# Demonstration of superluminal and slow light propagation in Erbium-doped fiber

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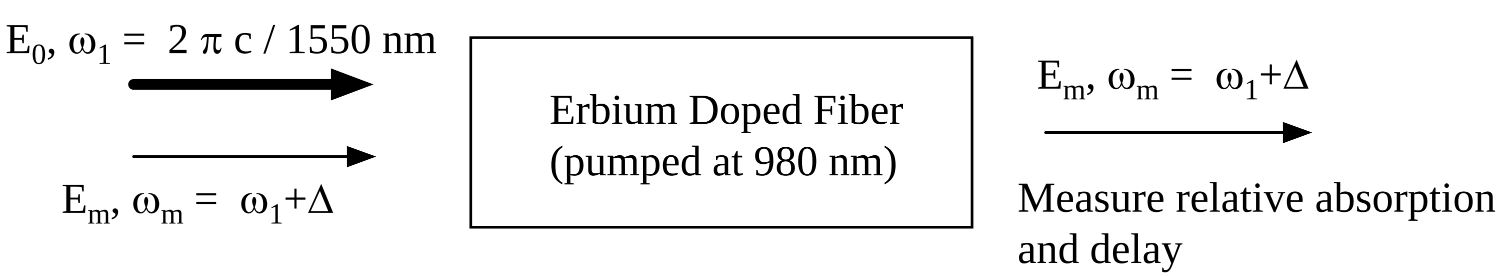
# Outline

- Theory of slow / fast light in Erbium doped fiber
- Advantages of using coherent population oscillations and EDF
- Demonstration of phase delay and advancement of sinusoidal modulation
- Experimental results with Gaussian pulses
- Conclusion

# 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.
  - $$\nu_g = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}}$$



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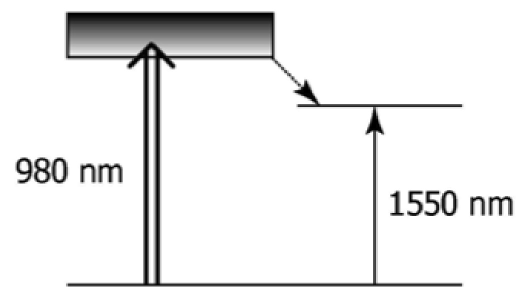
# Theory (EDF)

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, $\beta_s$ is the signal emission coefficient and $\alpha_p$, $\alpha_s$ are the pump and signal absorption coefficients [1]




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

# Theory (cont.)

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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:

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

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.

$\omega_c$ is an “effective corner 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 $n_\delta$ -> modulation gain, sine term -> phase advancement

