Pulse broadening or compression in fast-light pulse propagation through an erbium-doped fiber amplifier

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CLEO / QELS, Baltimore, May 8

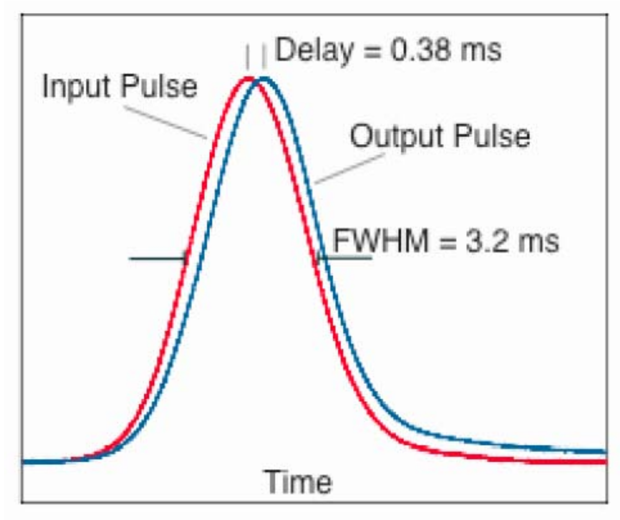
Motivation (Slow & fast light propagation)

- Application: telecommunication and information processing.*
- Requirement: Maximal delay (or advancement) with minimal distortion.
- Several investigations concerned with pulse-distortion compensation in slow-light pulse propagation.
  - D. Eliyahu, *et al*., *Opt*. *Lett*. **20**, 1412 (1995).
  - M. D. Stenner, *et al*., *Opt*. *Express* **13**, 9995 (2005).
  - K. Y. Song, *et al*., *Opt*. *Express* **13**, 9758 (2005).
- Pulse-on-background method for reducing pulse distortion in fast-light pulse propagation.
  - H. Shin, *et al*., *Opt*. *Lett*. **32**, 906 (2007).

* R. W. Boyd and D. J. Gauthier, *Nature* **441**, 701 (2006).

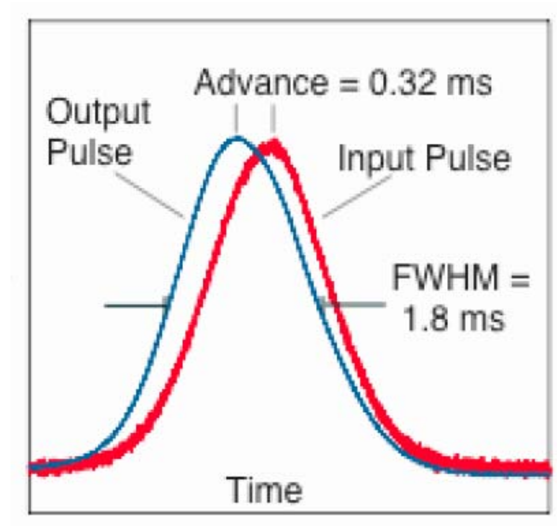
Slow & fast light in an EDFA

Slow-light



P_{pump} = 0 mW
n_g = 1.2 x 10^4

Fast-light



P_{pump} = 12 mW
n_g = - 5600

- Controllable delay (or advancement) by pump power.*
- Solid, room temperature, and 1550-nm wavelength.
- This large (or small or even negative) group refractive index, n_g, is induced by coherent population oscillation.

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* A. Schweinsberg, *et al.*, *Europhys. Lett.*, **73**, 218 (2006).

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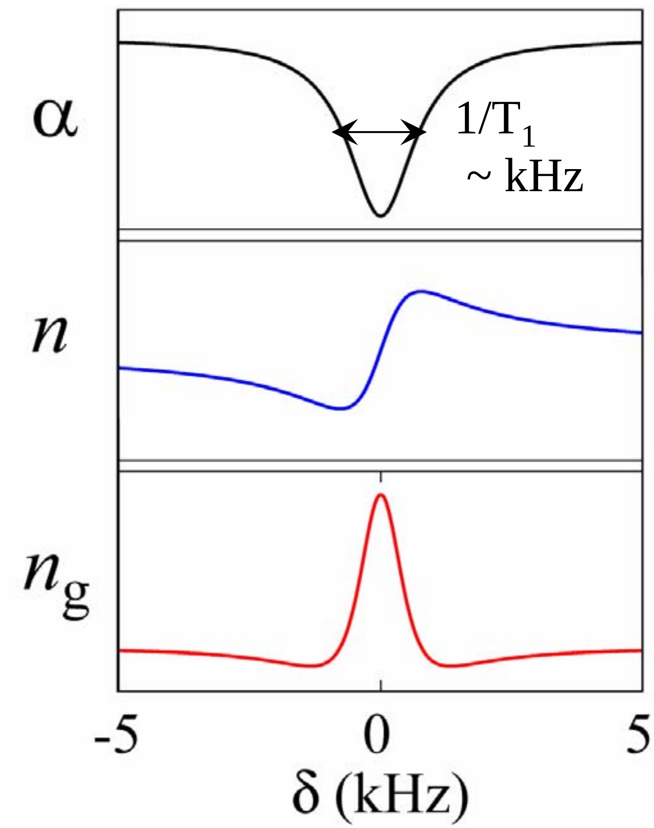
Coherent population oscillation

- Periodic modulation of the ground state population at the beat frequency between two fields can cause a dip in the broad absorption (or gain) spectrum.*

→ Coherent population oscillation (CPO)

- When $\delta \leq 1/T_1$, the absorption changes dramatically.

