Storage and Retrieval of Photonic Information

— from Electromagnetically Induced Transparency to Reduce of the Light Speed

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The Phenomenon of Electromagnetically Induced Transparency (EIT)
Quantum Interference

Coupling

|3⟩ = |2⟩ + |path i⟩ + |path ii⟩ + |path iii⟩ + ........

Transition amplitudes: $A_i$, $A_{ii}$, $A_{iii}$, ........

Transition probability of $|1⟩ \rightarrow |2⟩ = |A_i + A_{ii} + A_{iii} + ........|^2$

EIT is the destructive interference between $A_i$, $A_{ii}$, $A_{iii}$, ........

$\Rightarrow$ The probe absorption is suppressed.
Experimental Setup

- Typically, we trap $10^9$ $^{87}\text{Rb}$ atoms in the vapor-cell MOT.
- The probe and coupling fields propagate nearly in the same direction and they are switched by AOMs individually.
Experimental Spectrum without the Coupling Laser
Experimental Spectrum of 100% Transparency
Narrow and High-Contrast EIT Window

**Linewidth of 85 kHz**
Chromatic Dispersion

\[ k = n \frac{\omega}{c}, \quad v_g = \frac{d\omega}{dk} = \frac{1}{n} + \frac{\omega}{c} \frac{dn}{d\omega} = \frac{c}{n + \omega \frac{dn}{d\omega}} \]
The index refraction of fused quartz. \( \omega \frac{dn}{d\omega} \approx 0.01 \)
The Optical Bloch Equation

\[ \frac{d\hat{\rho}}{dt} = \frac{1}{i\hbar} \left[ H_0 + H_c + [H_\mu, \hat{\rho}] \right] + \left\{ \frac{d\hat{\rho}}{dt} \right\} \]

\[ \hat{\rho}_{31}(t) = \rho_{31}(t) e^{-i\omega_\rho t}, \text{ where } \hat{\rho} \text{ is the slowly-varying part of } \rho. \]

- Solve the optical Bloch equation to obtain the optical coherence of the probe transition.  
  \( I_{\text{out}} = I_{\text{in}} e^{-\text{OD}} \)

\[ \Rightarrow \quad \text{OD} = NL \left( \frac{3\lambda^2}{2\pi} \right) \text{Im}[\rho_{31}] \left( \Gamma/\Omega_p \right), \]

\[ n = 1 + N \left( \frac{3\lambda^3}{8\pi^2} \right) \text{Re}[\rho_{31}] \left( \Gamma/\Omega_p \right), \text{ where } N \text{ is atomic density.} \]

- \( T_D \) calculated from the phase shift induced by the refractive index, \( n \), of the medium.

\[ \Rightarrow \quad T_D = \frac{\partial}{\partial \omega_\rho} \left( \frac{2\pi}{\lambda} n L \right). \]
Group Velocity

\[ v_g = \frac{c}{n + \omega \frac{dn}{d\omega}} \]

Determine \( \gamma = 0.002\Gamma \)
Measure Light Speed in a Medium

\[ v \approx \frac{l}{t_d} \]
Reduction of the Light Speed due to EIT

Length of the atom cloud $\approx 1$ mm and delay time $\approx 1.5$ $\mu$s $\Rightarrow 600$ m/s
Storage of Light Pulses (1/3)
Storage of Light Pulses (2/3)
Storage and Retrieval of Light Pulses

\[ \Omega_c = 0.26 \Gamma; \quad \Omega_p = 0.07 \Gamma \]
Delay time = 2.8 \(\mu s\)
Probe pulse 1/e width = 2.4 \(\mu s\)
Pulse Period = 100 ms
Oscilloscope LP filter = 20 MHz
The Beat-Note Interferometer

Reference Beat Note: \( E_z^2 + E_f(t)^2 + 2E_zE_f(t) \cos(\omega_a t + \phi_r) \)

Probe Beat Note: \( E_z^2 + E_f(t)^2 + 2E_zE_f(t) \cos(\omega_a t + \phi_p + \Delta \phi) \)

- \( \phi_r \) and \( \phi_p \) are the phases that result from the optical paths, the AOM switching, or other factors.
- \( \Delta \phi \) is the phase shift induced by the atoms.
- Although \( \phi_r \) and \( \phi_p \) vary from one pulse to another, their difference is always fixed.
Phase Coherence of Stored Photonic Information

Probe Transmission (arb. units)

Beat Note (arb. units)

Time (μs)
Experimental and Theoretical Data in the EIT Condition
\[ \Delta_p = \pm 0.05\Gamma. \]

- Blue and black lines are the probe transmissions in the absence and presence of the atoms; the peak powers are about 4 and 0.4 nW.
- The measured phase shifts of \(-1.5\pm0.5\) and \(1.8\pm0.4\) radians are in agreement with the predicted values.