Slow-Light Fourier Transform Interferometry

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at *FiO 2007 / LS XXIII*, San Jose, CA
10:45 am, September 20th, 2007

Paper: FThG2

Session: General Optical Design and Instrumentation II

Motivation

- A desired spectroscopic interferometer
  - Fine resolution / high sensitivity
  - Compact device size
  - High stability
  - Fast measurement
  - High SNR
  - …

Slow light can benefit interferometers in all these aspects!

Introduction of slow light

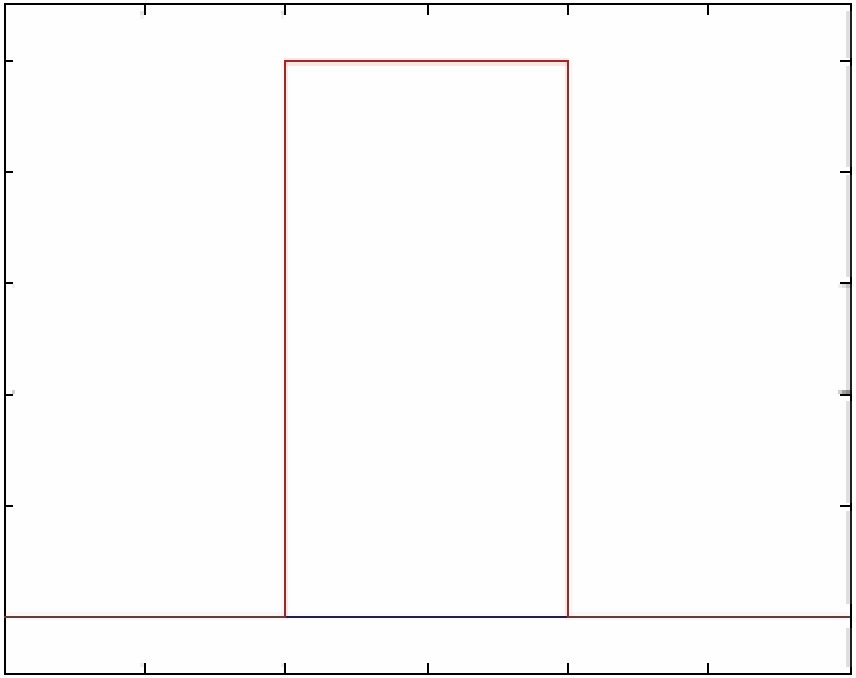
- Pulse propagation in a medium

Group velocity

$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g}$$

Group index

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



$$n_g = 2$$

Realizations of slow light

- Absorption / gain resonances
- Electromagnetically induced transparency
- Coherent population oscillation
- Other nonlinear effects: SBS, SRS, FWM
- Bandedge effects: PhC, fiber gratings, etc.
- Ring resonators
- …

Atomic Vapor $n_g \approx 1.76 \times 10^7$

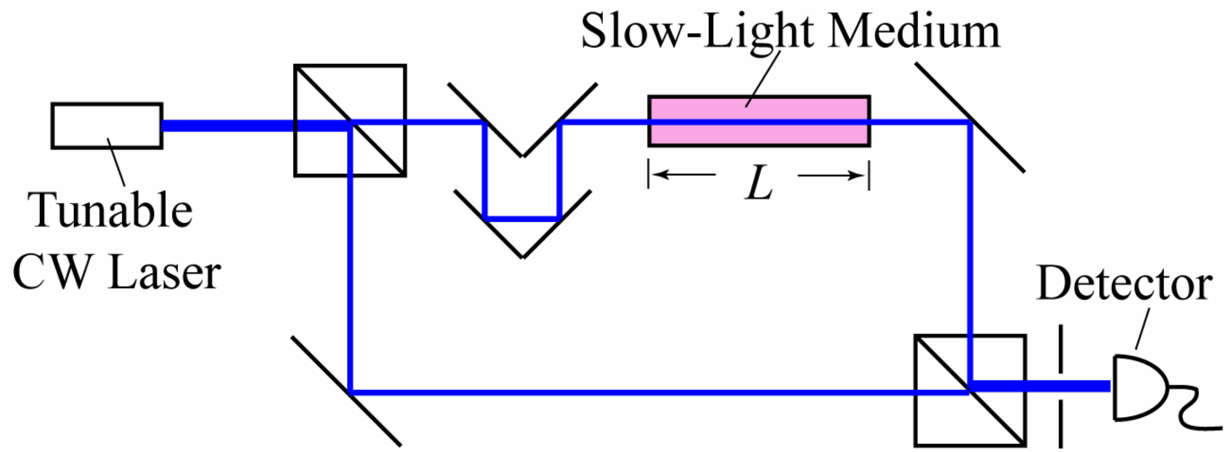
Hau, *et al.*, Nature **397**, p.594 (1999).