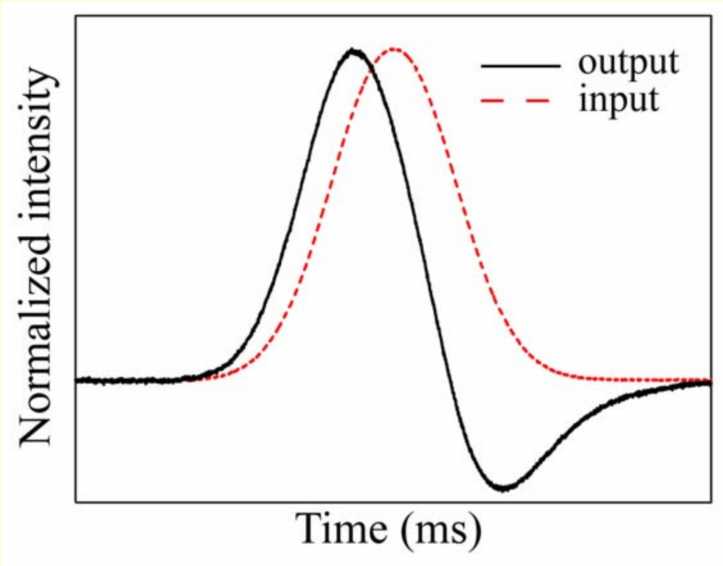
- A narrow dip in the broad absorption (or gain) induces large (or small) group refractive index.



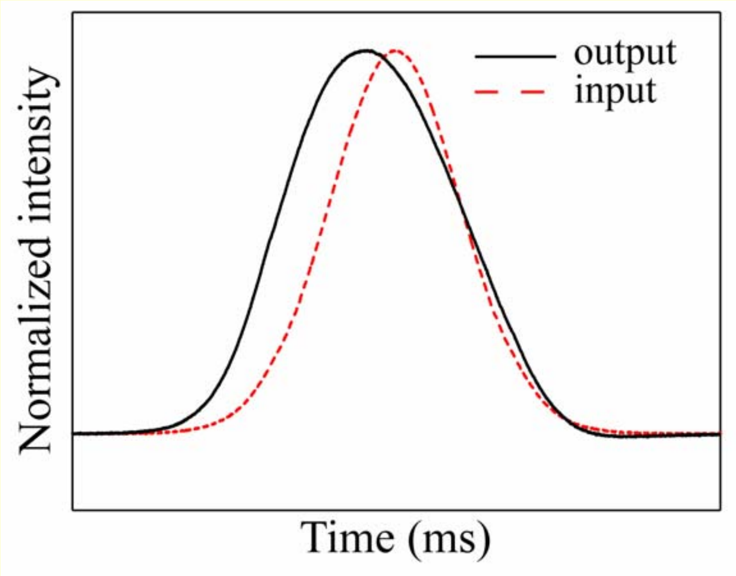
$$n_{group} = n + \omega \frac{dn}{d\omega}$$

* M. S. Bigelow, *et al.*, *Phy. Rev. Lett.* **90**, 113903 (2003)

Fast-light propagation in an EDFA



Pulse on a large background



Pulse on no background

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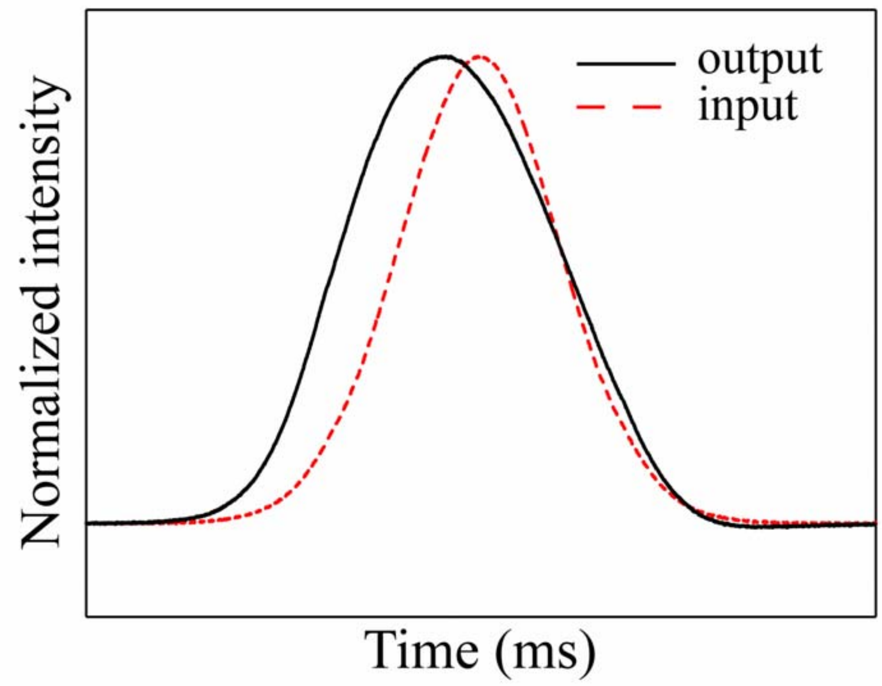
Mechanism for pulse broadening

- Fast light by CPO occurs in the nonlinear regime.

$$P_{sig} \gtrsim P_{sat}$$

- Without any background, the gain of an amplifier is saturated by the leading edge of a pulse.
- If $\tau_{\text{in}} \sim$ the lifetime of the metastable state, τ_{lifetime}, a strong P_{pump} can re-excite the amplifier.*
- The trailing edge of the pulse experiences the recovered gain, broadening the pulse.