# 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

# Experimental Setup (modulation)

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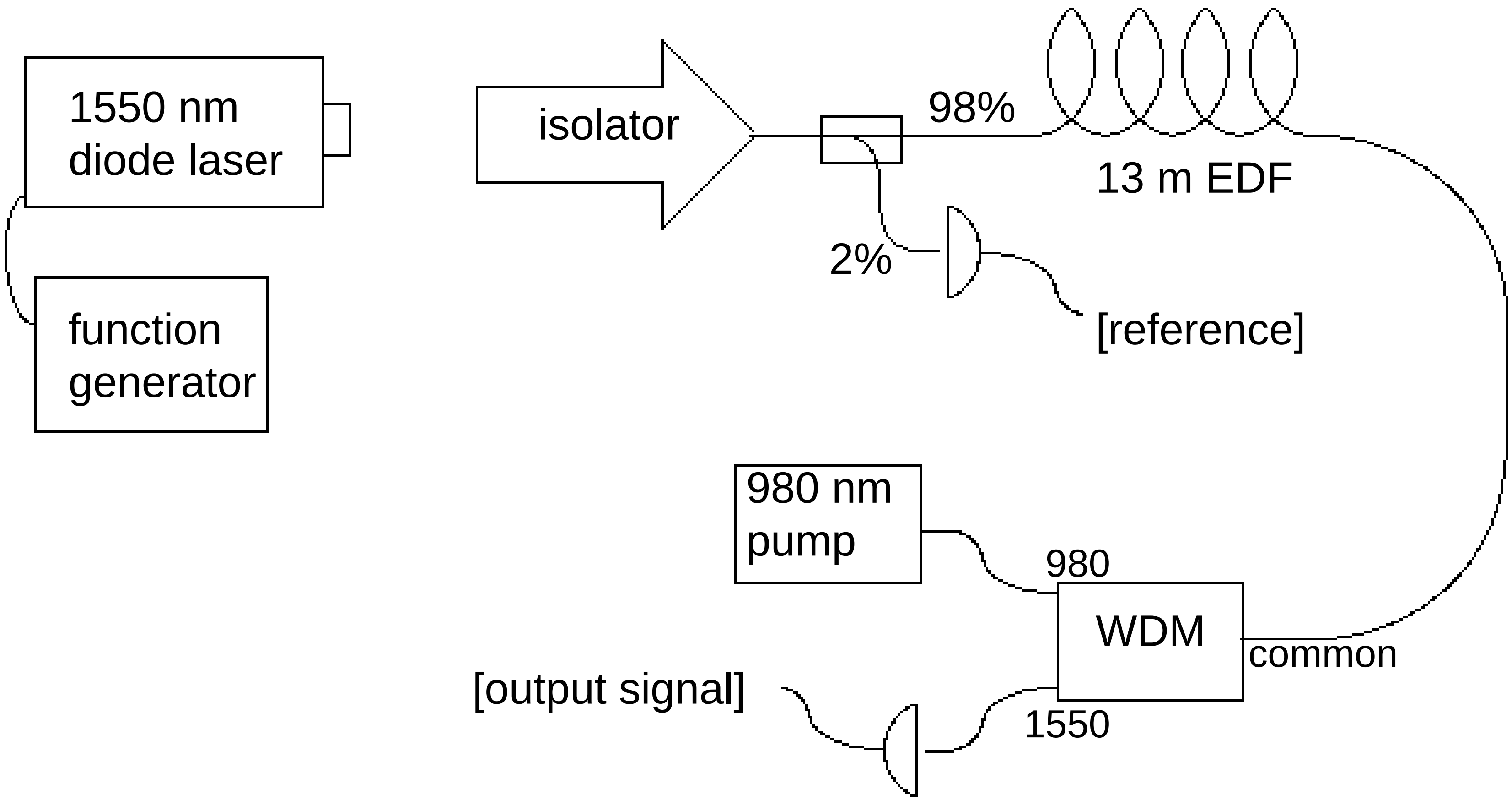
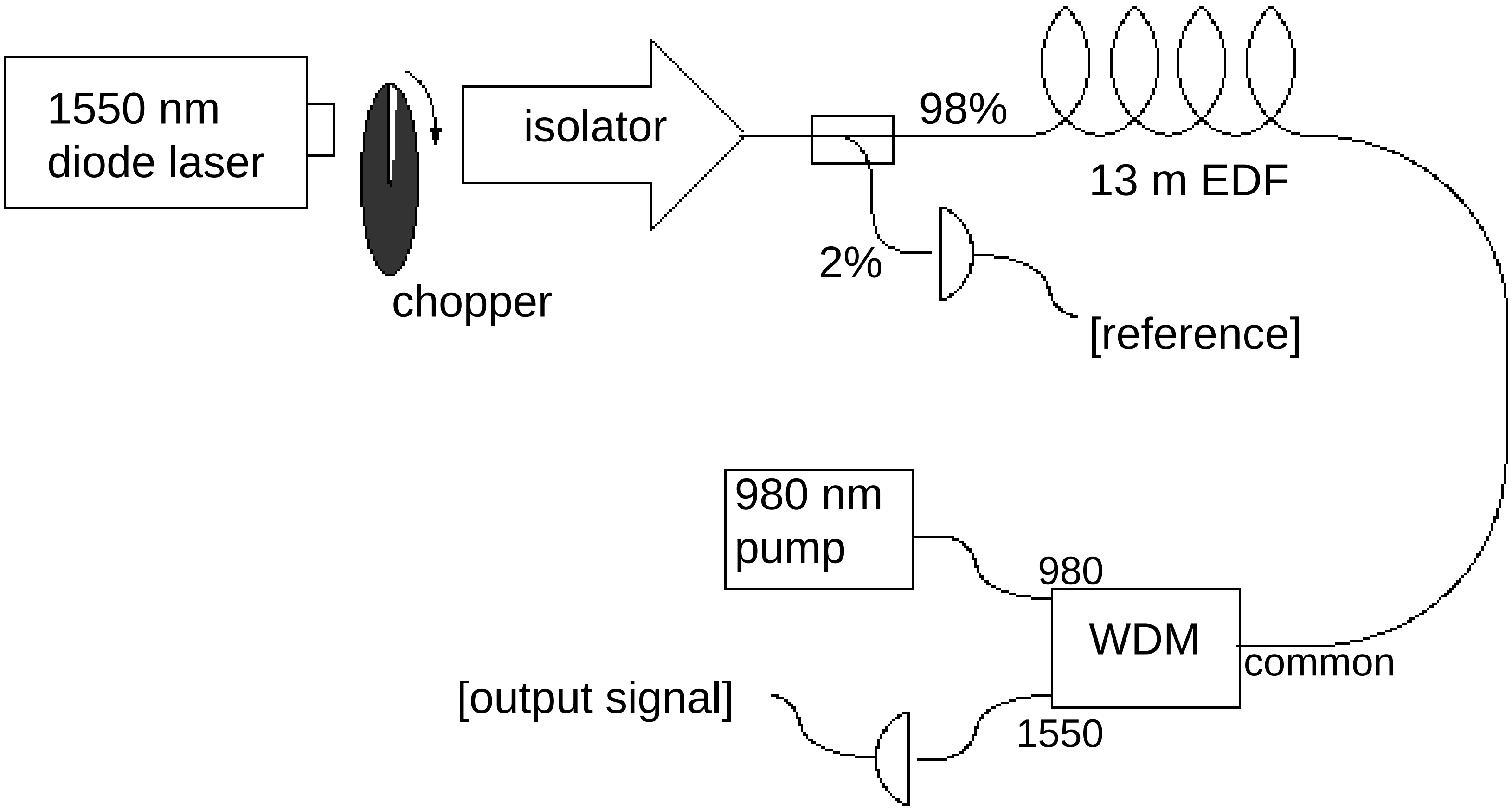