Solid system $n_g \approx 5.2 \times 10^6$

Bigelow, *et al.*, Science, **301** , p.200 (2003).

Slow-light interferometry

- M-Z Interferometer

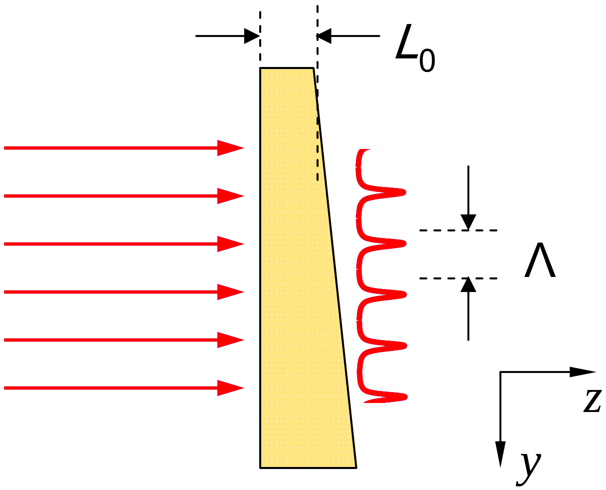


$$T(\omega) = \frac{1}{2}(1 + \cos\Delta\phi) = \frac{1}{2} + \frac{1}{2}\cos\frac{L\omega n(\omega)}{c}$$

$$\frac{d\Delta\phi}{d\omega} = \frac{L}{c}\left(n + \omega\frac{dn}{d\omega}\right) = \frac{L n_g}{c}$$

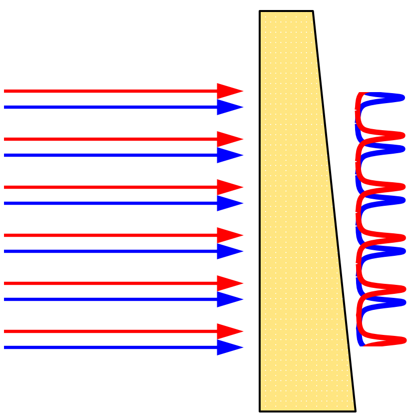
Slow-light interferometry

- Wedged shear interferometer



❖ Spectral sensitivity

$$\mathcal{S} = \frac{1}{\Lambda}\frac{dy_m}{d\lambda} = \frac{2L_0 n_g}{\lambda^2}$$

