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All-Optical Delay with Large Dynamic Range Using Atomic Dispersion

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Motivation

- The optical telecommunications industry needs a method to tunably delay optical signals without electrical transduction to allow:
 - pulse train synchronization,
 - data packet buffering.
- The ability to controllably delay non-classical states of light would be a useful tool for quantum information processing.

Aims

- To experimentally determine the feasibility of producing an all-optical delay line in a vapour of natural isotopic Rb.
- Telecommunication requirements:
 - Large bandwidth \sim GHz,
 - Delay bandwidth product,
 - The delay must be tunable,
 - Minimal pulse distortion.

$$\delta\Delta\nu = \delta / \tau > 1$$

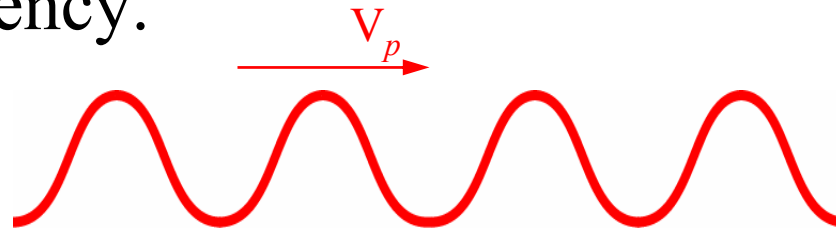
Talk Outline

1. Introduction
2. Absorption resonance pairs
3. Spectroscopy of the Rb D_2 line
4. Modeling dispersion and transmission
5. Experimental setup
6. Slow light results
7. Conclusion

Introduction

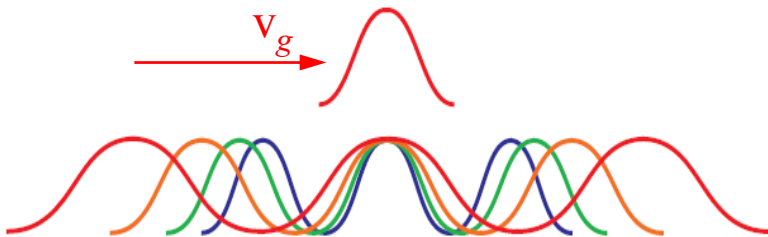
- Dispersion: $\partial n(\omega) / \partial \omega$, variation in the refractive index with frequency.

- Phase velocity:



$$v_p = \frac{c}{n(\omega)}$$

- Group velocity:



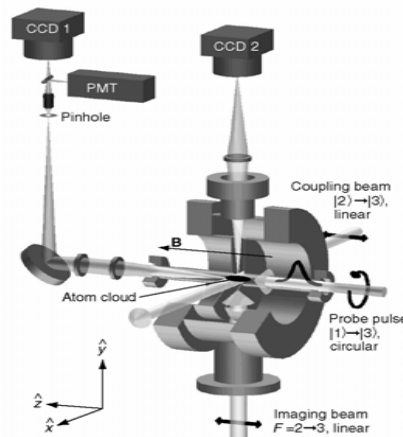
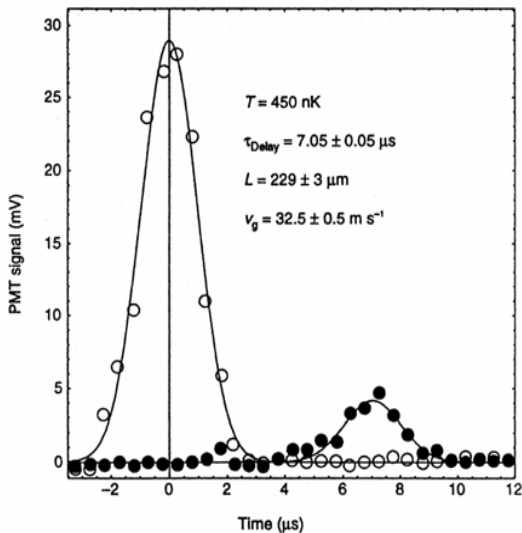
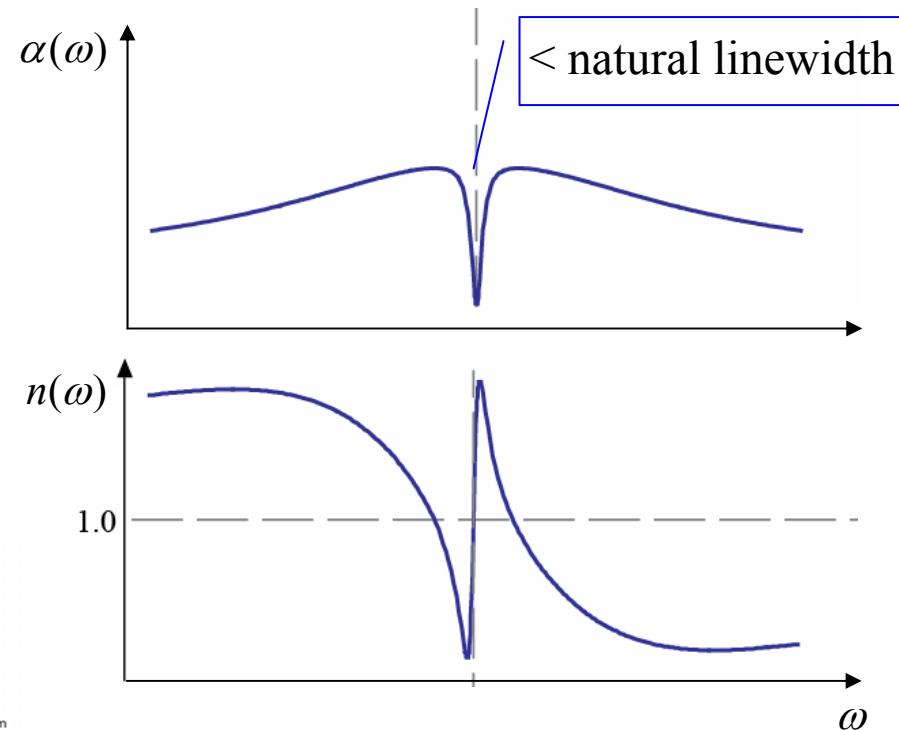
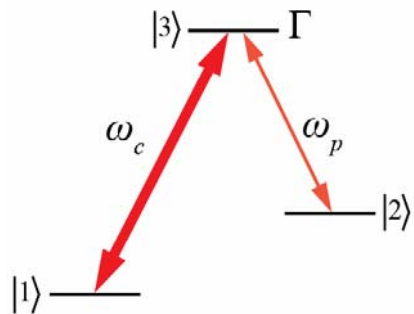
$$v_g = \frac{c}{n(\omega_0) + \omega_0 \frac{\partial n(\omega)}{\partial \omega}}$$

