Observation of Backwards Pulse Propagation in Erbium Doped Fiber

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Slow and Fast Light

- In dispersive media, pulses propagate at the group velocity

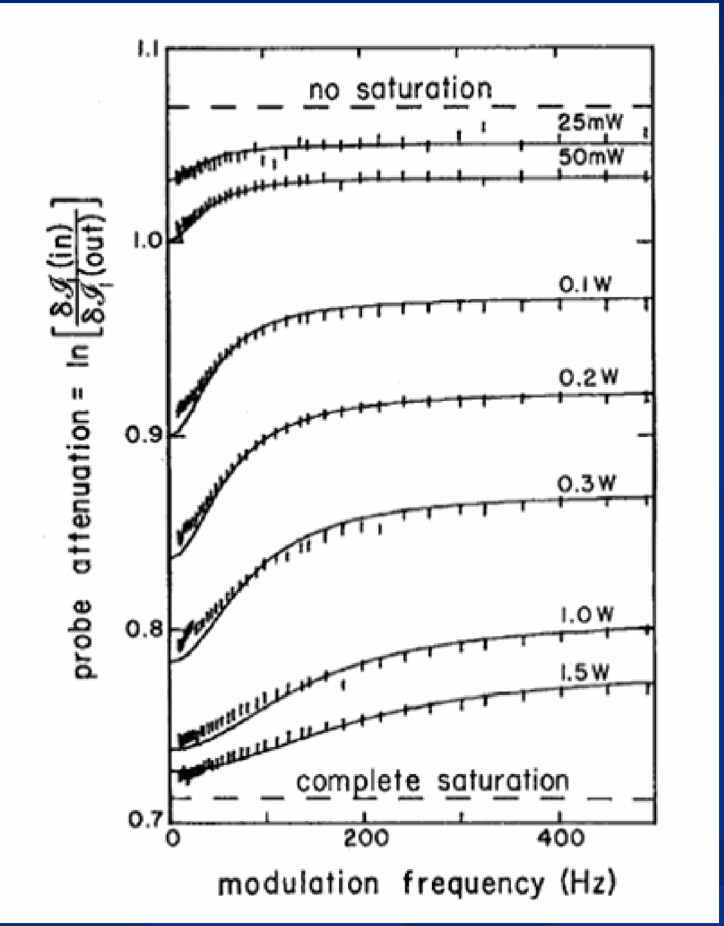
$$n_g = n + \omega \frac{dn}{d\omega}$$

- Dispersion and gain/absorption linked through the Kramers-Kronig relations
- Coherent Population Oscillations (CPO) utilized to create narrow spectral hole in an absorption or gain feature

Coherent Population Oscillations

- The excited state population oscillates at the beat frequency between pump and probe fields

- Resultant spectral hole can be very narrow, creating a rapid change in the refractive index

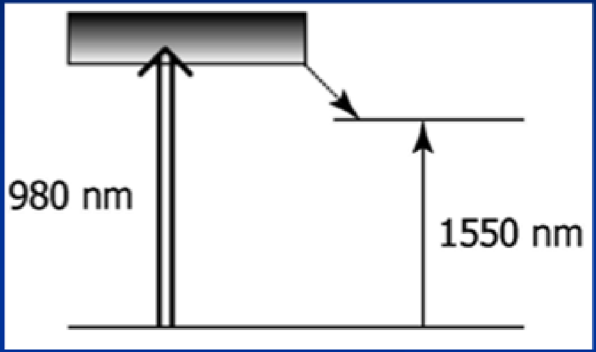


Coherent Population Oscillation effect in a ruby crystal.

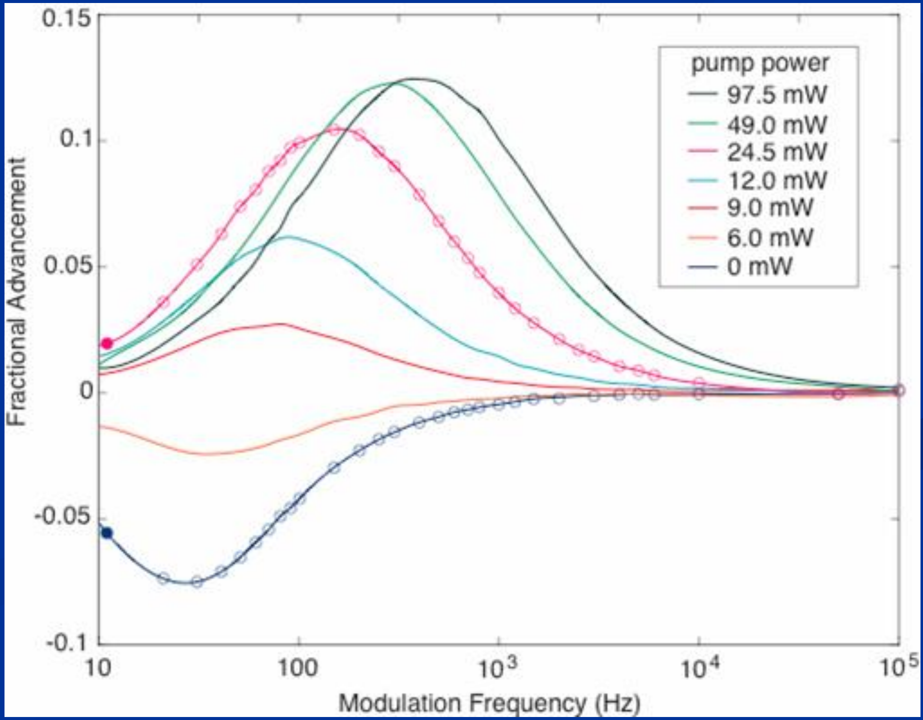
Hillman, Boyd, Krasinski and Stroud, Jr., *Optics Communications* **45,** No. 6, 416-419 (1983).