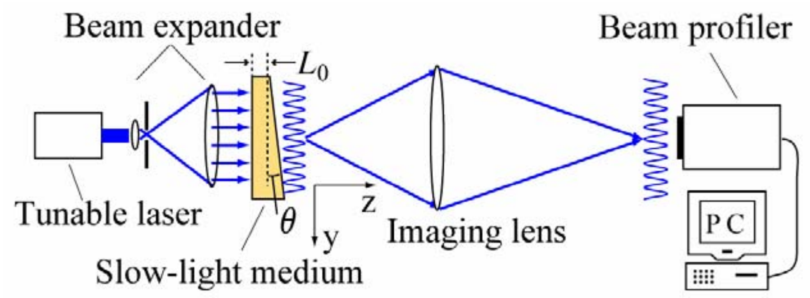


❖ Resolving Power

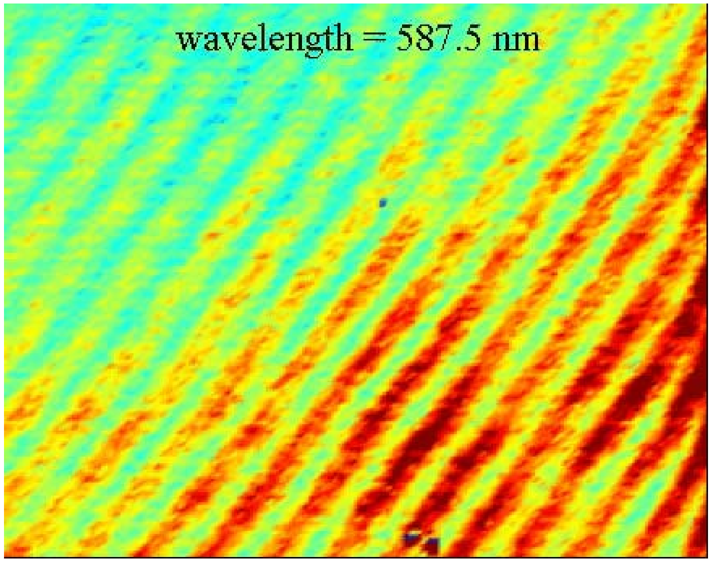
$$\mathcal{R} = \frac{\lambda}{\Delta\lambda_{\min}} = \frac{\pi L_0 n_g \sqrt{\mathcal{F}}}{\lambda}$$

Proof-of-principle experiment

- CdSSe single crystal
- Rhodamine 6G dye laser



Fringe movement as λ is tuned



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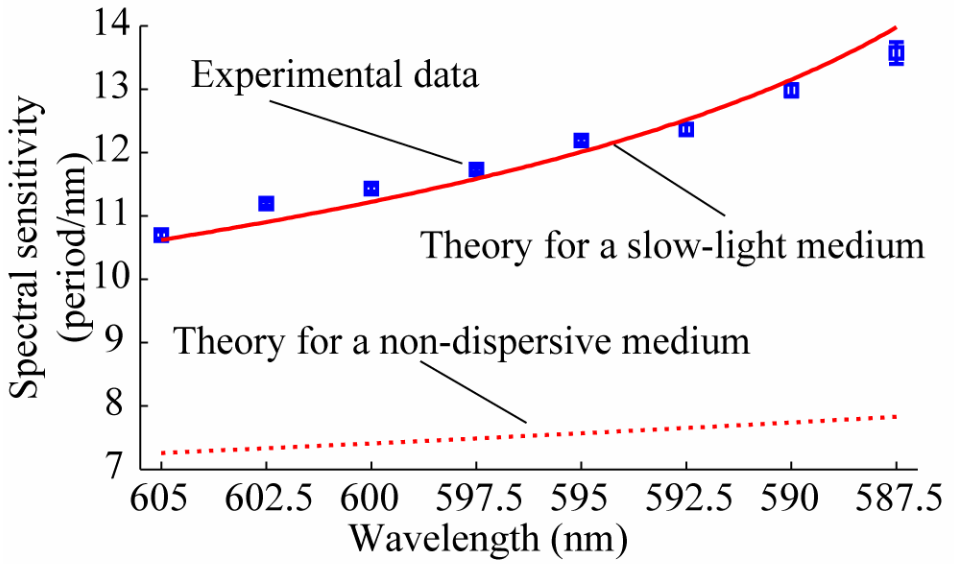


[1] Shi, Boyd, Gauthier, and Dudley, *Optics Lett.* **32**, p.915-917 (2007)