- What is ‘slow light’?
 - In normal (positive) dispersive media, spectral components ‘rephase’ such that $v_g < c$.
- *Can also get ‘fast light’.*

Group Velocity Demonstration

'Slow Light' Techniques - EIT

- Electromagnetically induced transparency.



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

Other ‘Slow Light’ Techniques

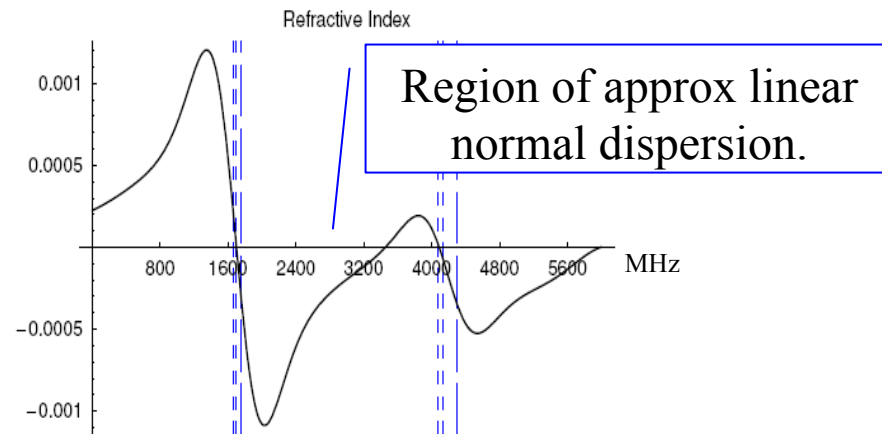
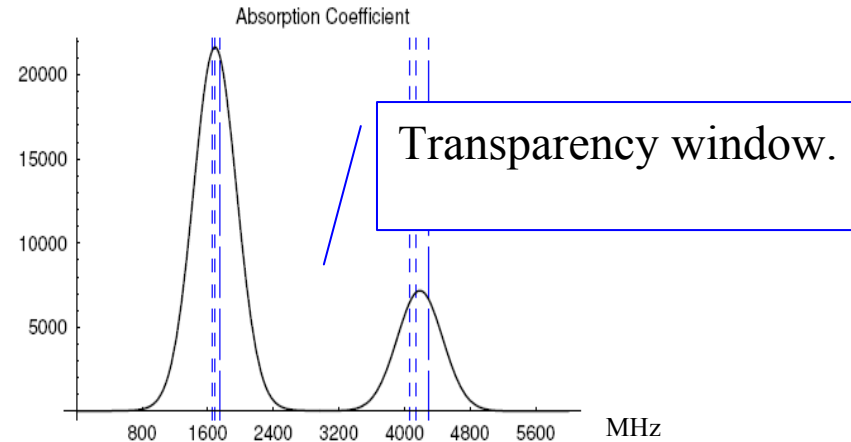
- Gain lines in fibre
 - Raman amplification,
 - Brillouin scattering.

J.E Sharping et al. *Opt. Express* **13**, 6092 (2005)
Y. Okawachi et al. *Phys. Rev. Lett.* **94**, 153902 (2005)

- These, & EIT have the common disadvantage of narrow bandwidth.

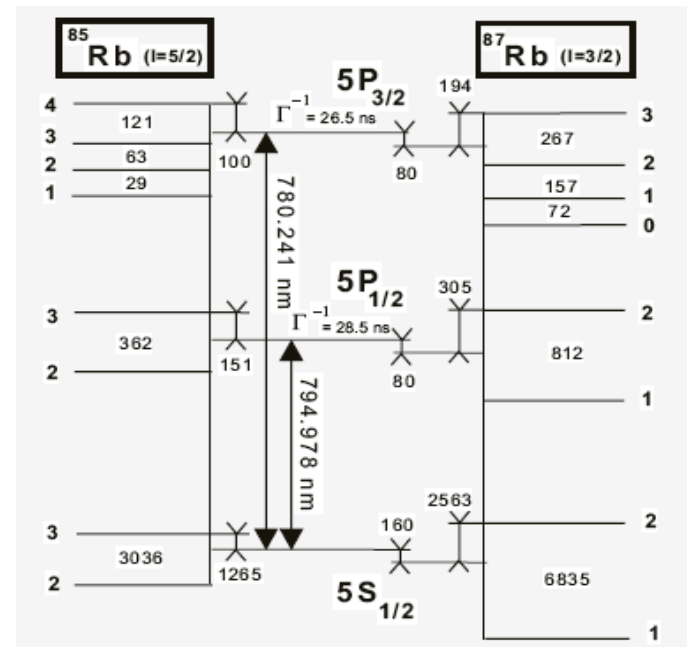
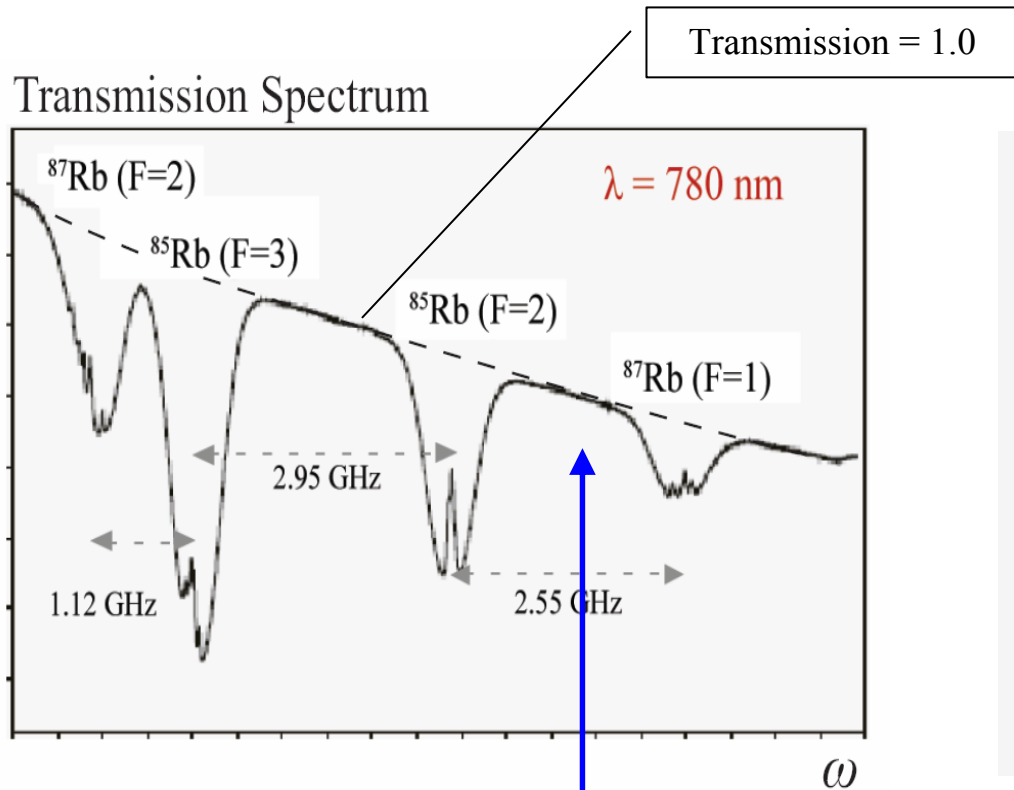
Absorption Resonance Pairs