Why EDOF?

- Erbium doped optical fiber exhibits gain or loss depending on optical pumping power at 980 nm



- Fiber geometry is favorable
  - Tight confinement
  - Large interaction lengths



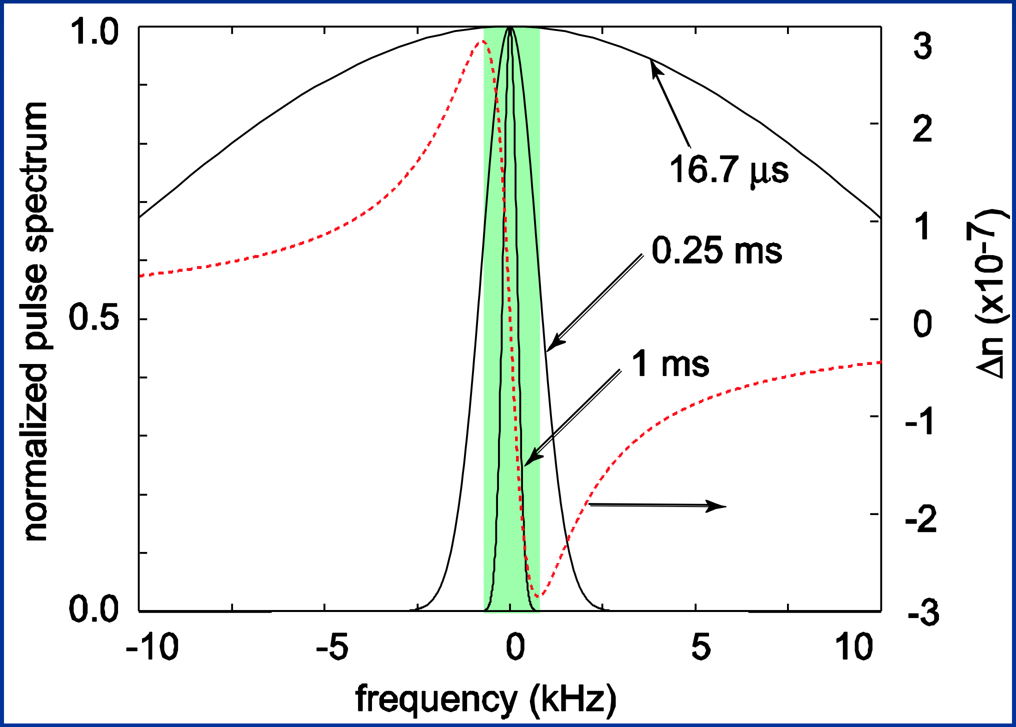
CPO Bandwidth

- "Useful" spectral region limited by the width of the spectral hole
- This width is inversely proportional to the excited state lifetime, and can be power broadened by the pump and signal fields

$$\Delta\omega = \frac{2}{\tau} + \frac{2\alpha_p I_p}{\rho} + \frac{2(\alpha_s + \beta_s) I_s}{\rho}$$

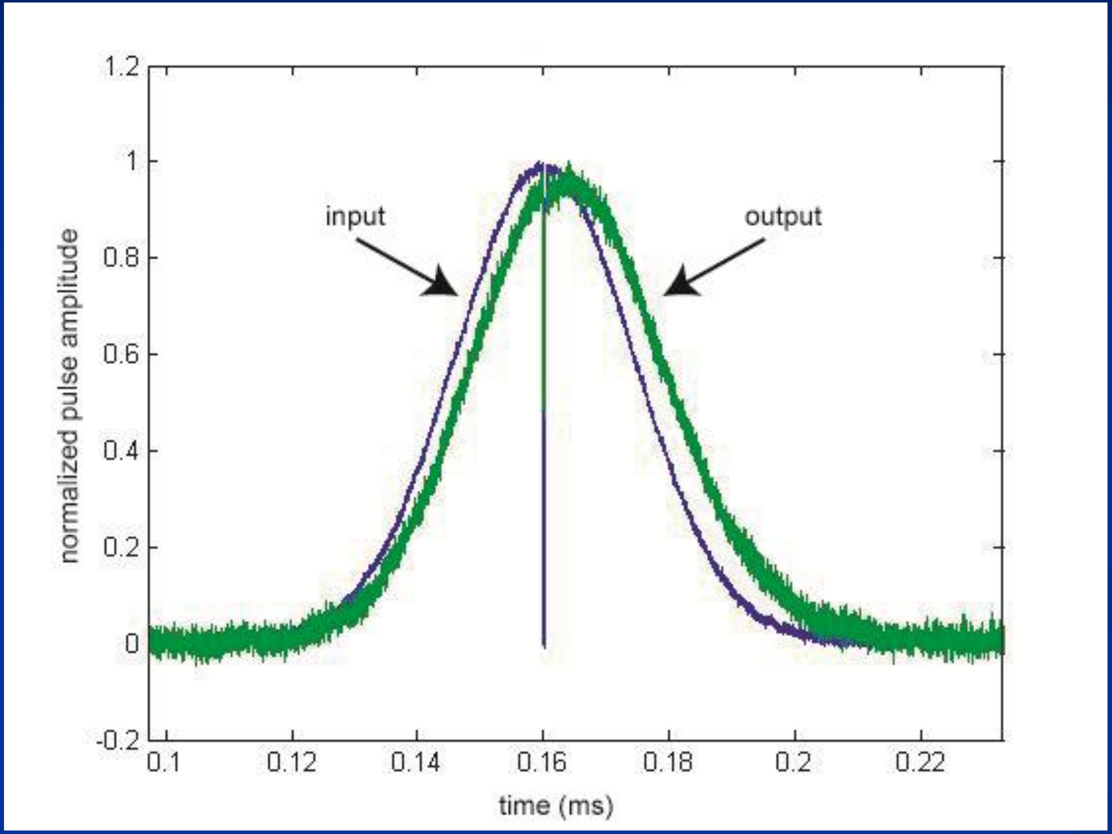
A. Schweinsberg, N. M. Lepeshkin, M. S. Bigelow, R. W. Boyd, S. Jarabo, *Europhysics Letters* **73**, Issue 2, p218 (2006).

