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
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.

\[ \nu_g = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}} \]

\( E_0, \omega_1 = \frac{2 \pi c}{1550 \text{ nm}} \)
\( E_m, \omega_m = \omega_1 + \Delta \)

Erbium Doped Fiber (pumped at 980 nm)

Measure relative absorption and delay
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, \( \rho \) is the Er ion density, \( \tau \) is the metastable level lifetime (\( \sim 10.5 \text{ ms} \)), \( I_p \) 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]

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:

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

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)

1550 nm diode laser

function generator

isolator

13 m EDF

980 nm pump

WDM

980 common

1550

[output signal]

[reference]

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

At 11 Hz (largest fractional advancement / delay):
- 0 mW: $n_g = 1.2 \times 10^5$
- 24.5 mW: $n_g = -4.1 \times 10^4$
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.
Propagation equations can be solved numerically

Simulations display good agreement with experimental results
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

Gaussian pulses propagate with a group velocity that is either slow or superluminal depending on pump power.

For pulses shown: \( n_g(\text{slow}) = 8.8 \times 10^3 \), \( n_g(\text{fast}) = -2100 \)
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