- Slow light can be obtained for a pulse central frequency tuned between two widely spaced absorption lines.
- Large bandwidth \sim GHz.
- Pulse may distort due to:
 - Nonlinear dispersion
 - Non-flat absorption
- Distortion minimized as dispersive and absorptive mechanisms cancel one another.



R.M. Camacho et al. *Phys. Rev. A* **73**, 063812 (2006)
R.M. Camacho et al. *Phys. Rev. Lett.* **98**, 043902 (2007)

The Rb D_2 lines



Pulses tuned within this region.

Numerical Modeling of the Dispersion & Absorptive Characteristics of the Rb Vapor

- Natural homogeneous profile including:
 - saturation,
 - collisional broadening.



Lorentzian Function

$$\alpha(\omega) = \frac{e^2}{4\varepsilon_0 m_e c} \frac{\gamma_c}{(\omega_0 - \omega)^2 + (\gamma_c/2)^2}$$

$$n(\omega) = \frac{e^2}{4\varepsilon_0 m_e \omega_0} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + (\gamma_c/2)^2}$$

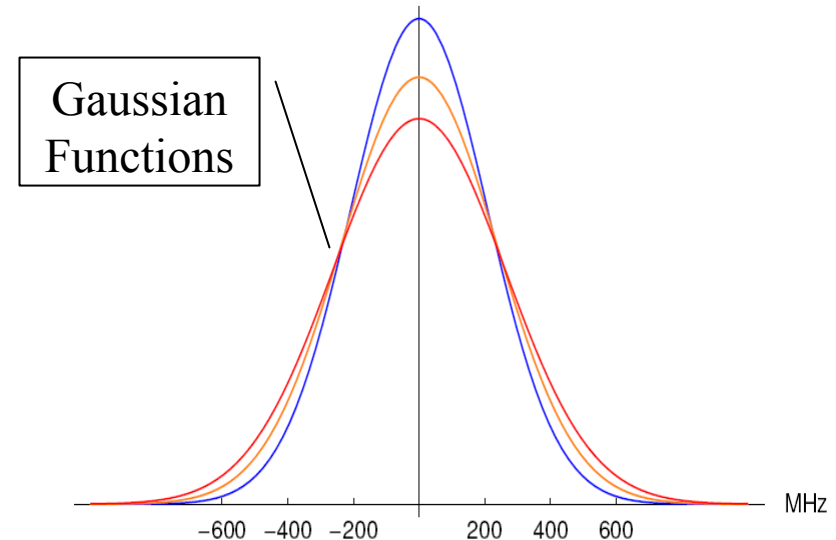
$$\alpha, n(\omega, S) = \alpha, n(\omega) \frac{1}{1 + S\Gamma(\omega)}$$

Theoretical Modeling of the Dispersion & Absorptive Characteristics of the Rb Vapor

- Atomic density increases with temperature from evaporation.
- Inhomogeneous thermal distribution. Doppler broadening.