Broad Spectral Components



- If the pulse contains spectral content that lies outside of this region, we expect the group velocity prediction to break down.
- If only a small part of the pulse power lies outside the window, the bulk of the pulse will still propagate at the expected group velocity.

Broad Spectral Components



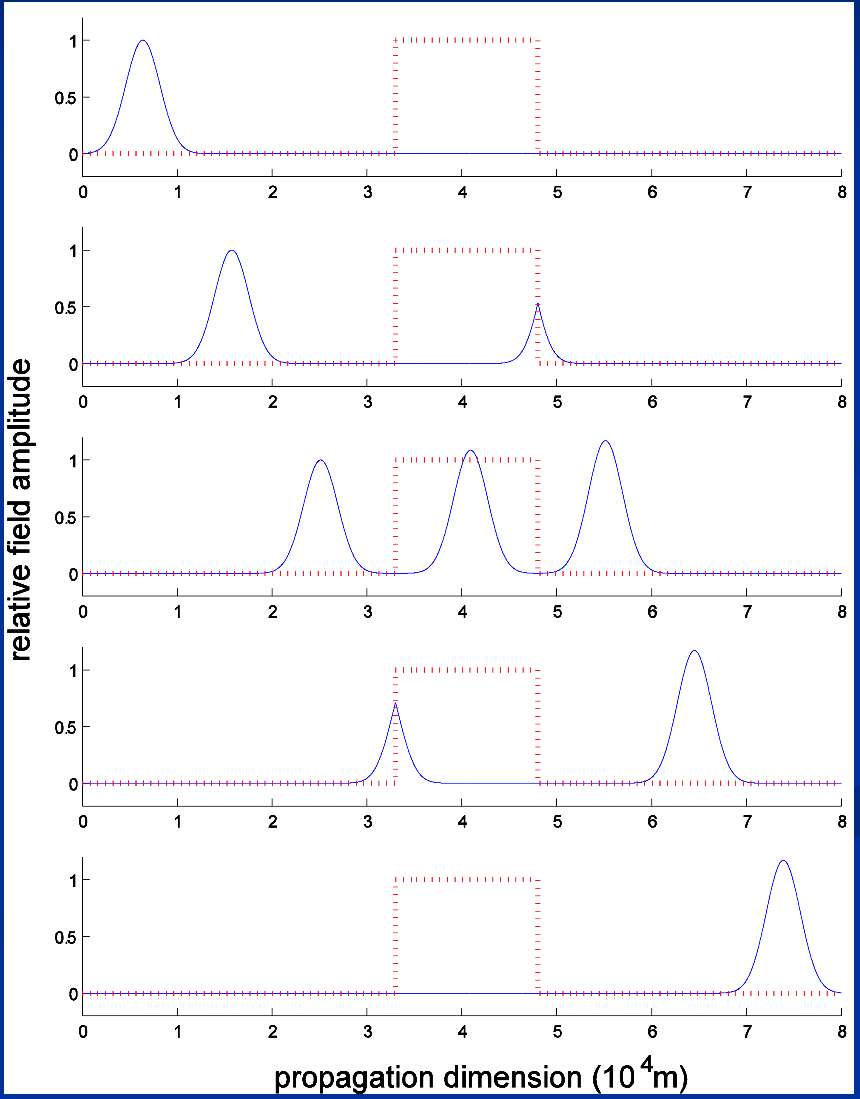
- Discontinuity propagates at phase velocity, while bulk of pulse experiences delay