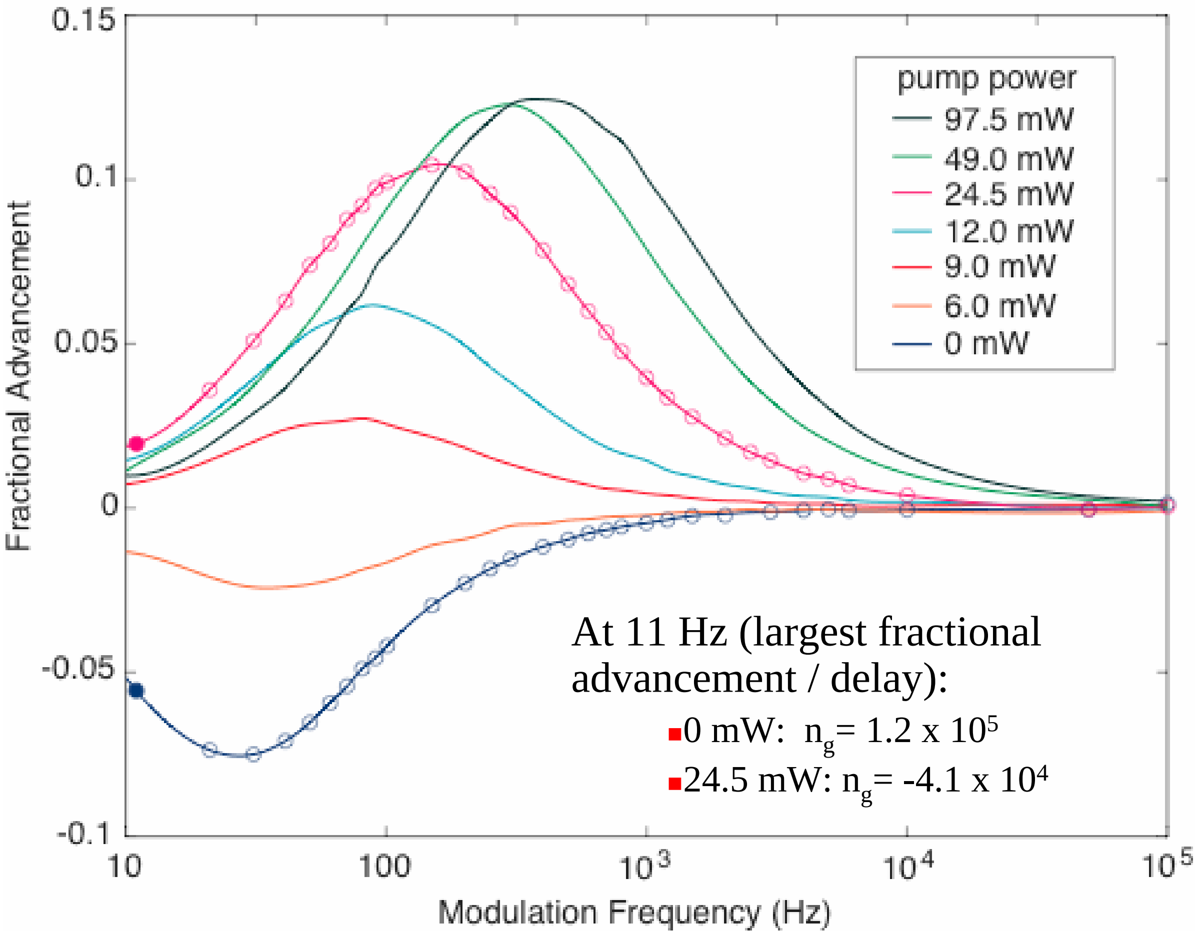

Input shaped either with current modulation from function generator (sinusoid) or with a chopper (Gaussian pulses)

# Experimental Setup (pulses)




Input shaped either with current modulation from function generator (sinusoid) or with a chopper (Gaussian pulses)

# Modulation frequency dependence of group velocity in EDF




- Traces with different pump powers, 0.8 mW of signal power
- Anomalous pulse propagation speeds occur over ~1.5 decades
  - magnitude and shift depend on pump and signal powers