$$N(T) = \frac{P(T)133.322}{k_B T}$$

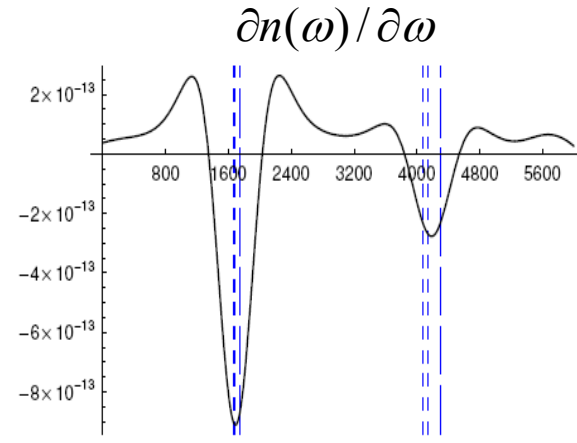
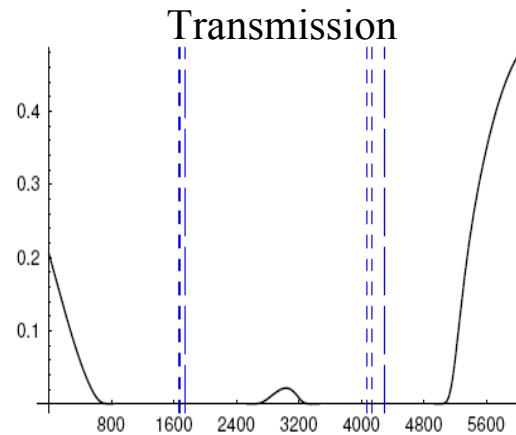
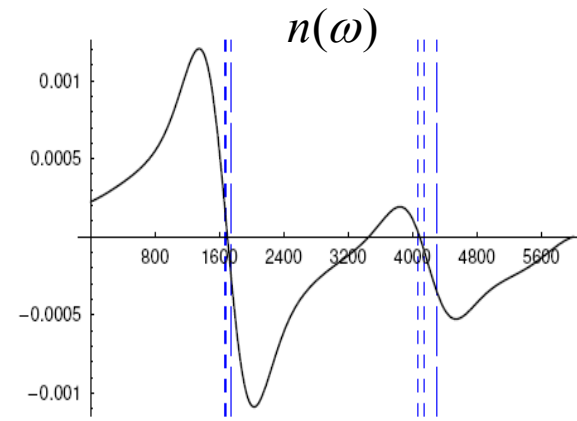
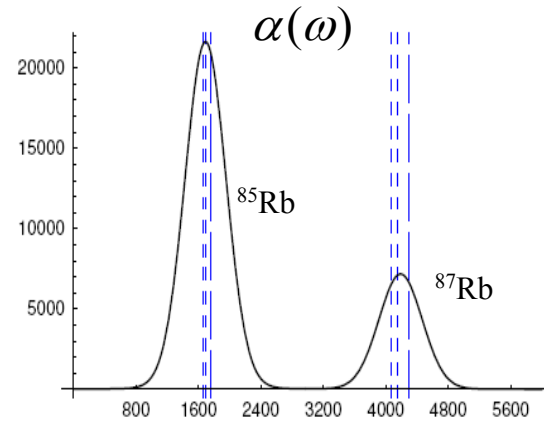
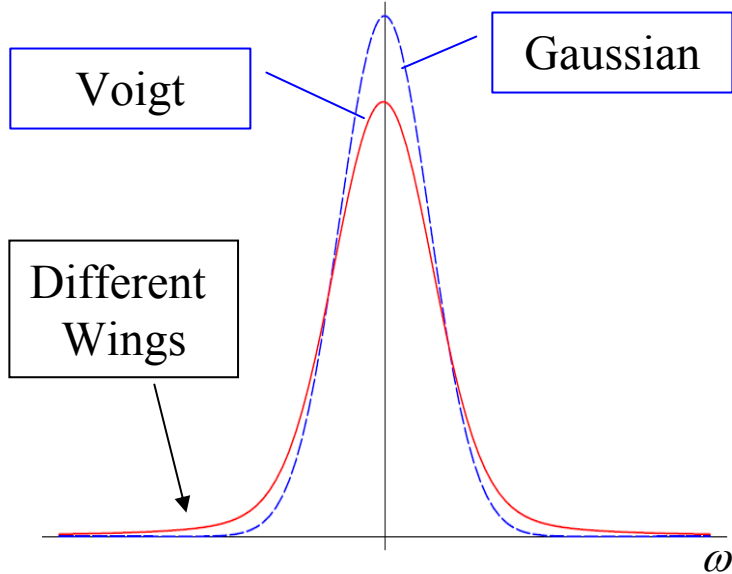
$$N(\omega) \propto N(T) \text{Exp} \left[- \left(\frac{c (\omega_0 - \omega)}{\omega_0 v(T)} \right)^2 \right]$$



Numerical Prediction

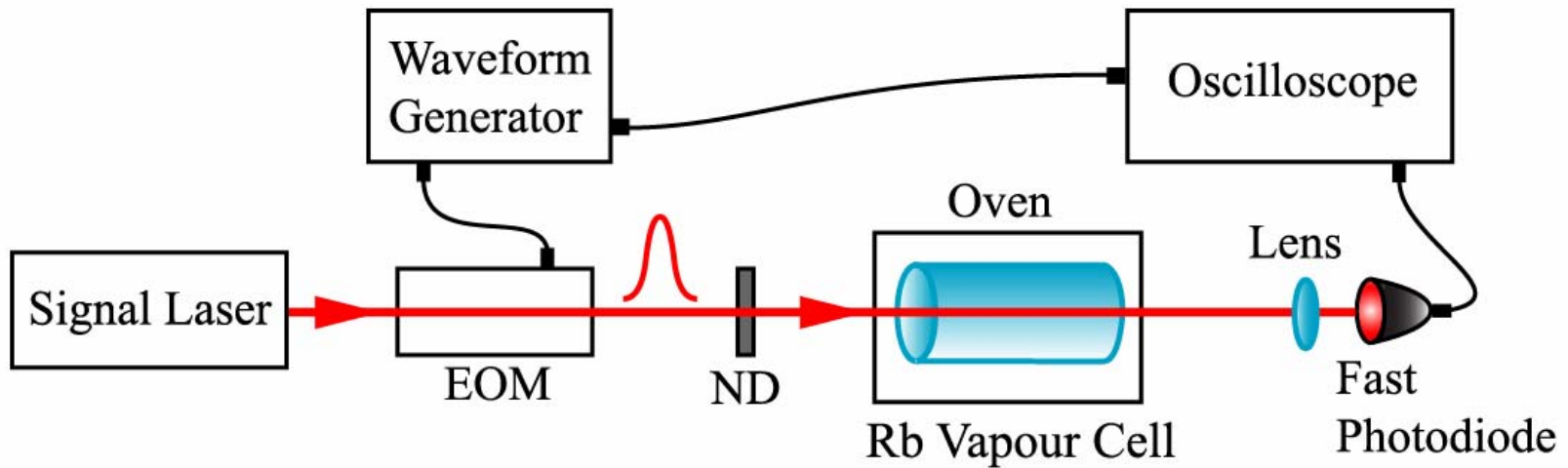
- Convolution of homogeneous with inhomogeneous mechanisms.

