical Modeling

theory

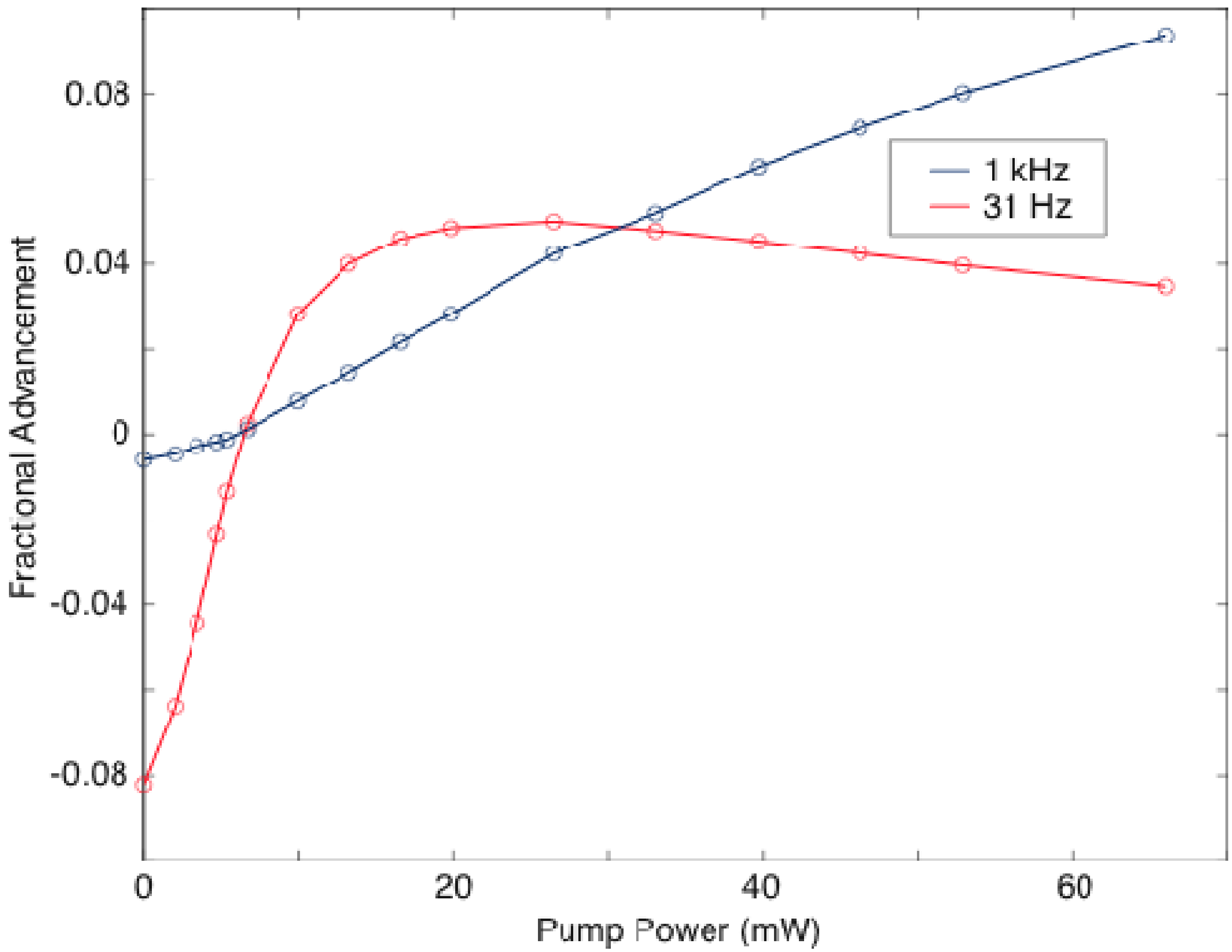


experiment



- Propagation equations solved numerically
- Good agreement between theory and experiment