Gain recovery

* G. P. Agrawal, *et al.*, *IEEE J. Quantum Electron*. **25**, 2297 (1989)

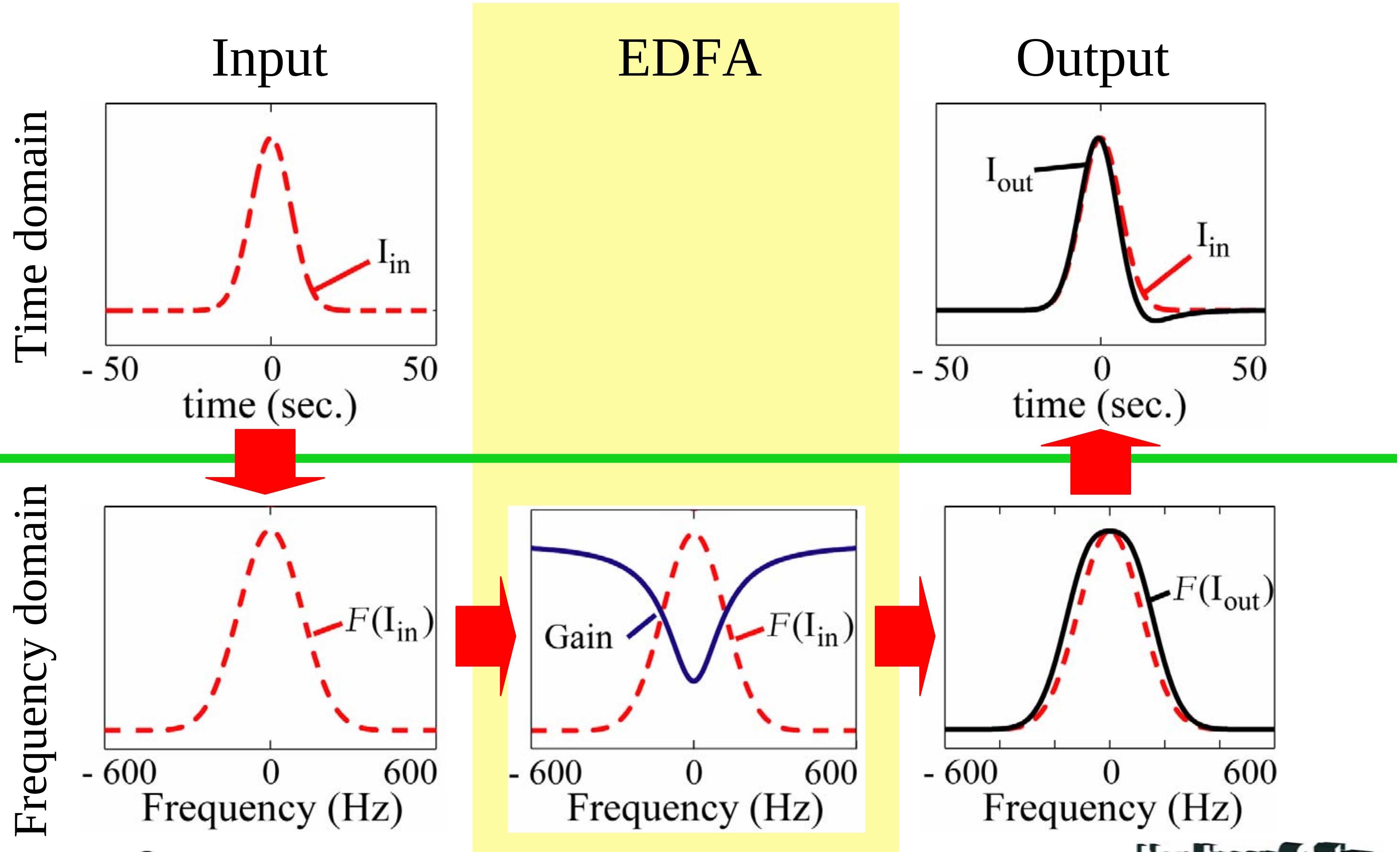
Mechanism for pulse compression

- Pulse propagation through a passive, linear, and anomalously dispersive medium always shows pulse compression and advancement.*
- A large background can induce a narrow dip in the broad gain spectrum in an EDFA.
- Output pulse spectrum is broadened in the frequency domain.
- In the time domain, output pulse is compressed.

Pulse spectrum broadening

* H. Cao, *et al.*, *IEEE J. Sel. Top. Quantum Electron*. **9**, 52 (2003)