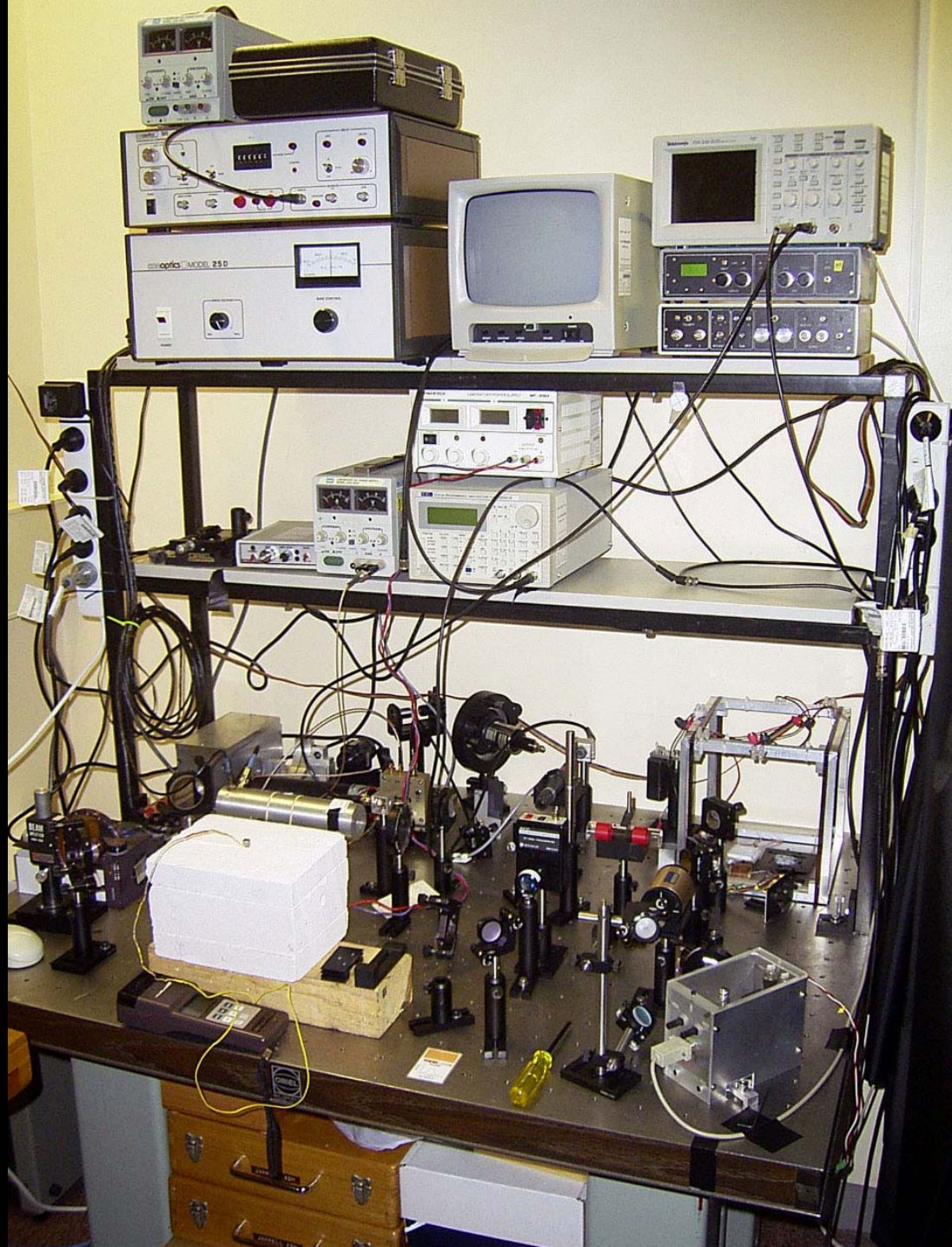
Gaussian and Voigt functions



(Horizontal axes in MHz. $T = 140^\circ\text{C}$)