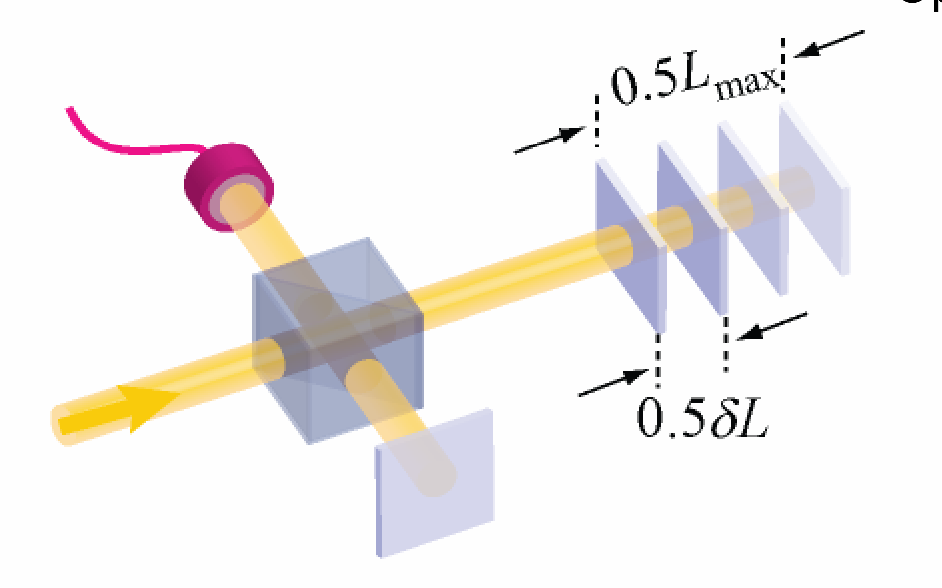
Conventional FT interferometer

- Conventional FT interferometer

$$I_{\mathrm{out}}(\tau_d) - 0.5 I_{\mathrm{in}} = \int_{-\infty}^{\infty} I_{\mathrm{in}}(\nu) e^{i2\pi\nu\tau_d} d\nu$$

Optical path delay time

$$\tau_d = nL/c$$



Conventional FT interferometer

- Pros:
  - – Only need single detector;
  - – High SNR (due to multiplexing);
  - – Can achieve high spectral resolution.

  Applications in biomedical engineering, metrology, astronomy, radiometry, etc.

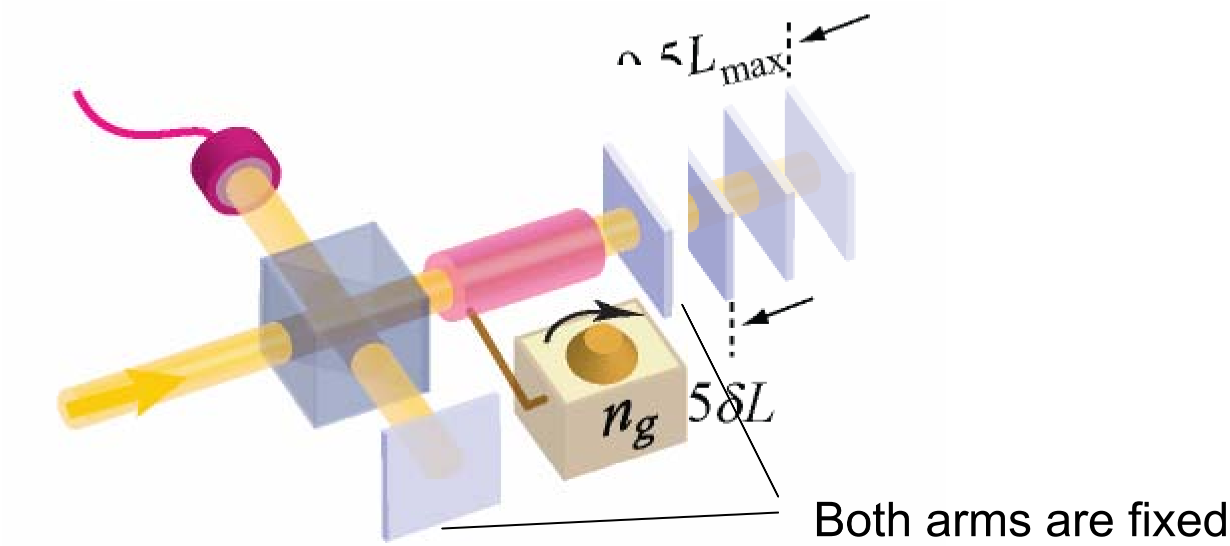
- Cons:
  - – Need a moving arm;
  - – Need a large device size, a large # of data, and a long time of measurement.