Pulse spectrum broadening



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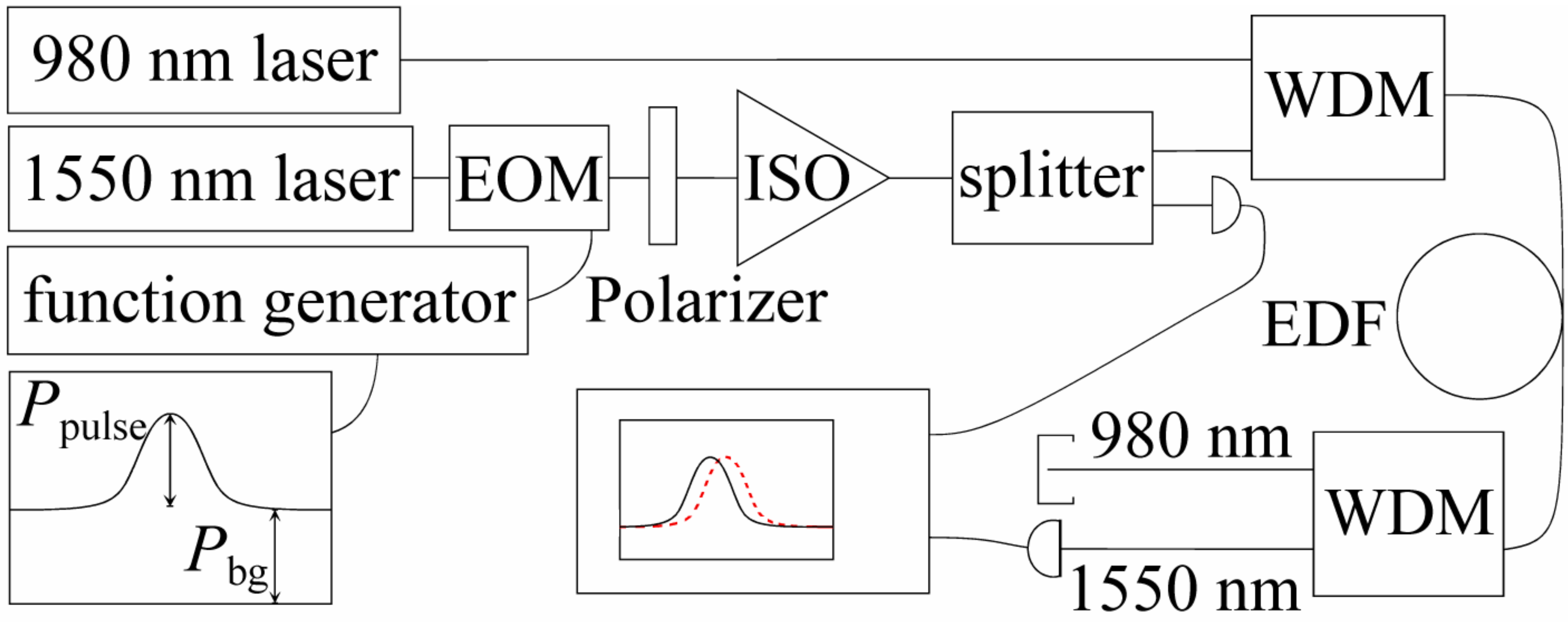
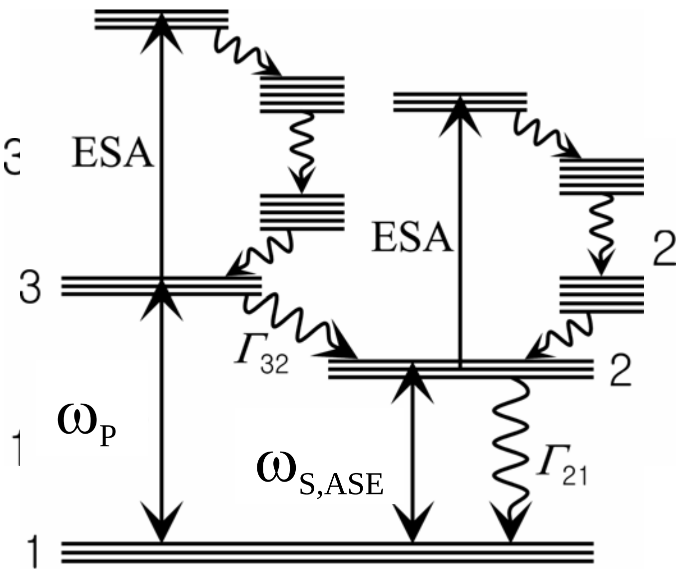
Experimental setup



EOM: Electro-optical modulator, ISO: Isolator, WDM: Wavelength division multiplexer, EDF: Erbium doped fiber, P_{pulse}: Peak power of the pulse, P_{bg}: background power

Energy-level diagram of Er^{3+}



$$\frac{dN_3}{dt}=\left(\frac{N_1\sigma^a(\nu_P)}{h\nu_P A_P}-\frac{N_3\sigma^e(\nu_P)}{h\nu_P A_P}\right)P_P-\frac{N_3}{\tau_{32}}$$

$$\frac{dN_2}{dt}=\sum_i\left(\frac{N_1\sigma^a(\nu_i)}{h\nu_i A_i}-\frac{N_2\sigma^e(\nu_i)}{h\nu_i A_i}\right)P_{S,ASE}(\nu_i)-\frac{N_2}{\tau_{21}}+\frac{N_3}{\tau_{32}}$$

$$\frac{dN_1}{dt}=\sum_i\left(\frac{N_2\sigma^e(\nu_i)}{h\nu_i A_S}-\frac{N_1\sigma^a(\nu_i)}{h\nu_i A_S}\right)P_{S,ASE}(\nu_i)+\left(\frac{N_3\sigma^e(\nu_P)}{h\nu_P A_P}-\frac{N_1\sigma^a(\nu_P)}{h\nu_P A_P}\right)P_P+\frac{N_2}{\tau_{21}}$$

$$\frac{dP_{ASE}^{\pm}(z,\nu_i)}{dz}=\pm\frac{Ac}{As}\left[N_2(z)\sigma^e(\nu_i)-N_1(z)\sigma^a(\nu_i)\right]P_{ASE}^{\pm}(z,\nu_i)\pm\frac{Ac}{As}N_2(z)\sigma^e(\nu_i)2h\nu_i\left(\frac{\Delta\nu_i}{n}\right)$$