Experimental Setup

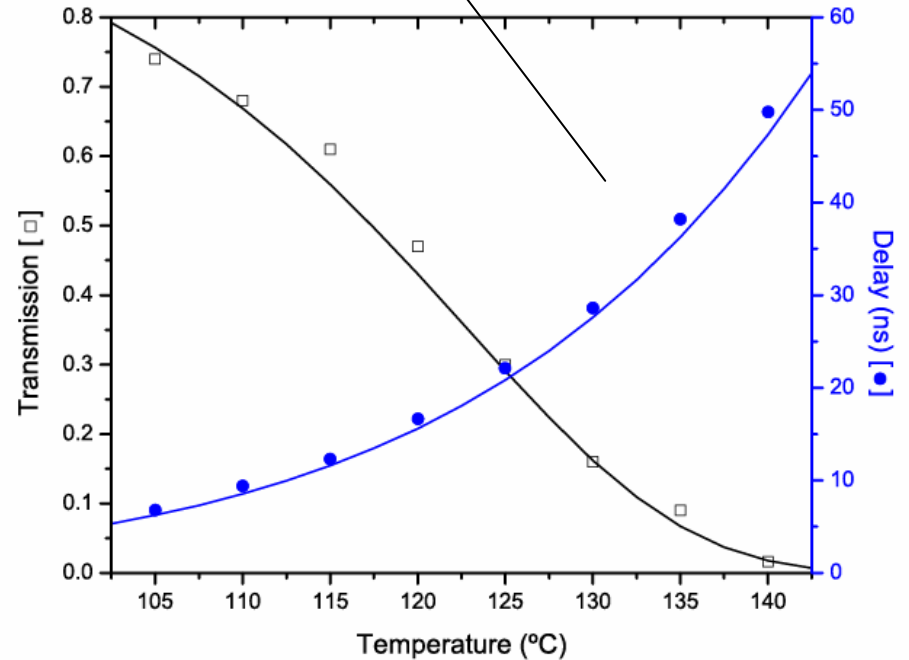
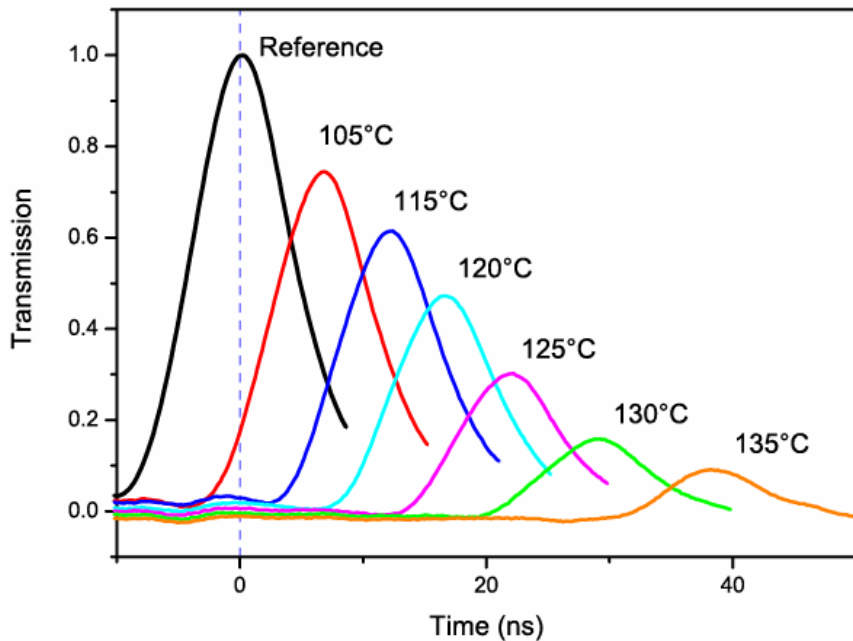






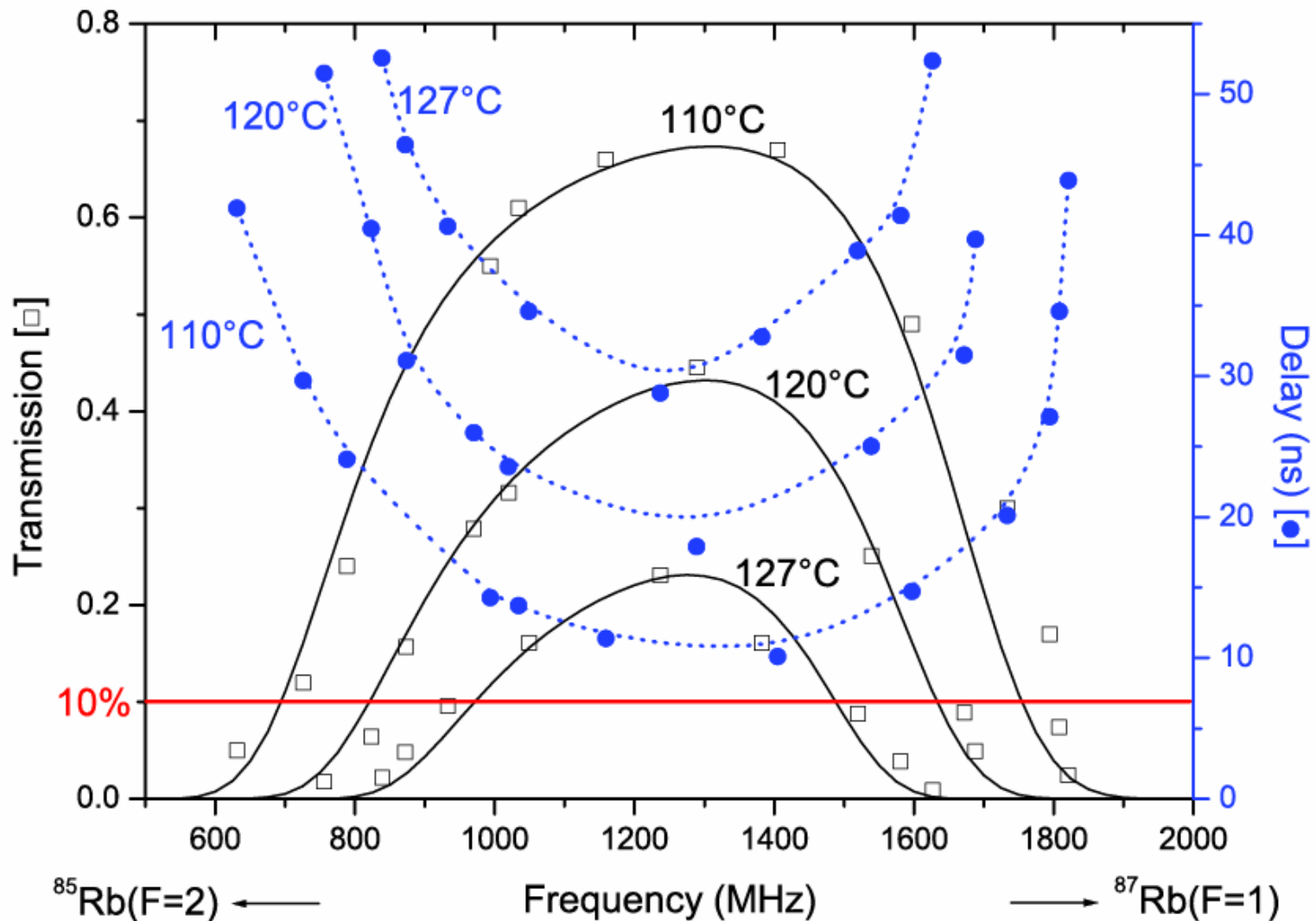
All-Optical Delay between $^{85}\text{Rb}(F=2)$ & $^{87}\text{Rb}(F=1)$

Trade-off between delay and transmission.