Negative Group Velocity

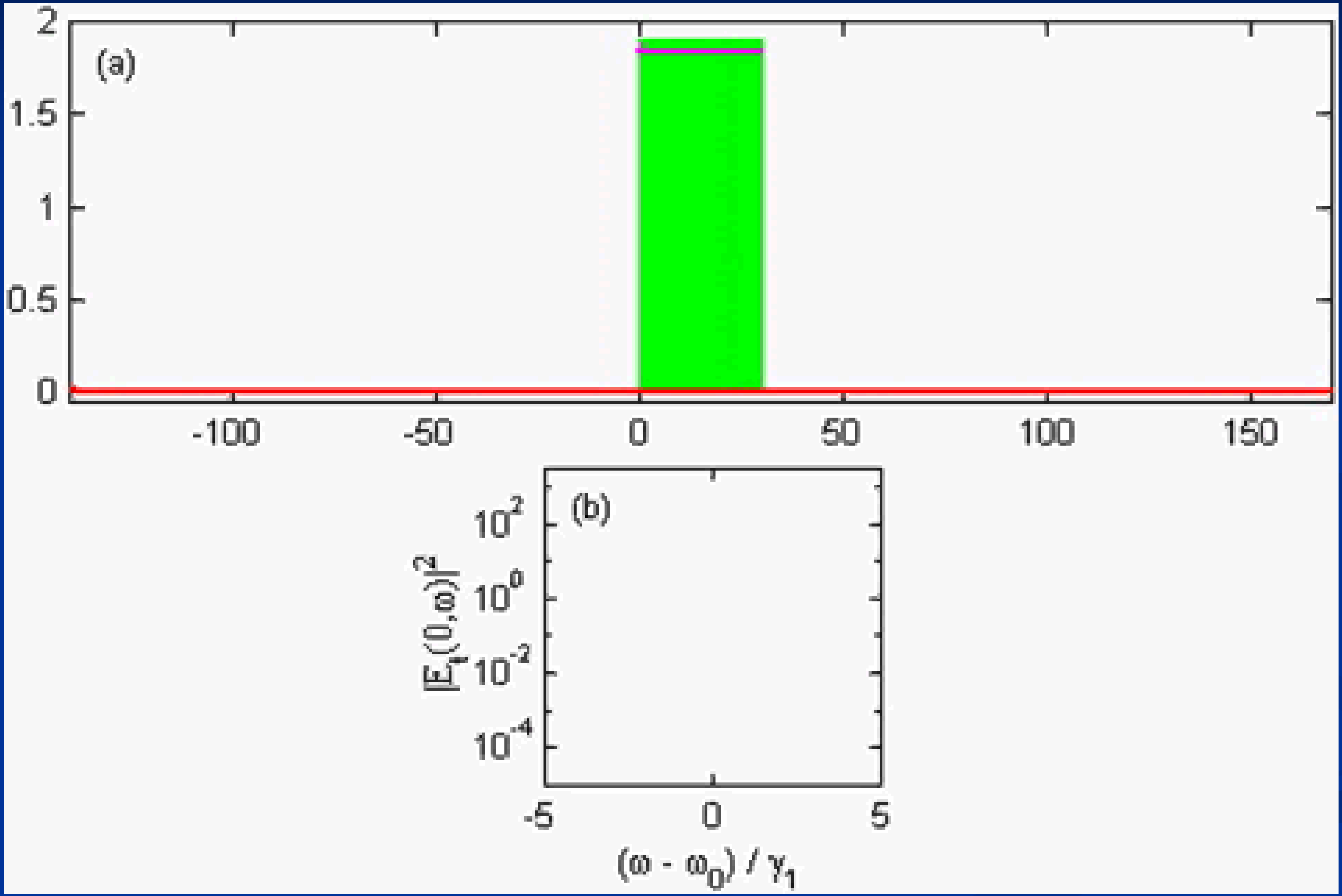
- When erbium fiber is pumped with 980nm light, it becomes an amplifier
- CPO will then create a spectral hole in the gain profile, making $dn/d\omega$ sufficiently negative
- The group velocity becomes negative
  - Pulse is advanced in time, with the peak of the output pulse exiting the material before the peak of the input pulse enters

Negative Group Velocity

- Inside the material, the peak is expected to travel backwards, linking output and input
- This inspires some important questions
  - Does this violate causality?
  - Is energy conserved, and if so, in what direction is energy flowing?