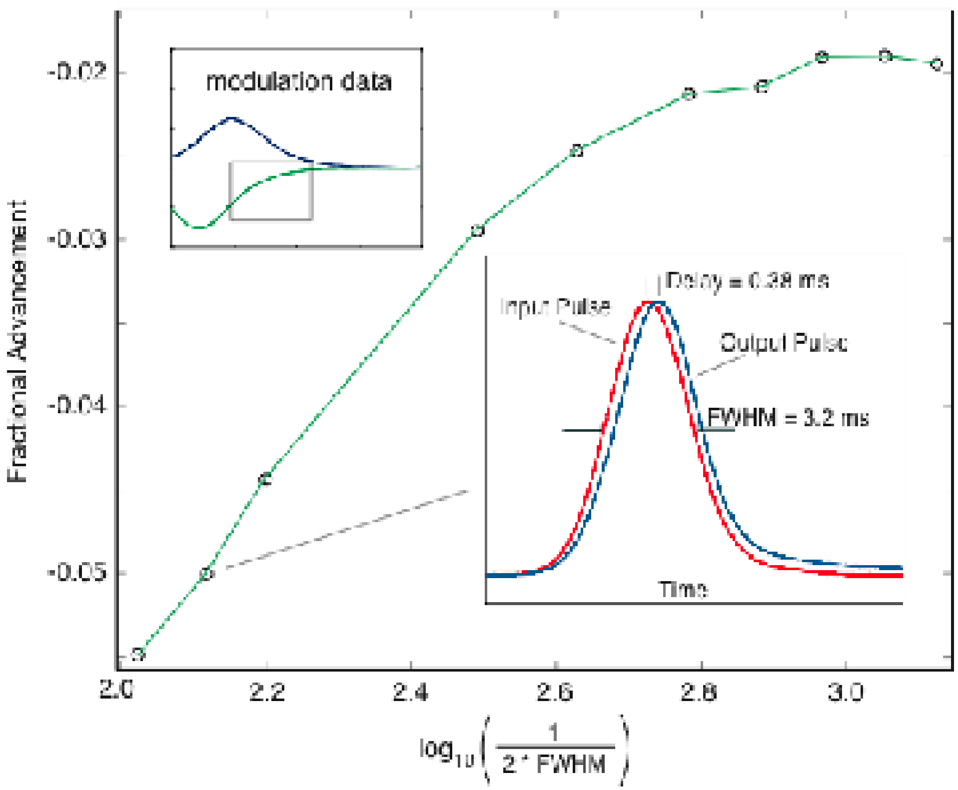
Delay Controllable through Pump Power



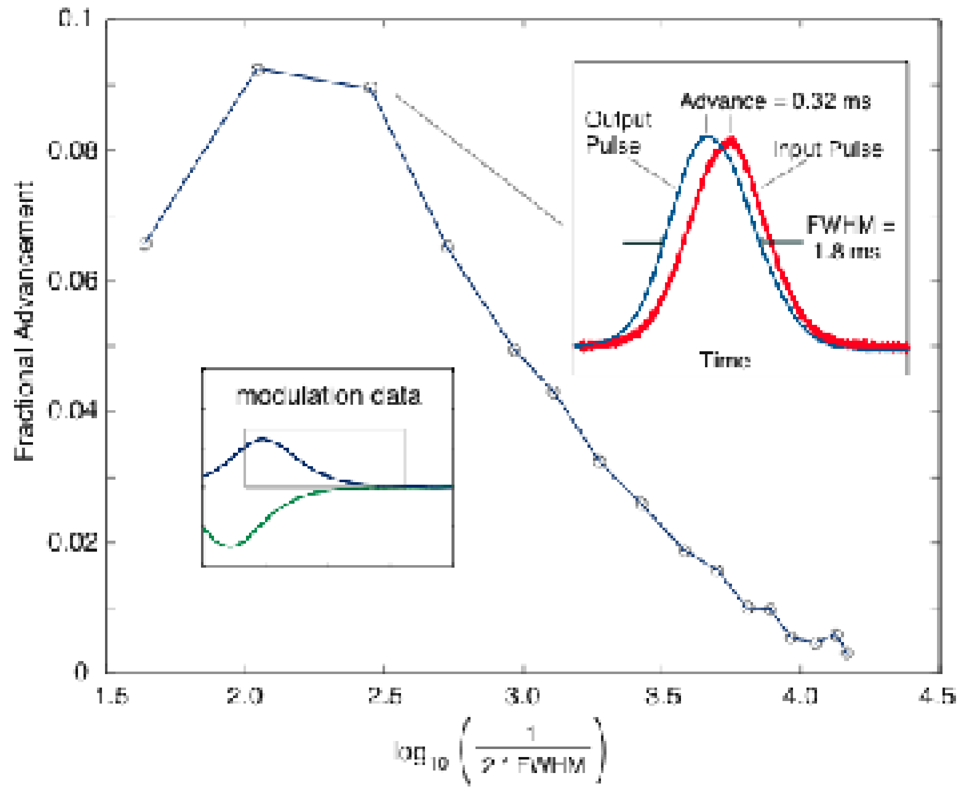
- At a given modulation frequency, the delay can be tuned continuously by changing the pump power
- Both slow and fast light observed in same system!