# The Hole in the Gain and Absorption Spectra (measured)

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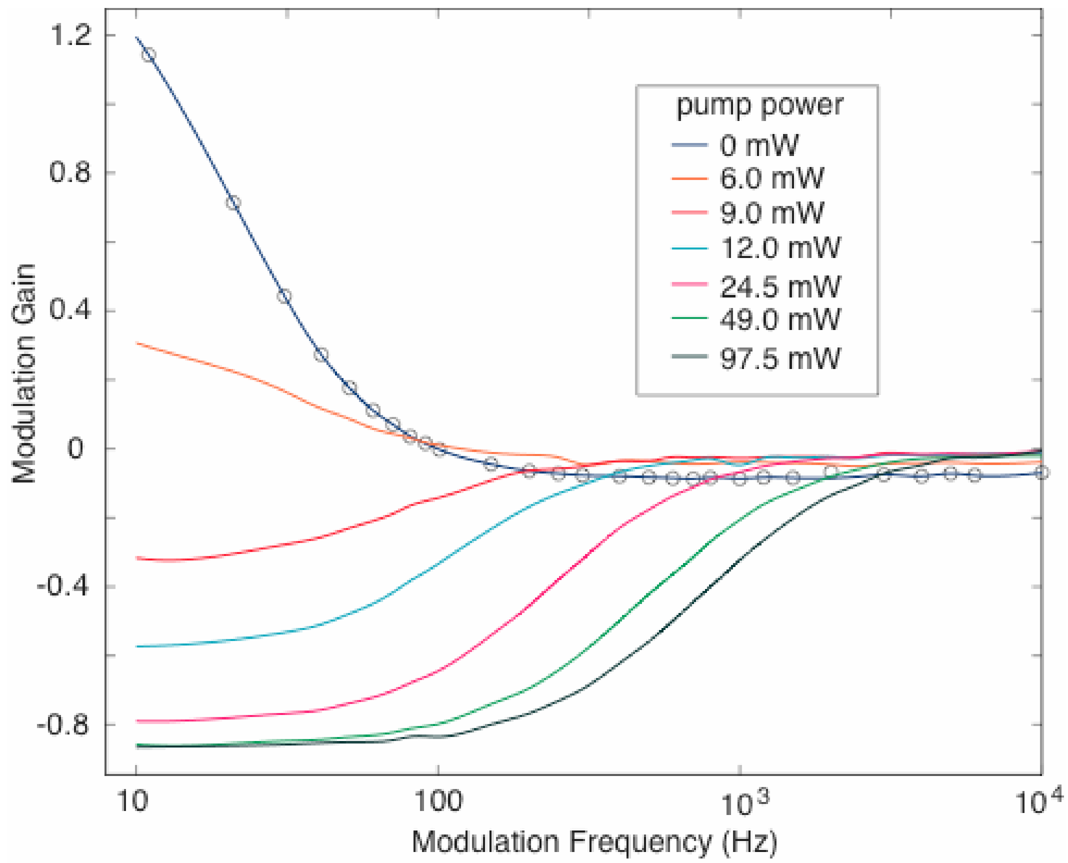
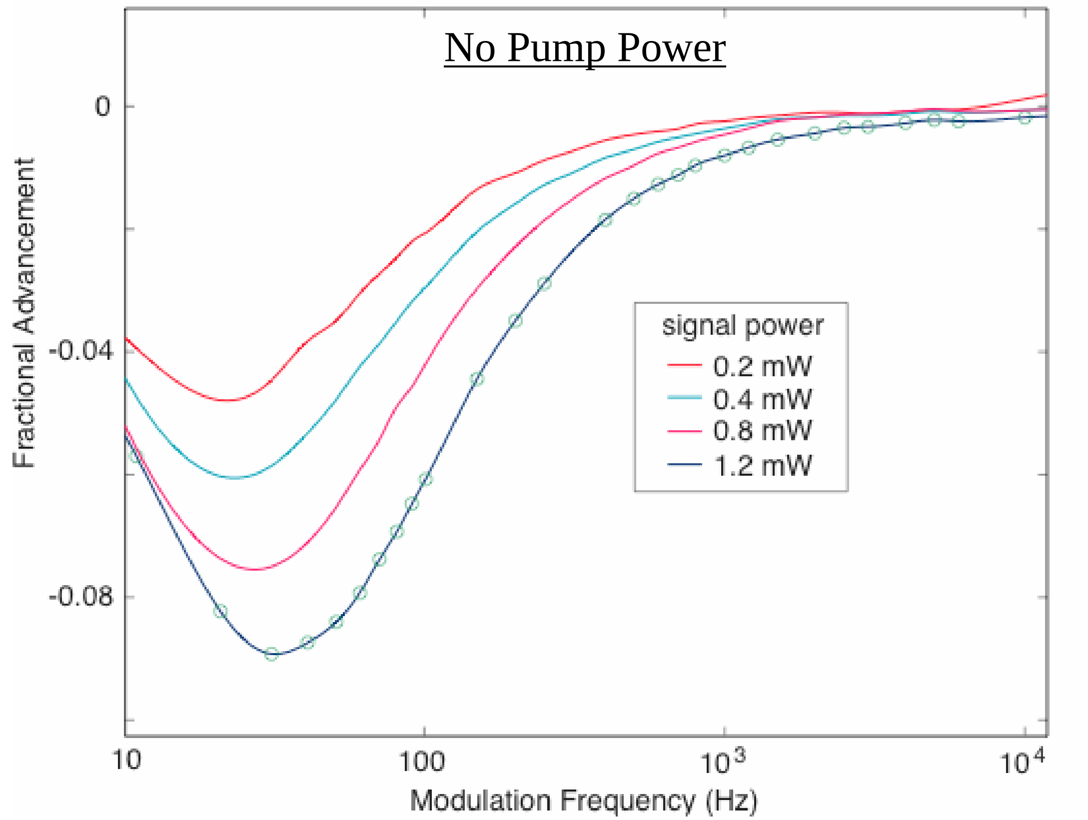



- As predicted by theory, the input field creates a spectral hole in the absorption or gain spectrum.
- With a minimum width of $1/\tau$, it is susceptible to power-broadening.

