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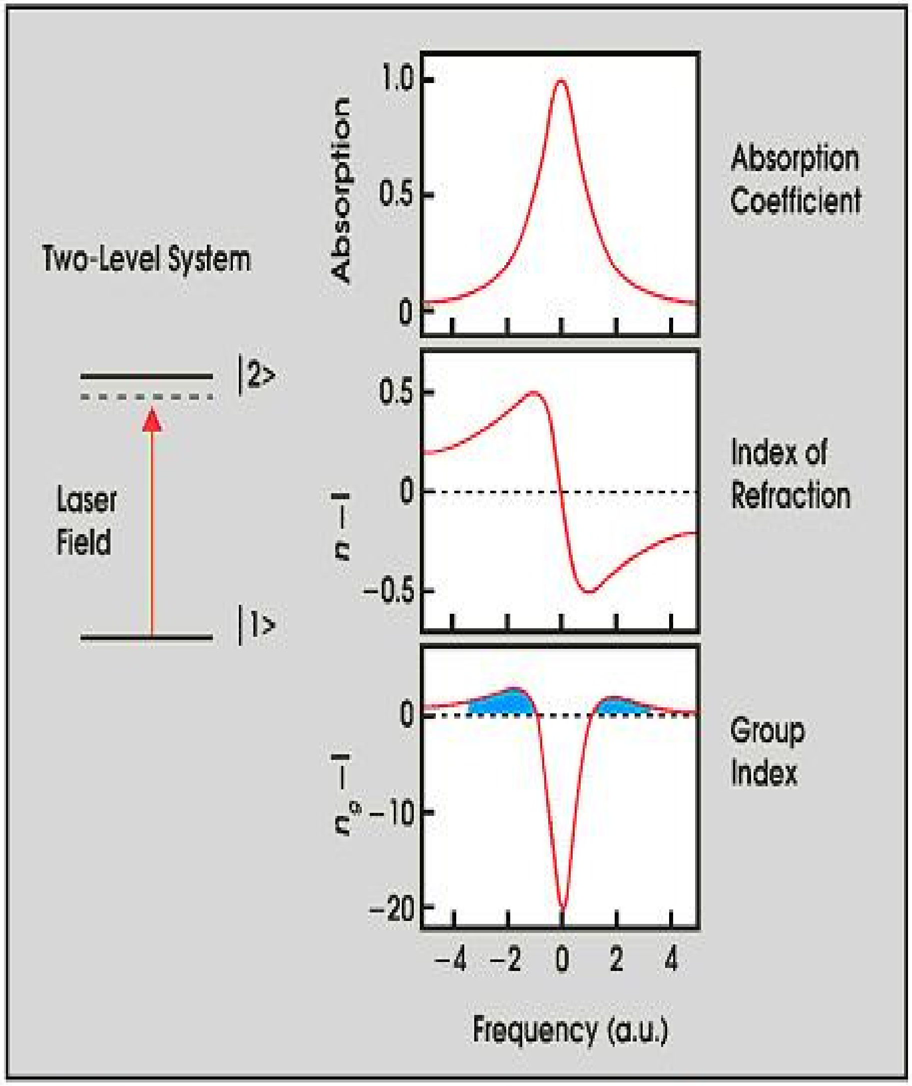
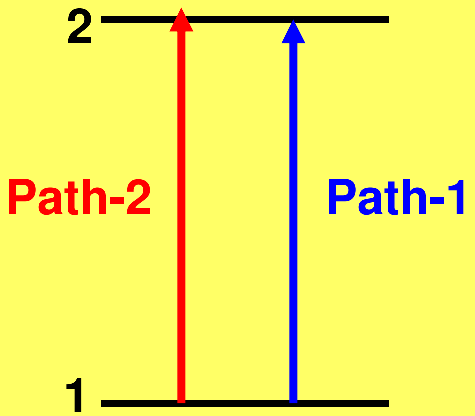
- Omics group has organised 500 conferences, workshops and national symposium across the major cities including SanFrancisco,Omaha,Orlado,Rayleigh,SantaClara,Chicago,Philadelphia,Unitedkingdom,Baltimore,SanAntanio,Dubai,Hyderabad,Bangaluru and Mumbai.