Delay and Advancement of Gaussian Pulses

Slow light (0 mW pump power)



Fast light (12 mW pump power)

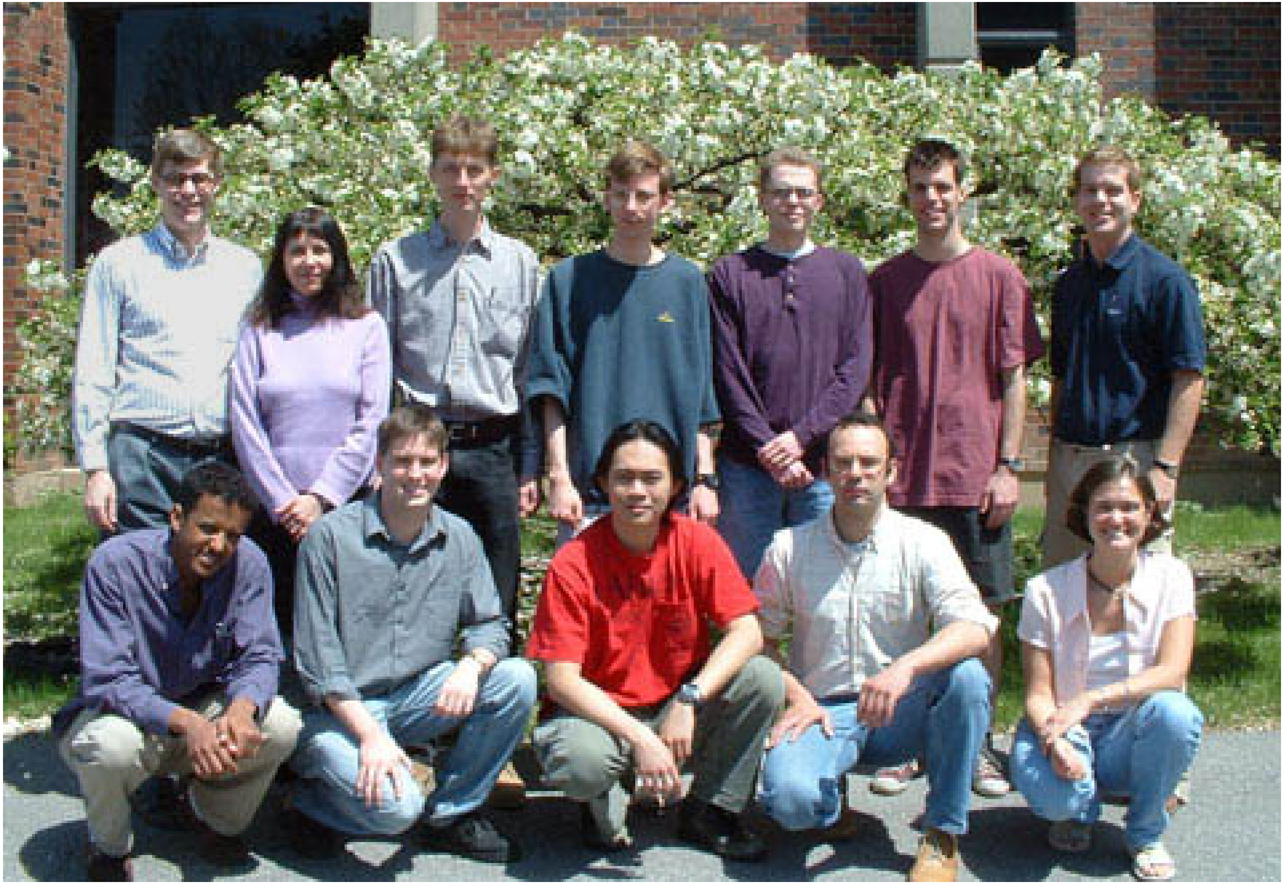


- Gaussian pulses propagate with a group velocity that is either slow or superluminal depending on pump power
- For pulses shown: $n_{g(slow)} = 8.8 \times 10^3$, $n_{g(fast)} = -2100$

Conclusions

- Slow and fast light observed in Erbium doped fiber
- Group velocity can be tuned by changing the pump power
- Effect observed both with sinusoidal modulation and Gaussian pulses
- Future work will focus on applications and systems engineering
  - Search for dopants with faster response time

Special Thanks to my Students and Research Associates



Thank you for your attention.

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