Instructional Video

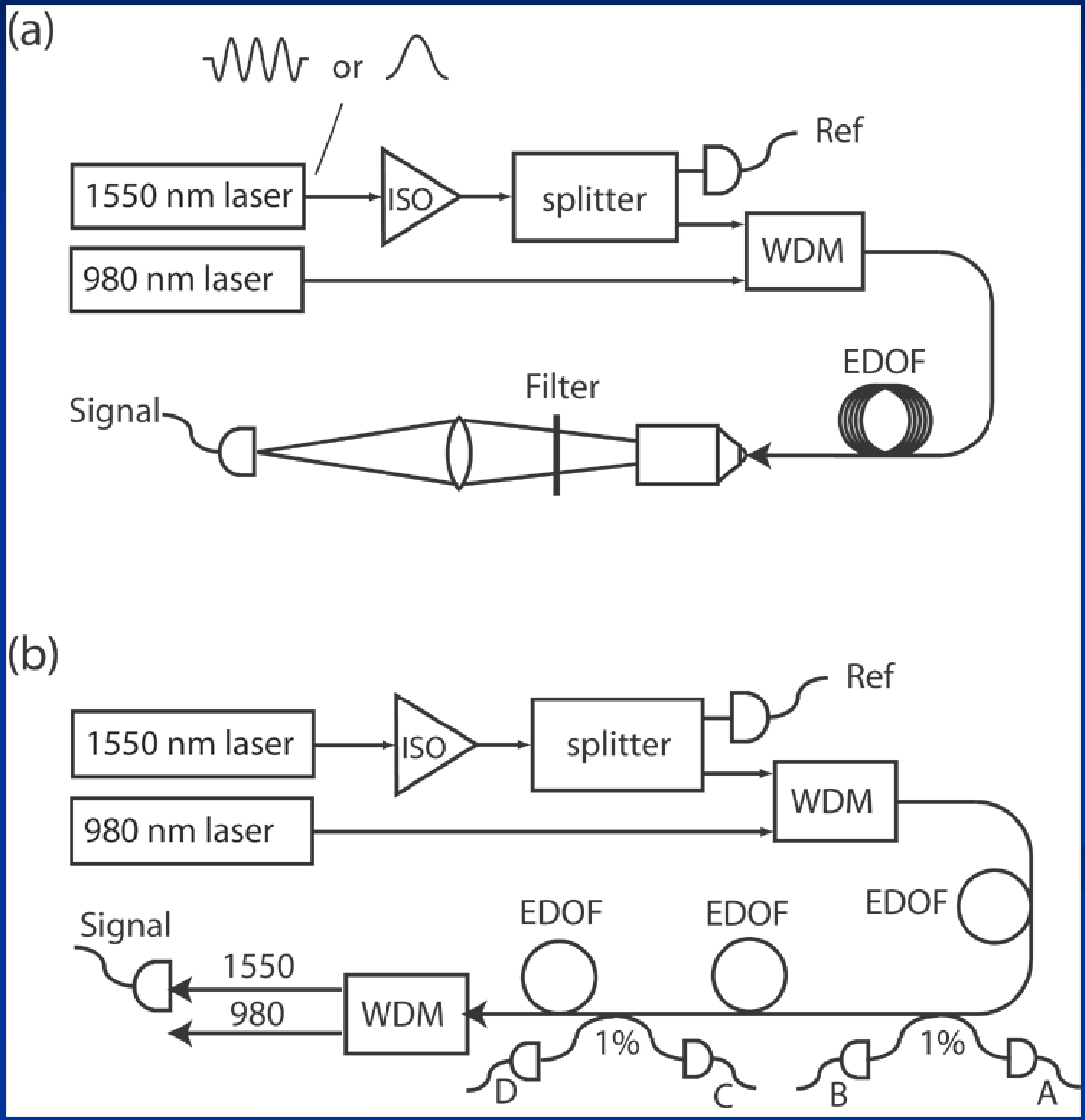


M. Ware, S. Glasgow, and J. Peatross, *Optics Express* **9**, 519-532 (2001)

Experimental Setup

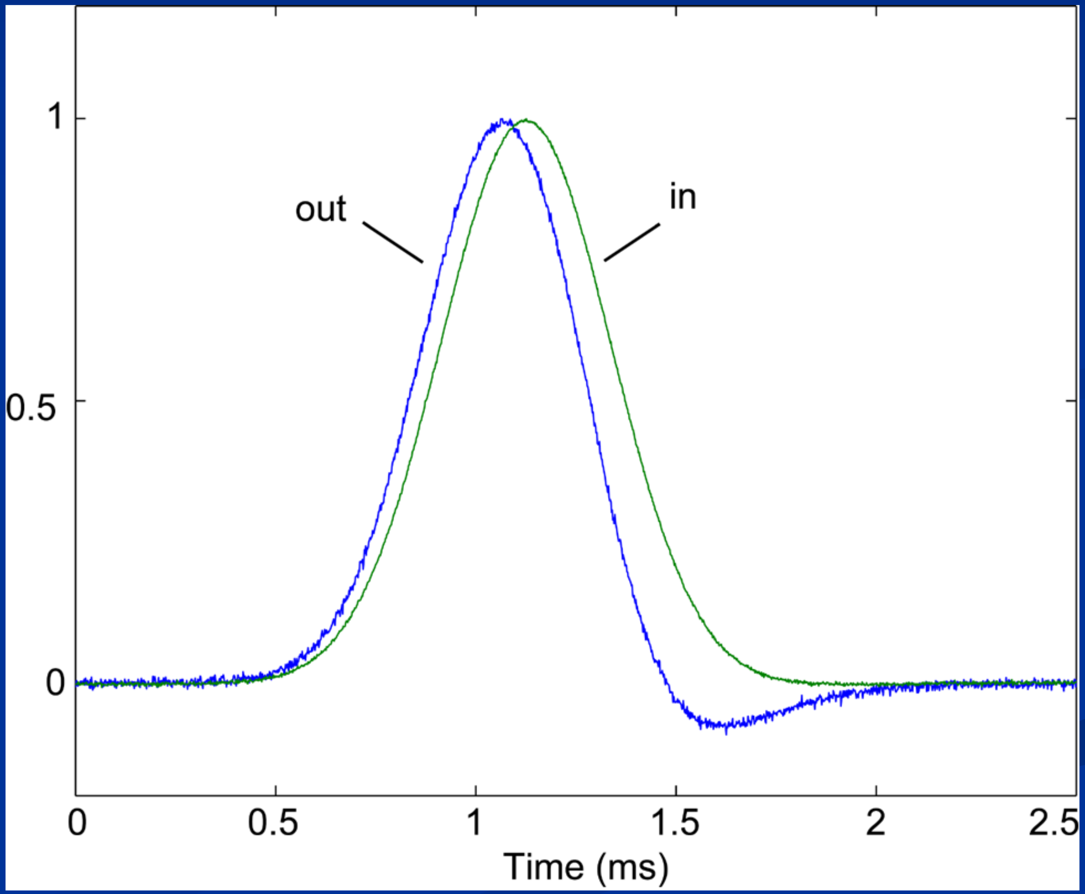
- Setup (a) is used to temporally resolve the propagation within the fiber.

- Setup (b) tests the direction of energy flow.