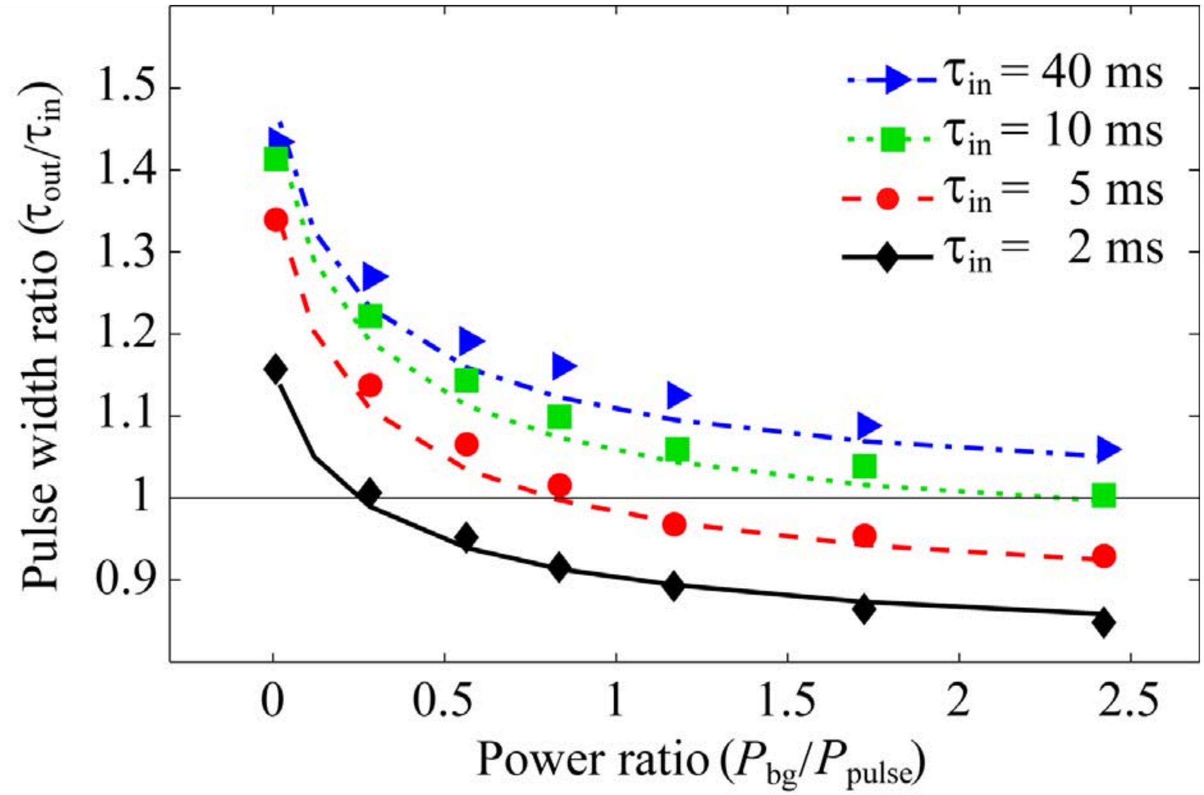
$$\frac{dP_S(z,\nu_S)}{dz}=\frac{Ac}{As}\left[N_2(z)\sigma^e(\nu_S)-N_1(z)\sigma^a(\nu_S)\right]P_S(z,\nu_S)$$

$$\frac{dP_P(z,\nu_P)}{dz}=-\frac{A_c}{A_P}\left\{N_1(z)\sigma^a(\nu_P)-N_3(z)\sigma^e(\nu_P)+[N_3(z)+N_2(z)]\sigma^a_{ESA}(\nu_P)\right\}P_P(z,\nu_P)$$

P. F. Wysocki *et al.*, *Proc. SPIE* **1789**, 66 (1992).

Pulse width ratio (τ_{out} / τ_{in})