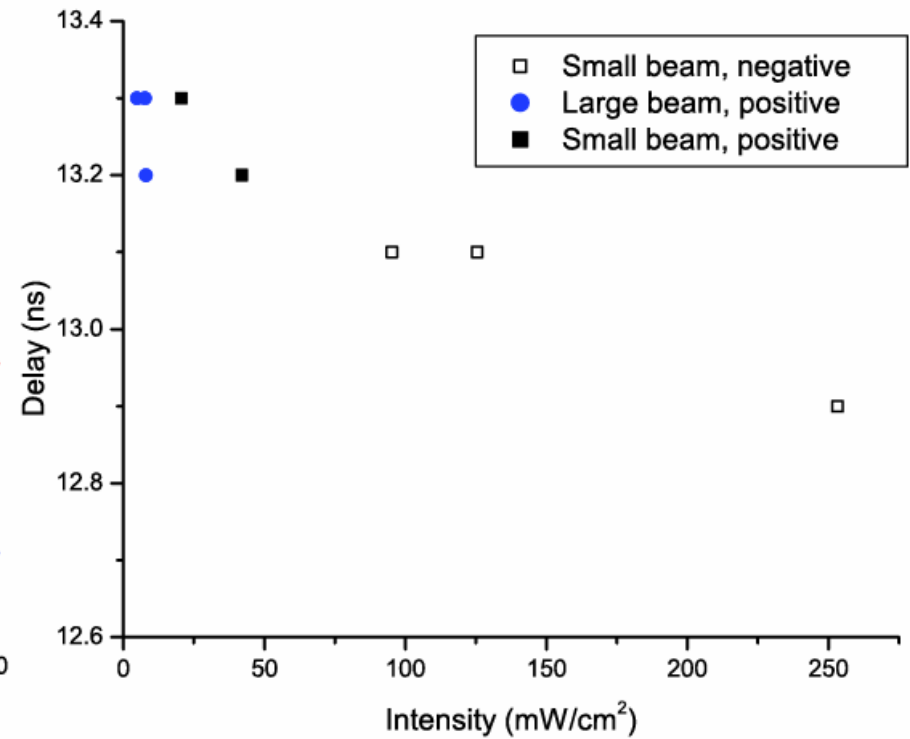
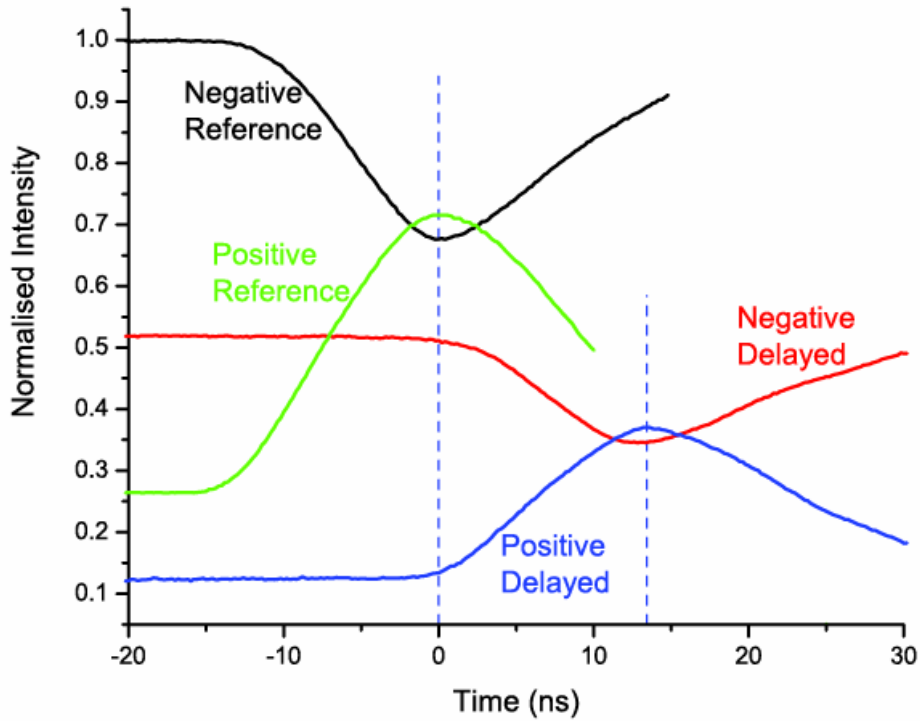


Pulse shape is preserved.

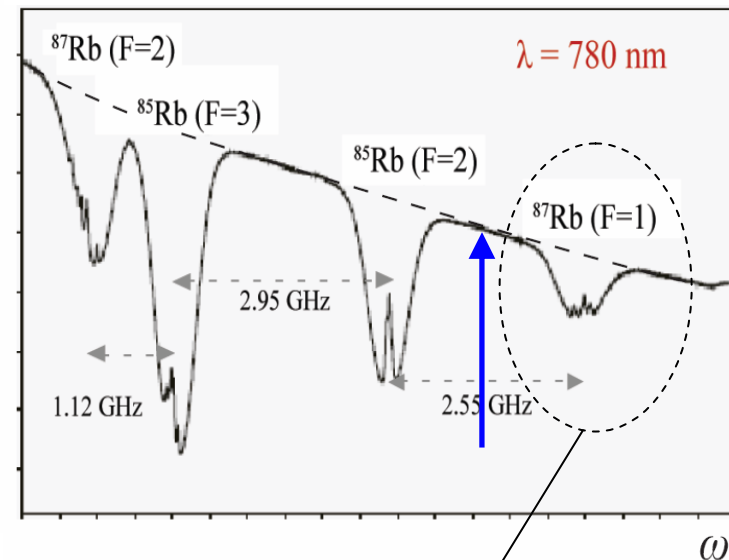
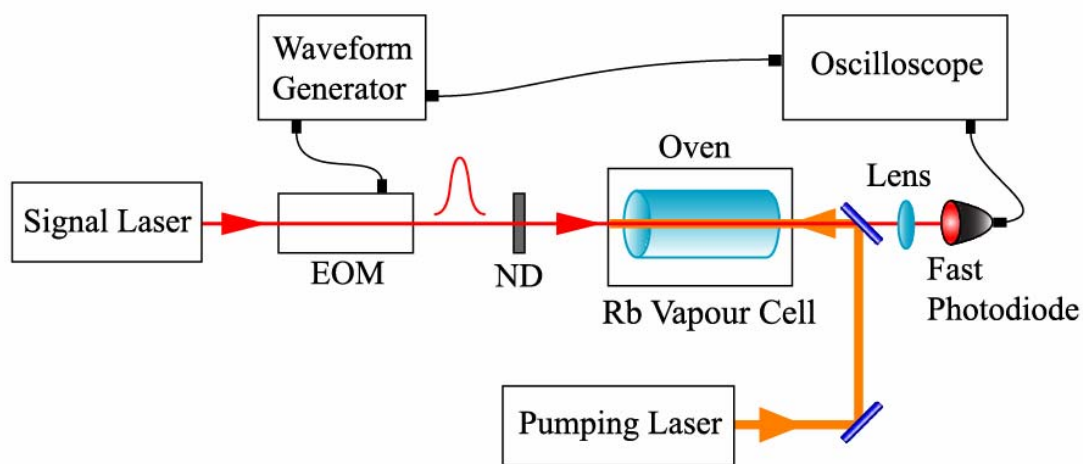
Frequency Dependence