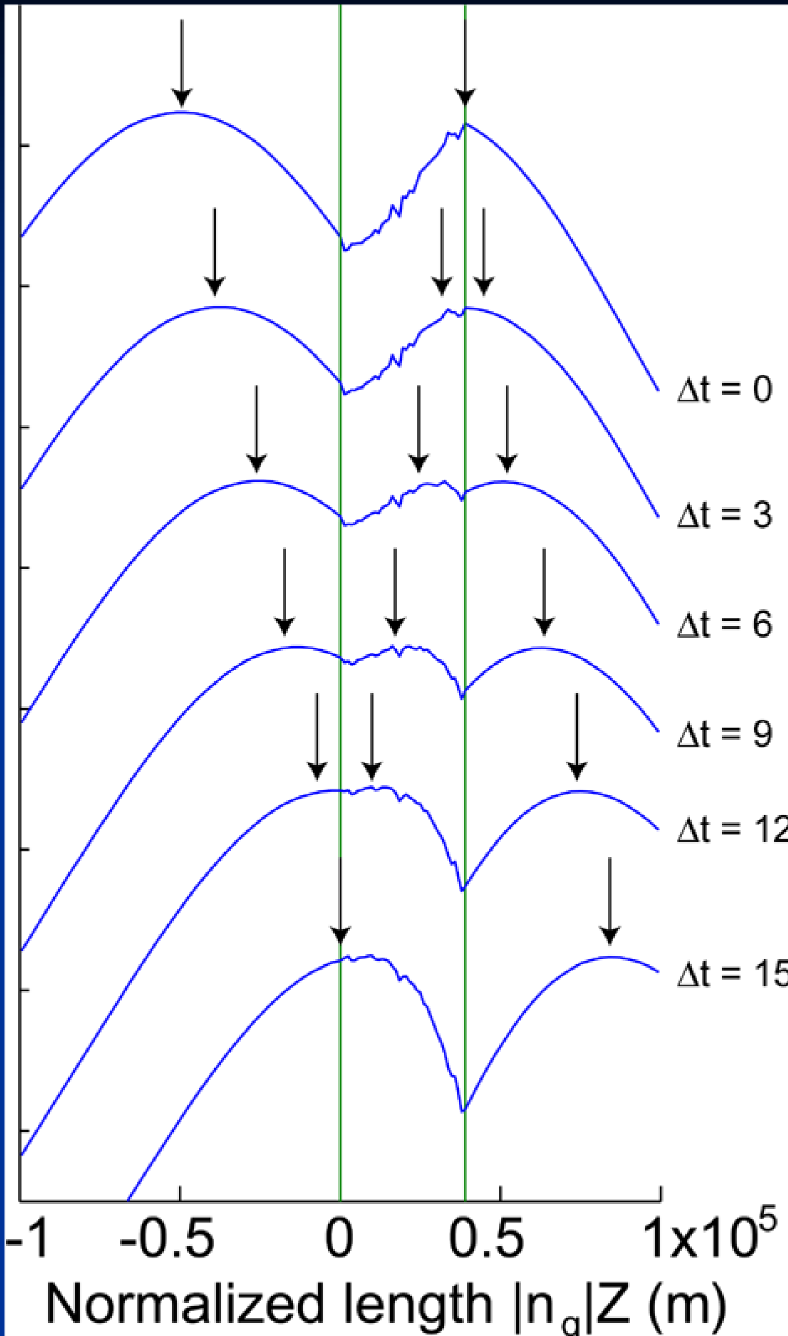


Example Data Trace

- Traces taken for lengths of fiber between 0 and 10 meters, in 25 cm intervals
- These traces are then arranged spatially and played back simultaneously



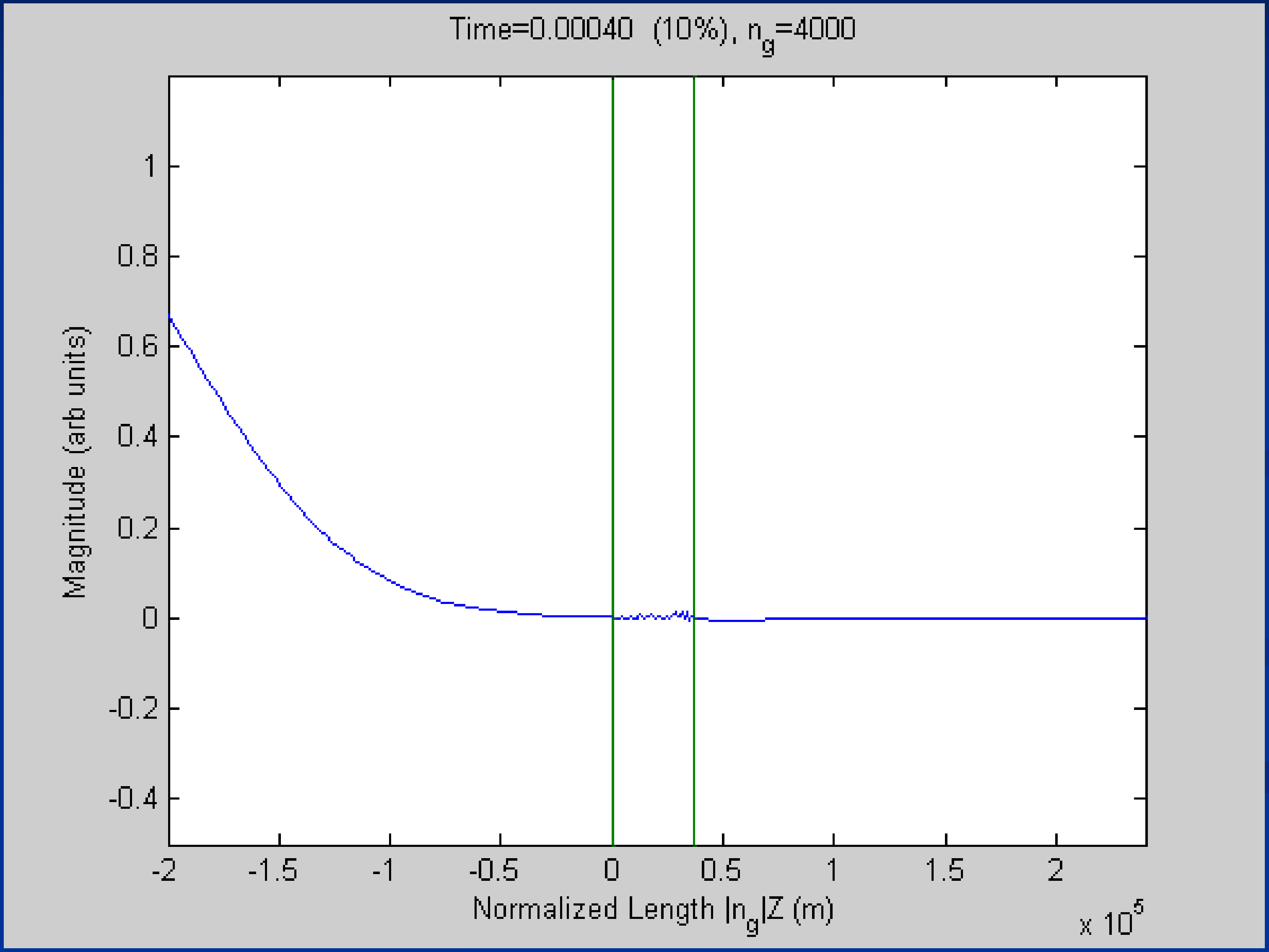
G. M. Gehring, A. Schweinsberg, R. W. Boyd, et al. *Science* **312**, 895 (2006).