For various pulse widths



- P_{pump} = 35 mW

→ $(N_e - N_g)/N_e = 0.9$

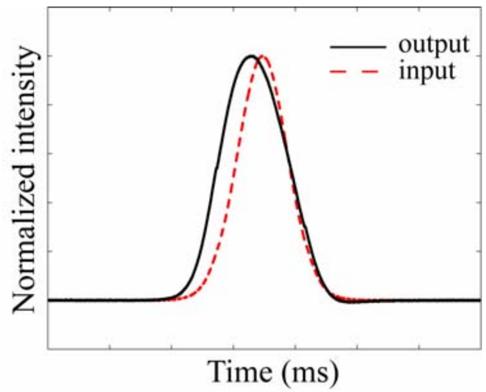
- P_{pulse} = 55 μW

: Theory

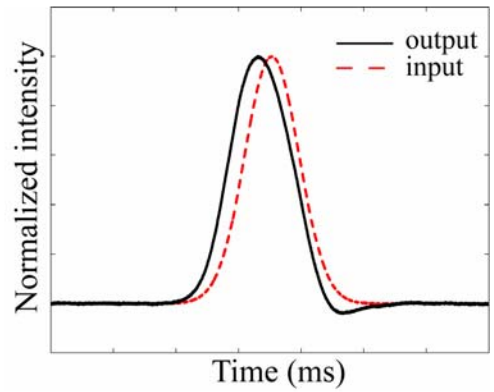
: Experiment

Normalized Input & output pulses

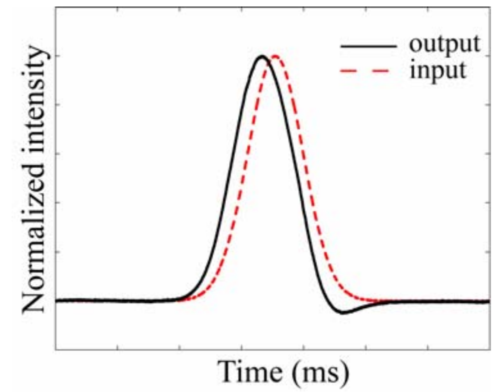
$\tau_{in} = 5$ ms



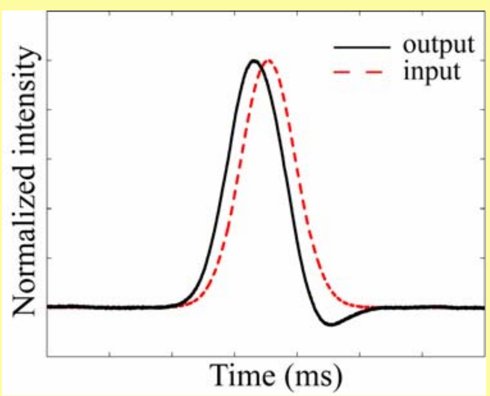
$P_{bg}/P_{pulse} = 0$



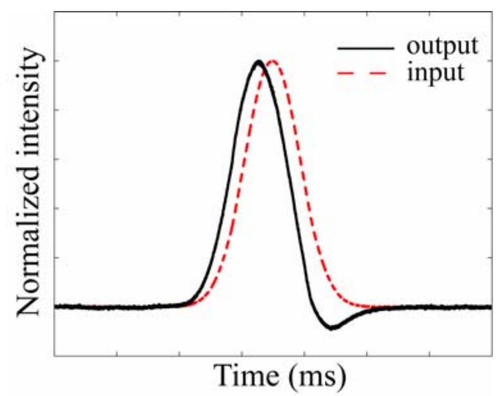
$P_{bg}/P_{pulse} = 0.25$



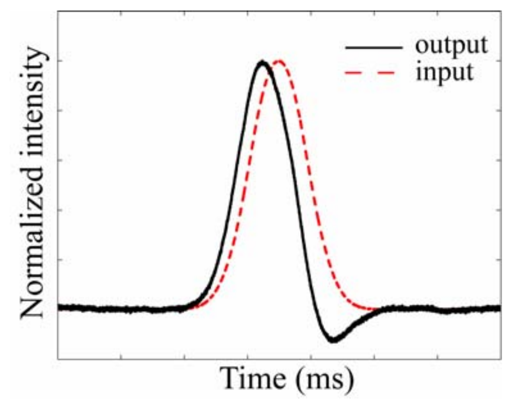
$P_{bg}/P_{pulse} = 0.5$



$P_{bg}/P_{pulse} = 0.8$



$P_{bg}/P_{pulse} = 1.15$

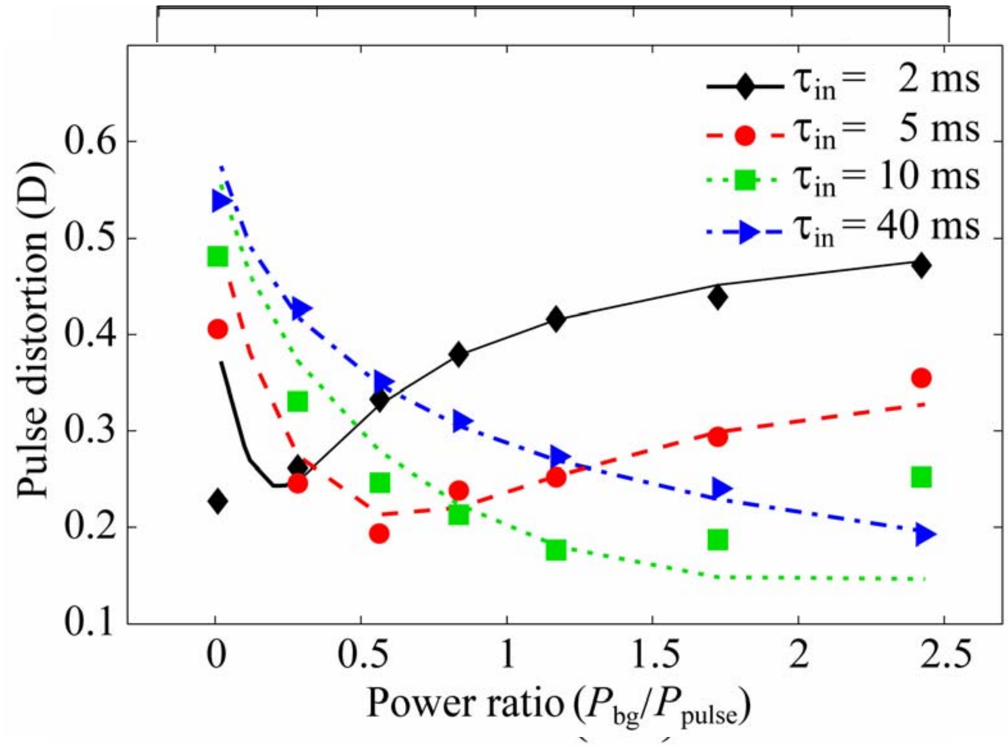


$P_{bg}/P_{pulse} = 2.4$

Pulse-shape distortion

For various pulse widths

$$D = \left(\frac{\int_{-\infty}^{\infty} \left| |E'(t+\Delta t)|^2 - |E(t)|^2 \right| dt}{\int_{-\infty}^{\infty} |E'(t+\Delta t)|^2 dt} \right)^{1/2} - \left(\frac{\int_{-\infty}^{\infty} \left| |E(t+\delta t)|^2 - |E(t)|^2 \right| dt}{\int_{-\infty}^{\infty} |E(t+\delta t)|^2 dt} \right)^{1/2}$$



E'(t) and *E*(t): the normalized output and input field envelopes.