# Broadening From Signal Power



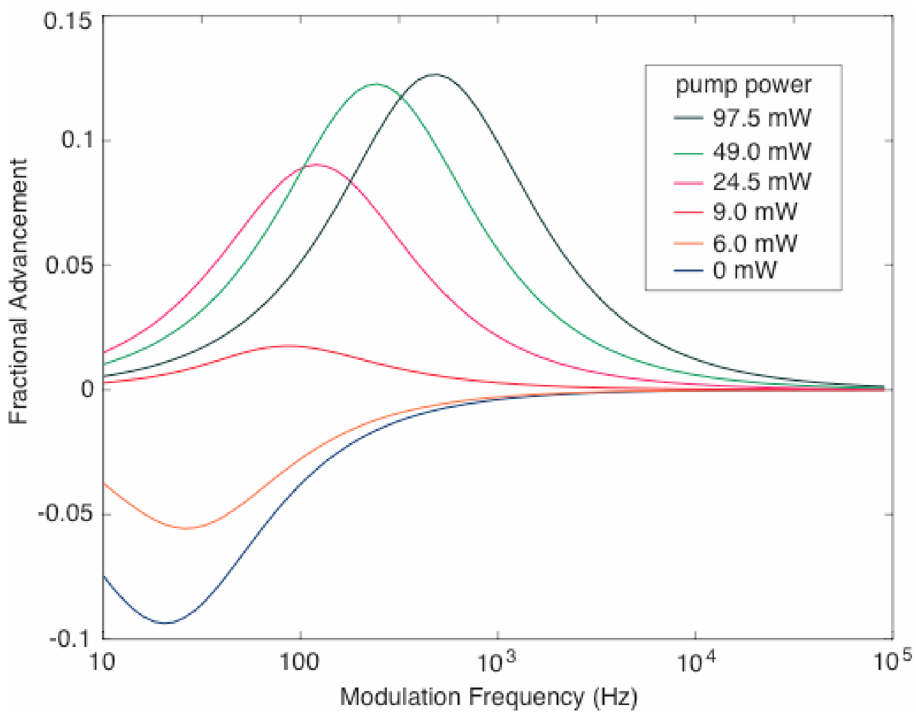



- With no pump, increasing the signal power will broaden the spectral hole significantly
- The magnitude of fractional delay is increased, and the peak is pushed to higher frequencies