Theory of slow-light FTI

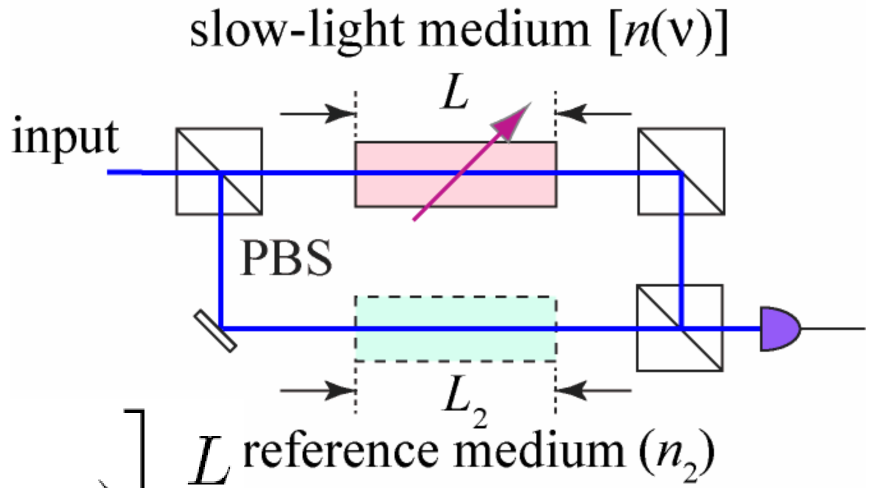
- Tunable slow-light medium

$$n(\nu) = n(\nu_0) + \frac{n_g^{(r)}}{\nu_0}(\nu - \nu_0)$$

$$n_g(\nu) = n + \nu\frac{dn}{d\nu} \approx n(\nu_0) + n_g^{(r)}$$



Theory of slow-light FTI



- lower arm

$$\phi_2(\nu) = 2\pi\nu n_2 \frac{L_2}{c}$$

- upper arm

$$\phi_1(\nu) = 2\pi\nu \left[n(\nu_0) + \frac{n_g^{(r)}}{\nu_0}(\nu - \nu_0) \right] \frac{L}{c}$$

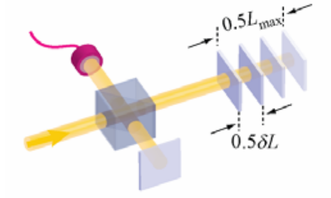
- phase difference when $n(\nu_0)L = n_2 L_2$

$$\Delta\phi(\nu) = 2\pi(\nu - \nu_0)\frac{n_g^{(r)} L}{c} = 2\pi(\nu - \nu_0)\tau_g$$