Δt : the time advancement of the pulse.

δt : the temporal resolution of our detection system.

: Theory

: Experiment

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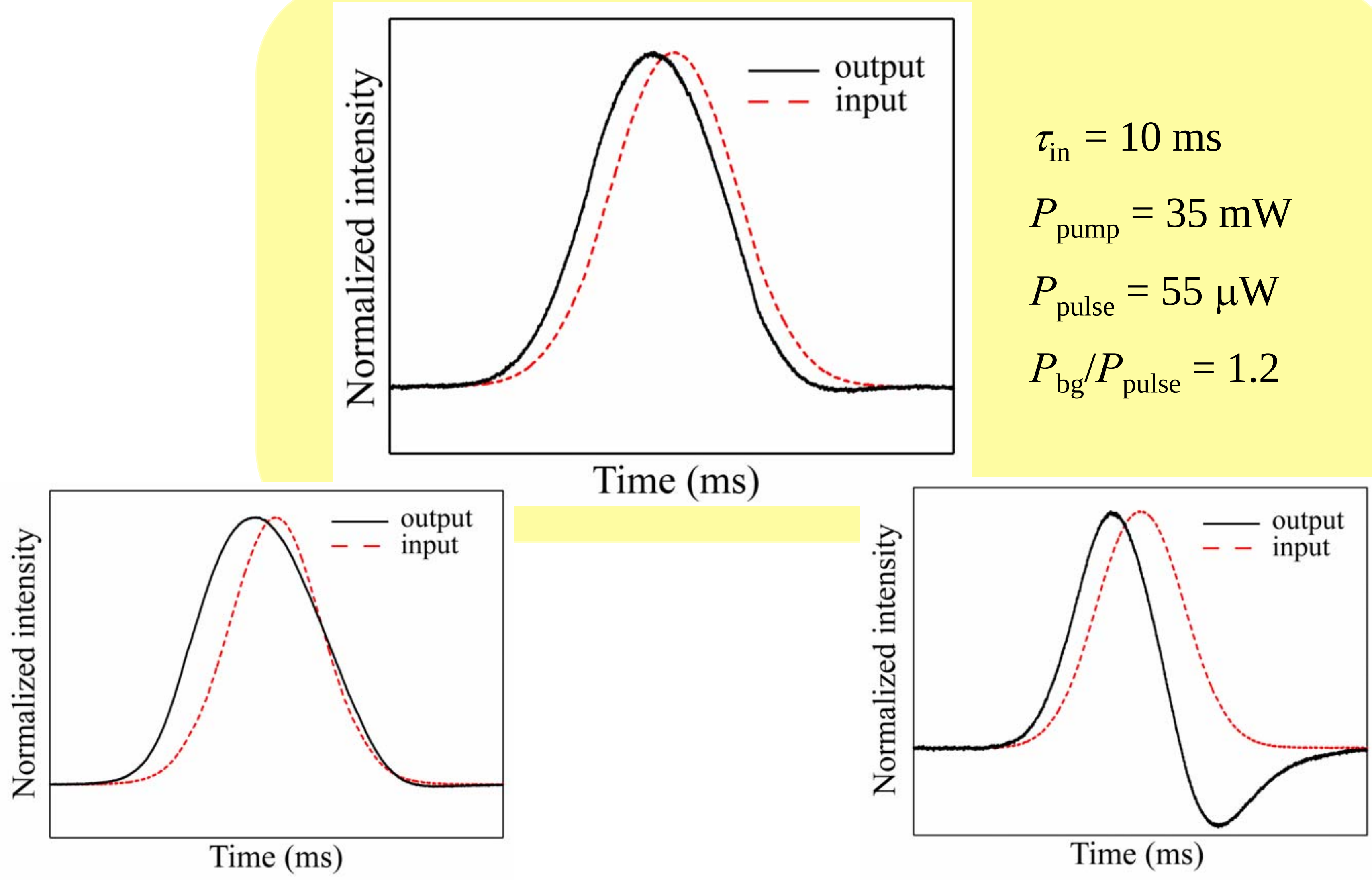
Minimum distortion