Video Frames

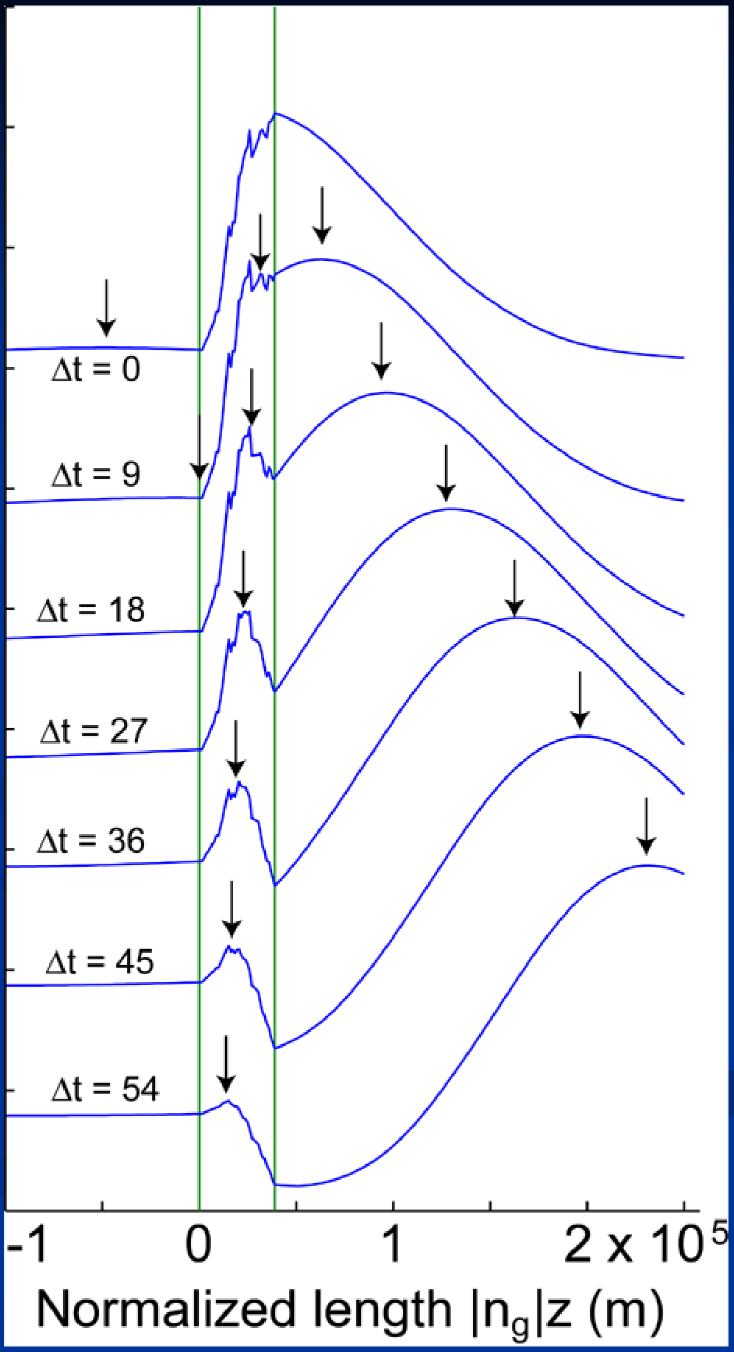
- Effects of gain removed to improve clarity
- Arrows emphasize peak positions inside and outside the material
- Peak position is clearly seen to travel from right to left inside the material
- $n_g \approx -4000$