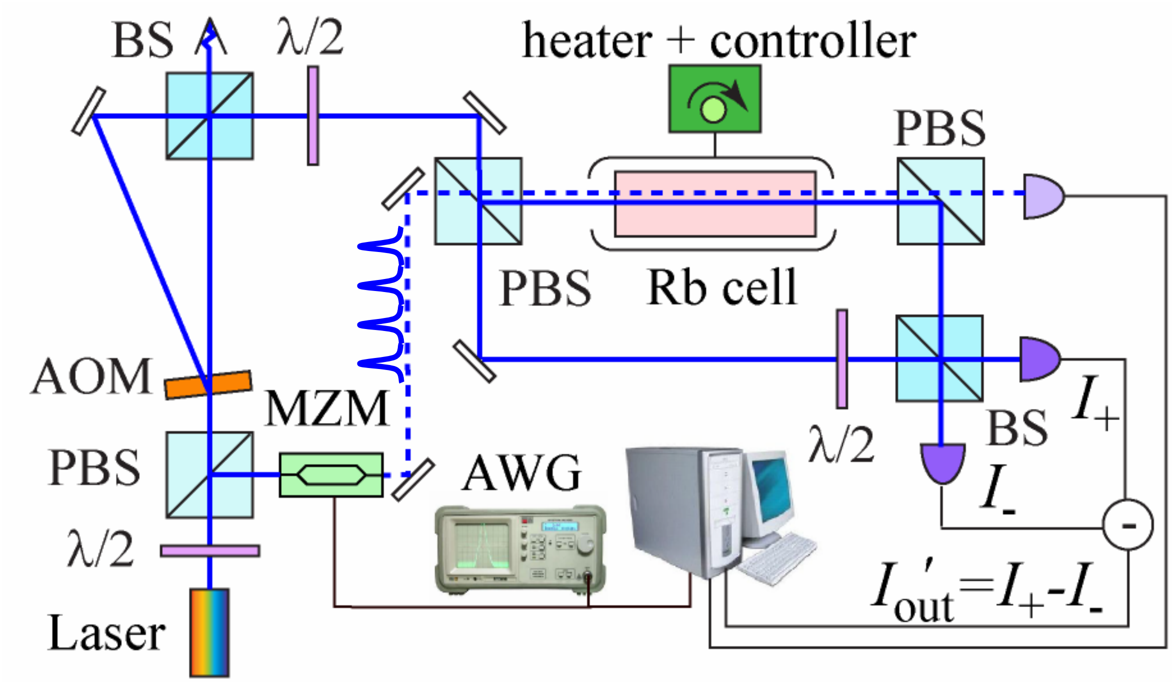
- FT relation

$$I_{\text{out}}(\tau_g) - \frac{1}{2} I_{\text{in}} = \frac{1}{2} \int_{-\infty}^{+\infty} I_{\text{in}}(\nu) e^{i2\pi\nu' \tau_g} d\nu$$

Comparisons

		
• FT pair	τ_d and ν	τ_g and ν'
• Delay	$\tau_d = nL/c$	$\tau_g = n_g^{(r)} L/c$
• Resolution	$\delta\nu_{\min} = \frac{c}{2nL_{\max}}$	$\delta\nu_{\min} = \frac{c}{2n_{g,\max}^{(r)} L}$