Intensity dependence



Experimental Setup for Rapid Delay Tuning

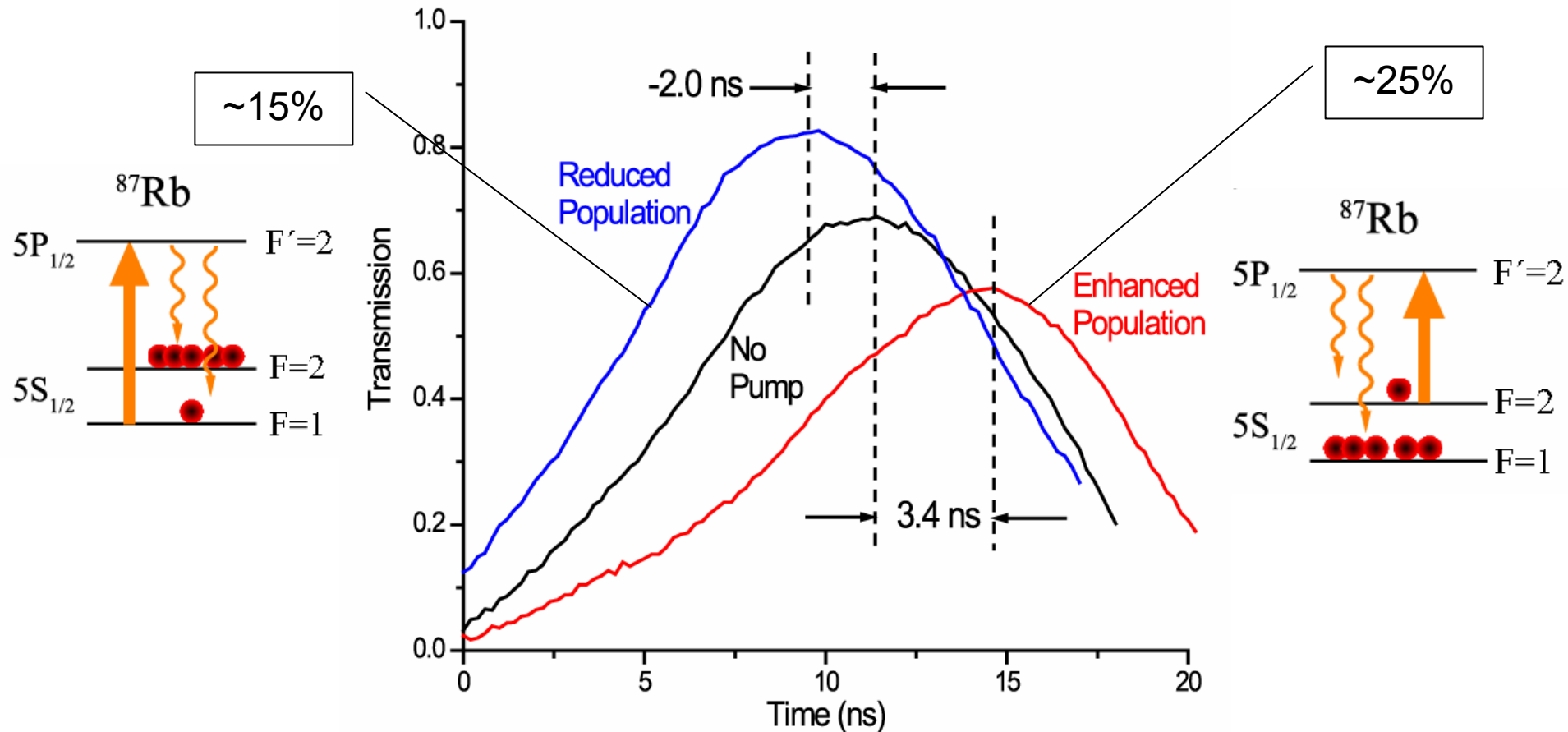


Additional laser used to control ^{87}Rb population.

The absorption of this component may be reduced or enhanced, thus modifying the dispersion.

Tunable Delay with Optical Pumping

- ^{87}Rb ($F=1$) population was reduced or enhanced by optical pumping on the D_1 line (795 nm).



Conclusion

- All-optical, low distortion, delay of classically encoded information, was achieved with fractional delays up to 4.3. This was limited by the pulse width and could be a factor of ten larger with narrower pulses.
- Dynamic Range:
 - tunability was provided by control of temperature and optical pumping.
 - operates over much larger intensity range than EIT.
- This scheme could provide a method for buffering non classical states of light (including images) for quantum information processing.
- Recently accepted for publication in Journal of Physics B: Atomic, Molecular & Optical Physics as a *Fast Track Communication*. (arXiv:0711.4172)

Stay Tuned

- We are currently investigating slow and fast light arising from the dispersion associated with resolved hyperfine transitions in a MOT.