τ_{in} = 10 ms

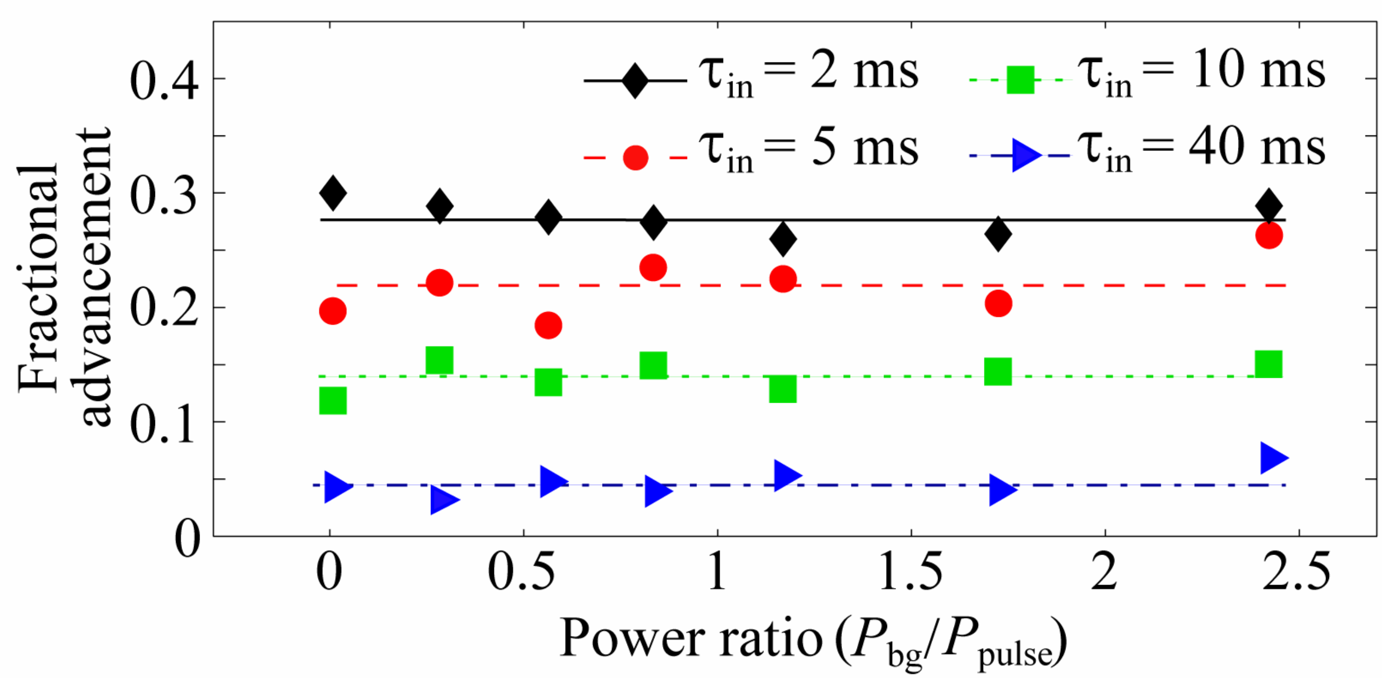
P_{pump} = 35 mW

P_{pulse} = 55 μW

P_{bg}/P_{pulse} = 1.2

Fractional advancement

For various pulse widths



- P_{pump} = 35 mW
- P_{pulse} = 55 μW
- $(N_e\text{-}N_g)/N_e = 0.9$

: Average

: Experiment

Conclusion

- Observation of pulse broadening and compression effects in fast-light pulse propagation through an EDFA, caused by gain recovery and pulse spectrum broadening.

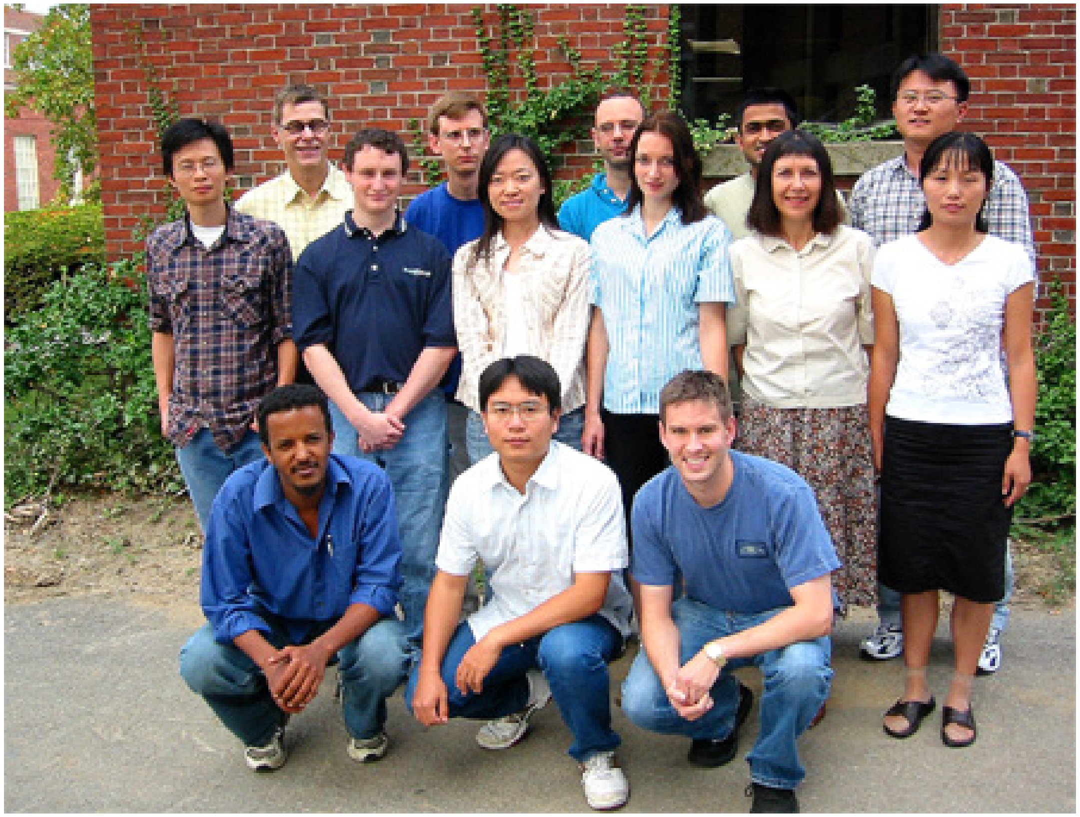
- Minimization of pulse distortion by adding a background of appropriate power.

Future work

- Investigation of the pulse-power dependence and incoherent background.

- Investigation of the application to other systems.

Acknowledgements



& Prof. Agrawal

Supported by
- the DARPA/DSO Slow Light program
- the Post-doctoral Fellowship Program of Korea Science and Engineering Foundation (KOSEF) and Korea Research Foundation (KRF)

Thank you for your attention!

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