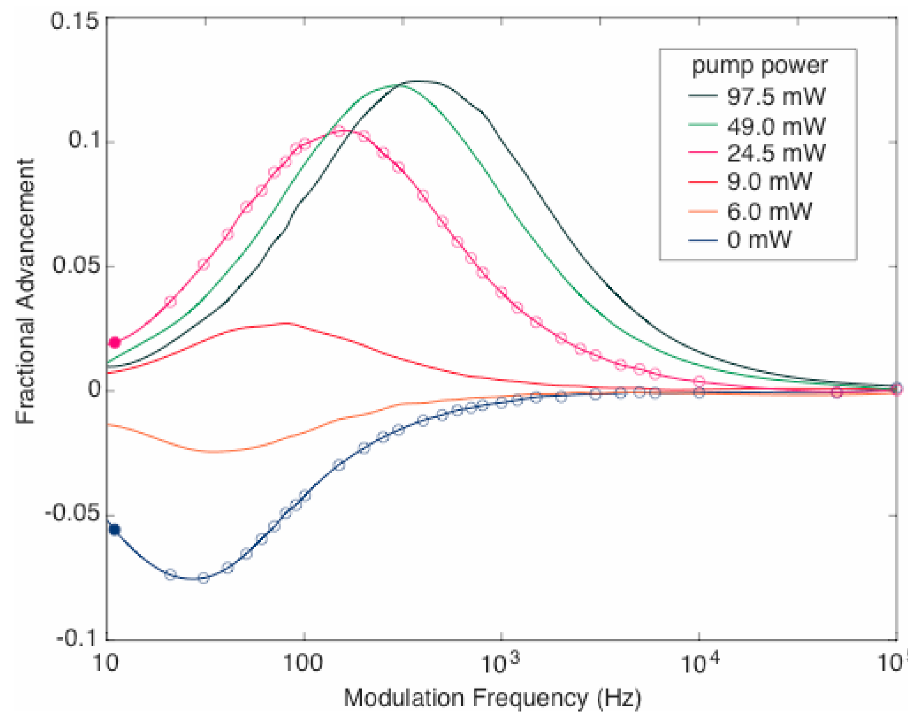
# Numerical Modeling



Model

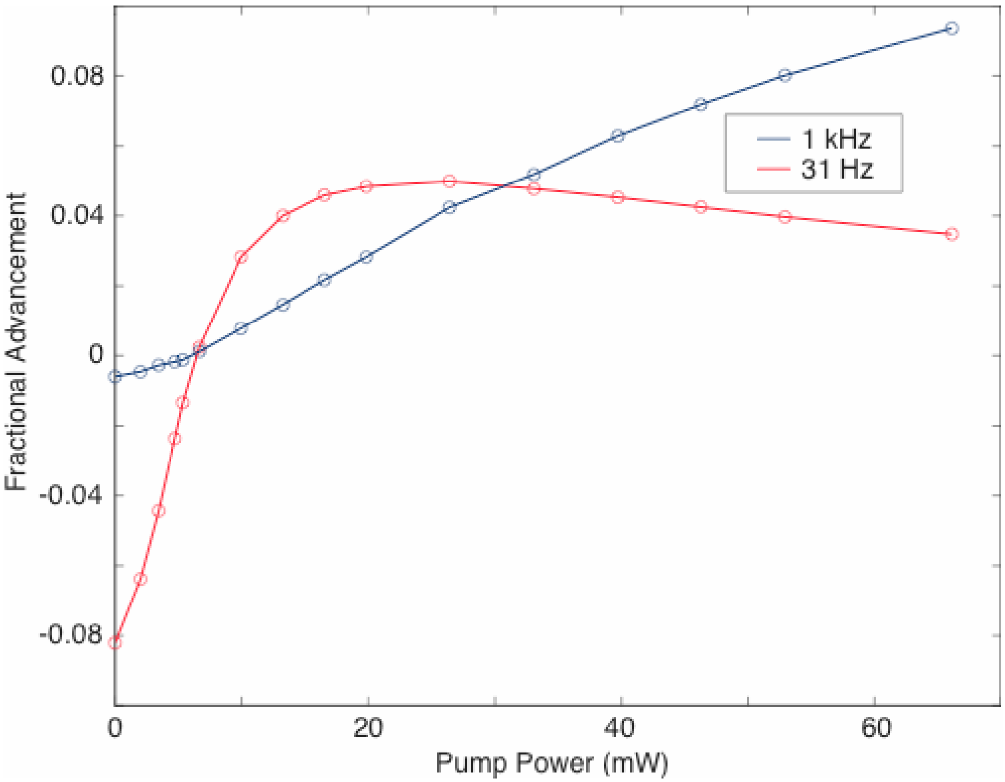



Experimental data




- Propagation equations can be solved numerically
- Simulations display good agreement with experimental results

# Tuning Delay with Pump Power




- For a given modulation frequency, the delay can be tuned continuously by changing the pump power
- Slow light <-> fast light!