• Device size	$L_{\max} = \frac{c}{2n\delta\nu_{\min}}$	$L = \frac{c}{2n_{g,\max}^{(r)} \delta\nu_{\min}}$
• # of data pts	$\nu_0/\delta\nu_{\min}$	$\Delta\nu_{\mathrm{SR}}/\delta\nu_{\min}$
• Moving arm	needed	not needed

Experiment setup



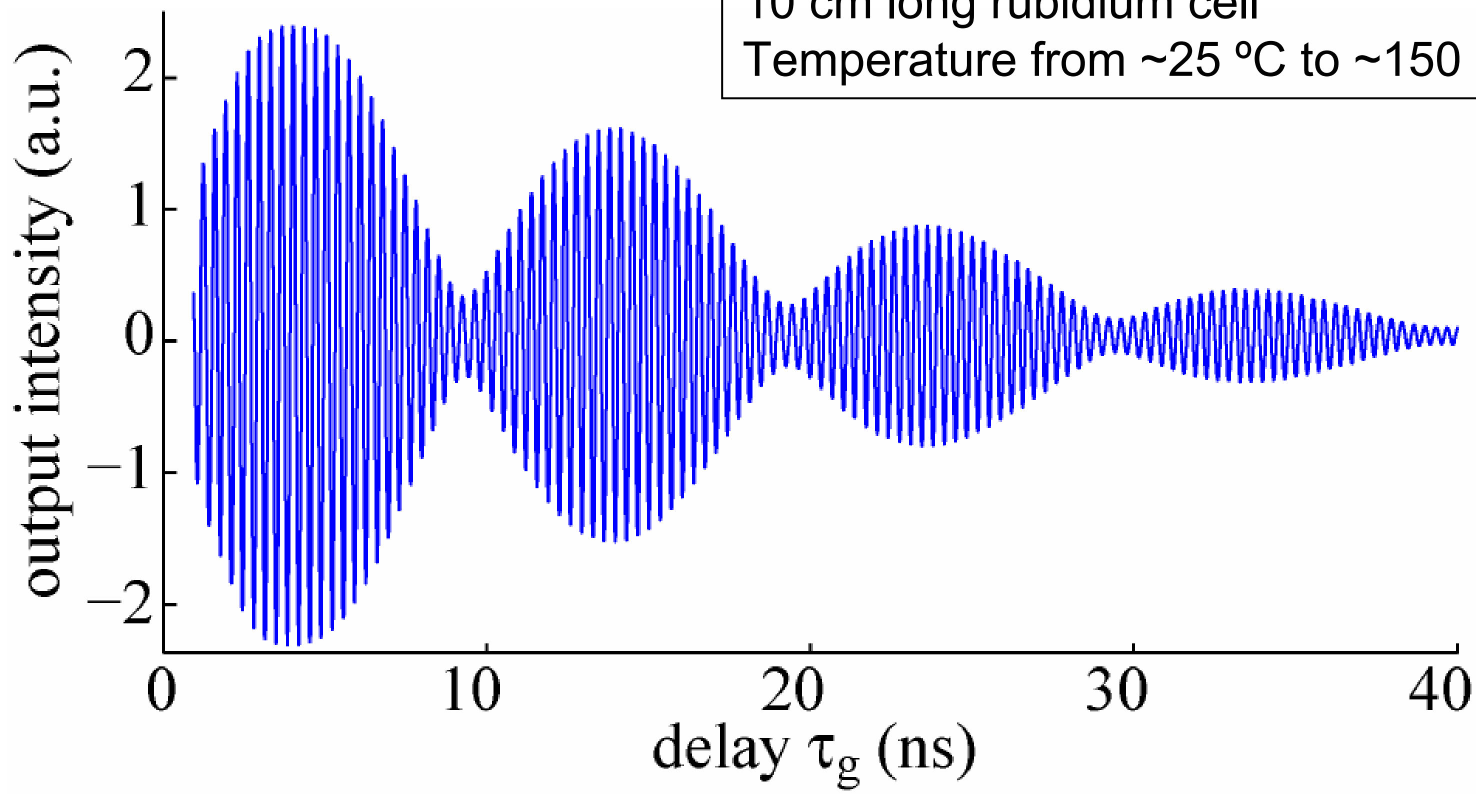
Schematic diagram of the experiment setup of an FT-interferometer using a rubidium cell as the slow-light medium.