Video – Gain Removed

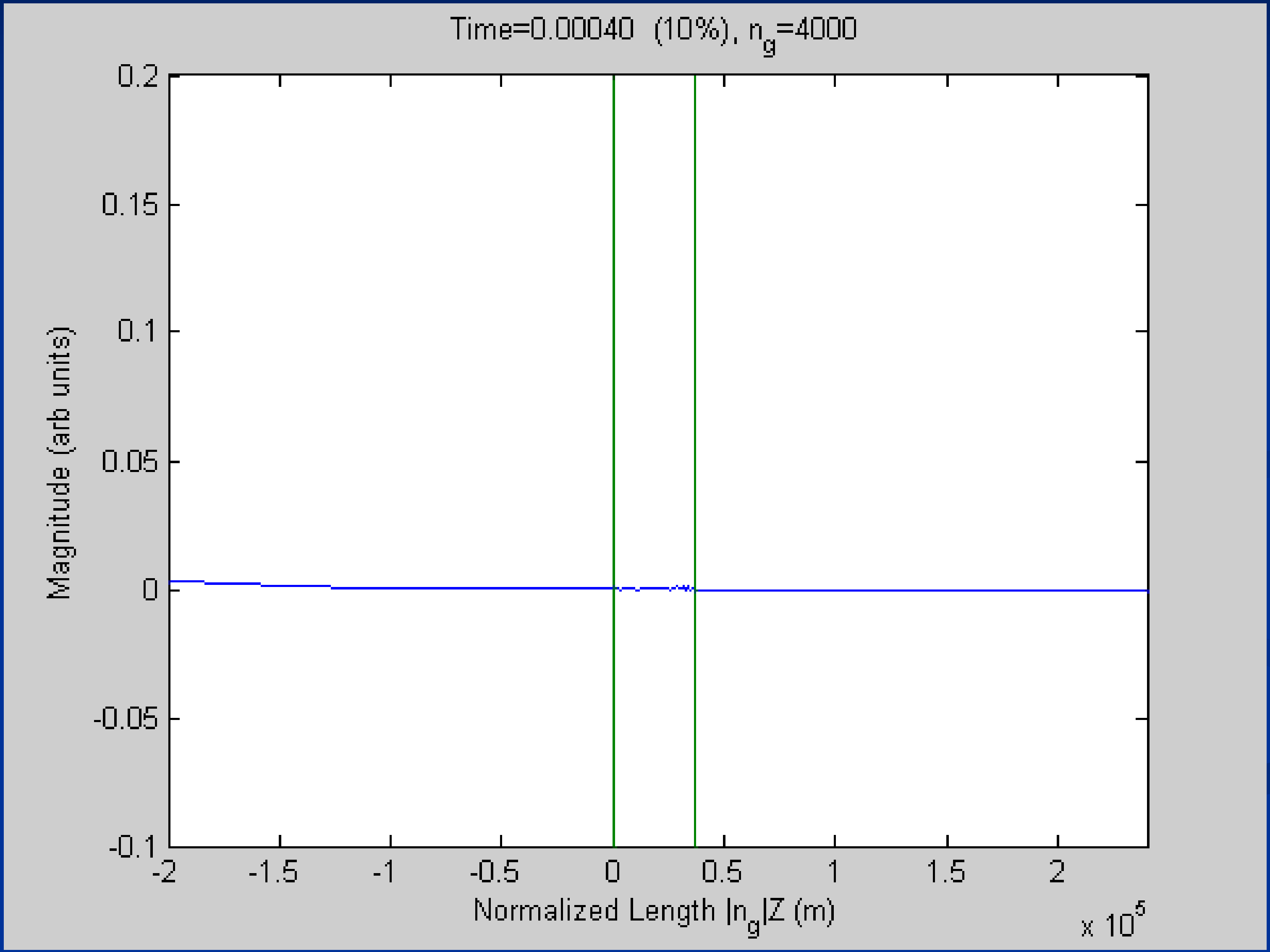


Video Frames

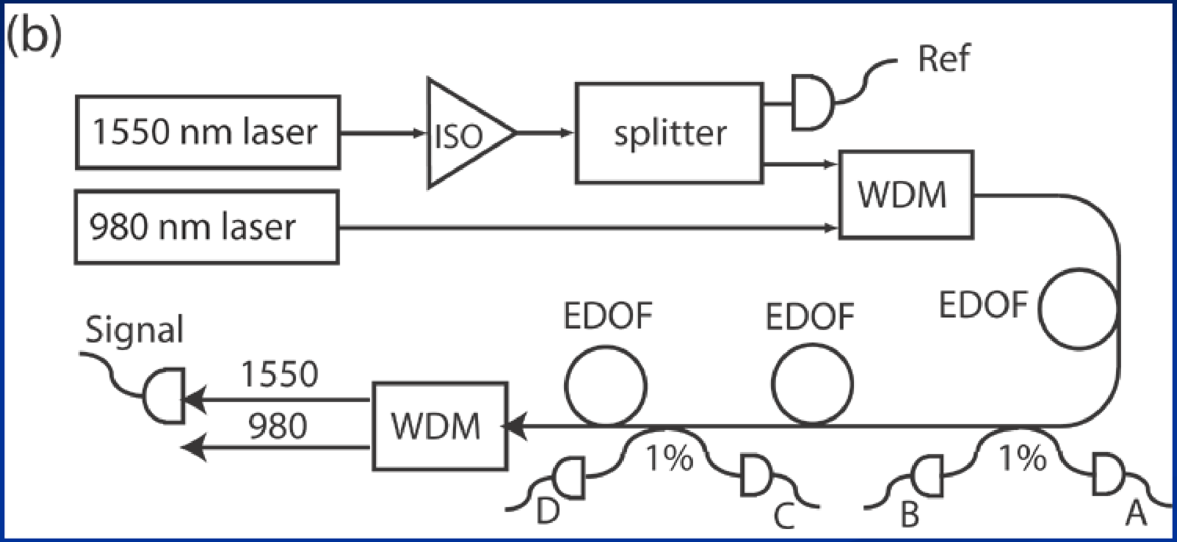
- Signal gain included
- Peak inside the material travels backward, but not with the predicted group velocity
- This is due to the exponential 'background' created by the signal gain.



Video – Gain Included



Energy Transport Direction



- When bi-directional couplers were added between segments of EDOF, the output on ports B and D agreed with previous results.
- Output on ports A and C were barely above noise threshold, and consistent with expected back reflections.

Summary

- Erbium doped fiber allows the study of exotic pulse propagation effects based on CPO
  - Propagation of discontinuities
  - Negative group velocities (backward propagation)
- For a pulse propagating through a medium with a negative group velocity
  - Pulse peak within the material moves backwards
  - Energy transport is always in the forward direction

Acknowledgements

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- http://www.optics.rochester.edu/~boyd/

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