# Delay and Advancement of Gaussian Pulses

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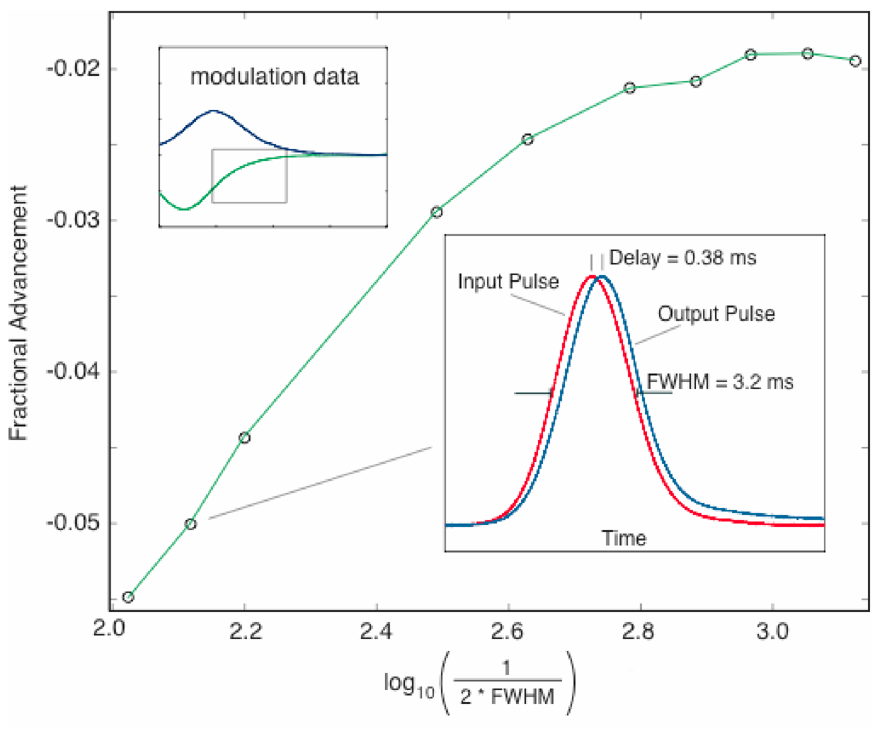
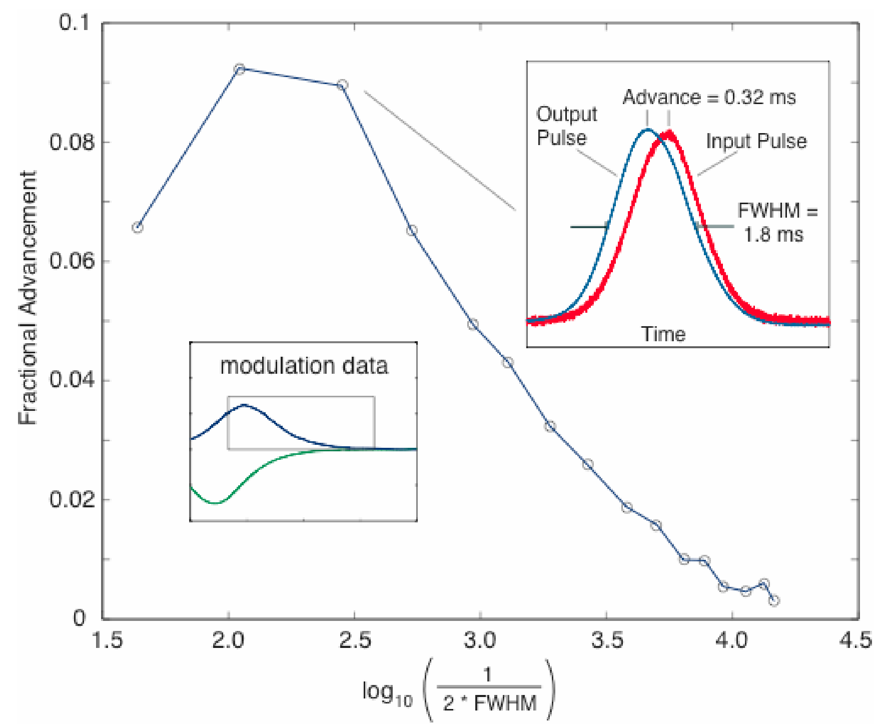
Slow light (0 mW pump)




Fast light (12 mW pump)




- 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