BS: beam splitter; AOM: acoustic optical modulator; PBS: polarization beam splitter; MZM: Mach-Zehnder modulator; AWG: arbitrary waveform generator.

Experimental results

- Output intensity *vs.* group delay

Double line separated by 80 MHz
10 cm long rubidium cell
Temperature from ~25 ºC to ~150 ºC

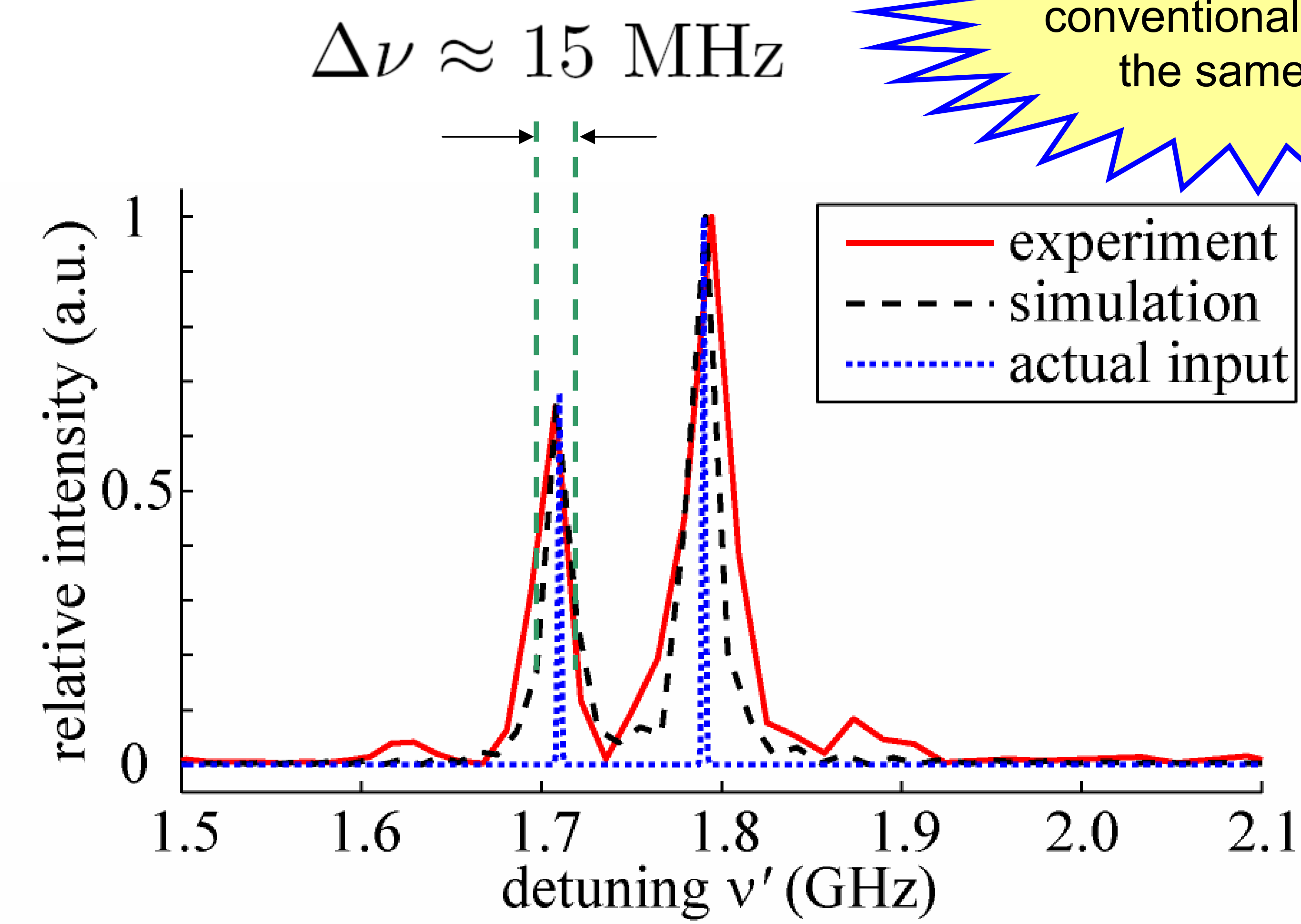


Shi, Boyd, Camacho, Vudyasetu, and Howell, *Phys. Rev. Lett.* (submitted)

Experimental results

- Retrieved input spectrum

100 times better than a conventional FTI with the same size



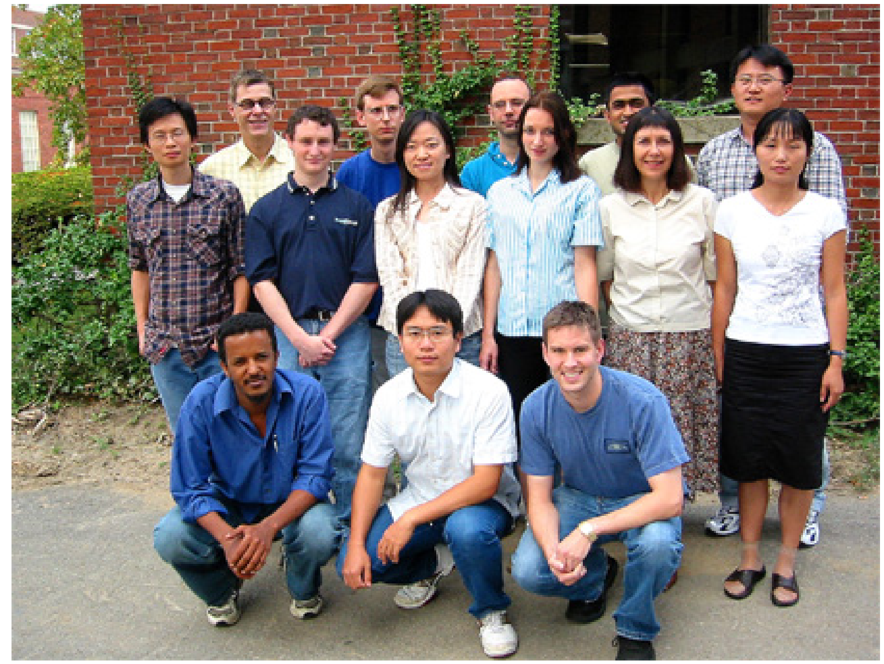
Summary

- A slow-light Fourier transform interferometer
  - Fine resolution ☺ $\sim 1/n_{g,max}$ (15 MHz)
  - Compact device size ☺ $\sim 1/n_{g,max}$ (10 cm)
  - High stability ☺ No moving parts
  - Fast measurement ☺ $\sim \nu_0/\Delta\nu_{SR}$ reduction in data
  - High SNR ☺ Single detector

Acknowledgement

- Ryan M. Camacho, Praveen K. Vudyasetu, and Prof. John C. Howell at Univ. of Rochester

- Research Group of Nonlinear Optics at Univ. of Rochester. www.optics.rochester.edu/~boyd



- Funding Agencies

Thank you for your attention!