Control of Coherence in a Ξ system and its utility in optical switching



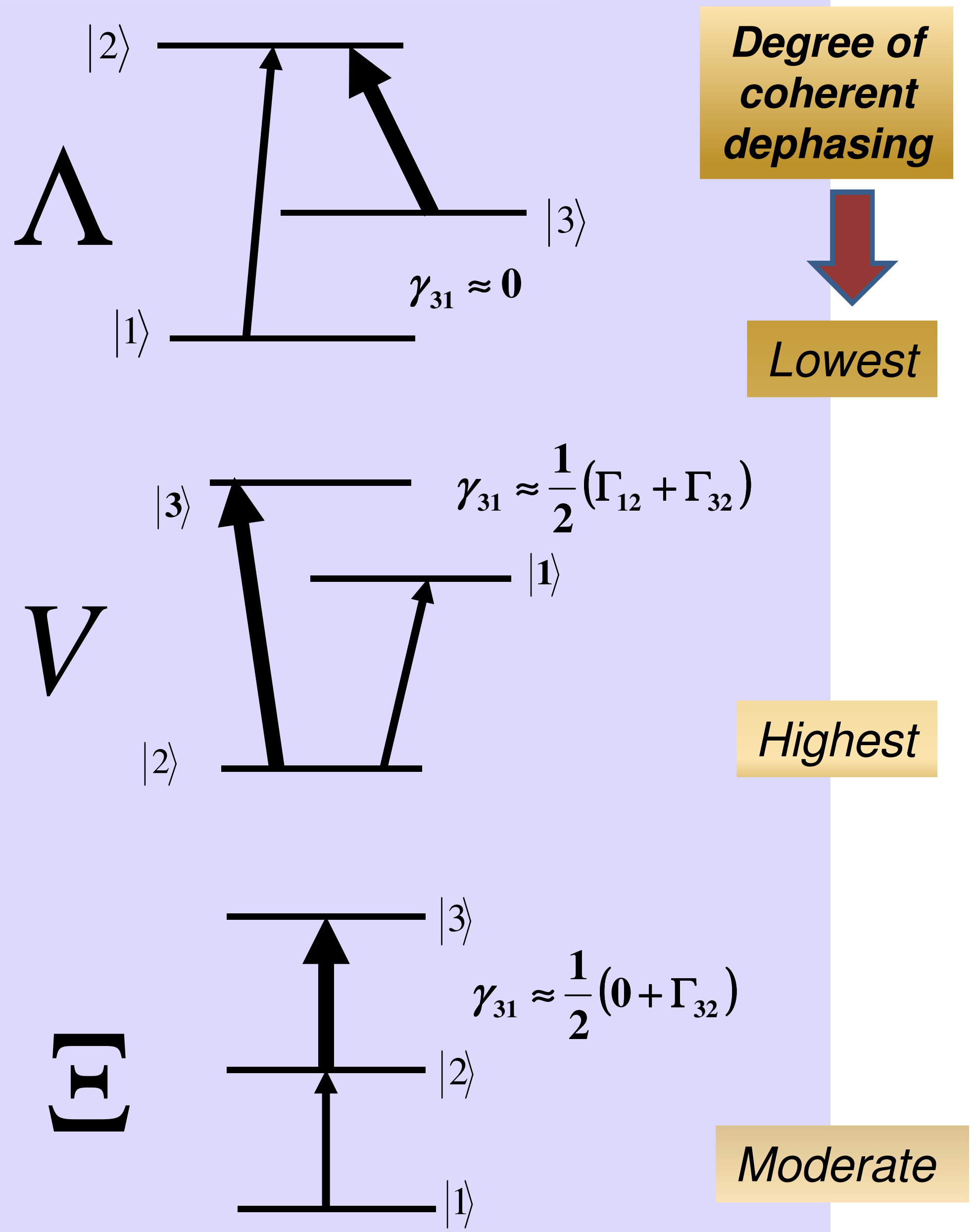
Ayan Ray
Radioactive Ion Beam Facility Group
Variable Energy Cyclotron Centre
Kolkata-700064
INDIA

Essence of Quantum Interference

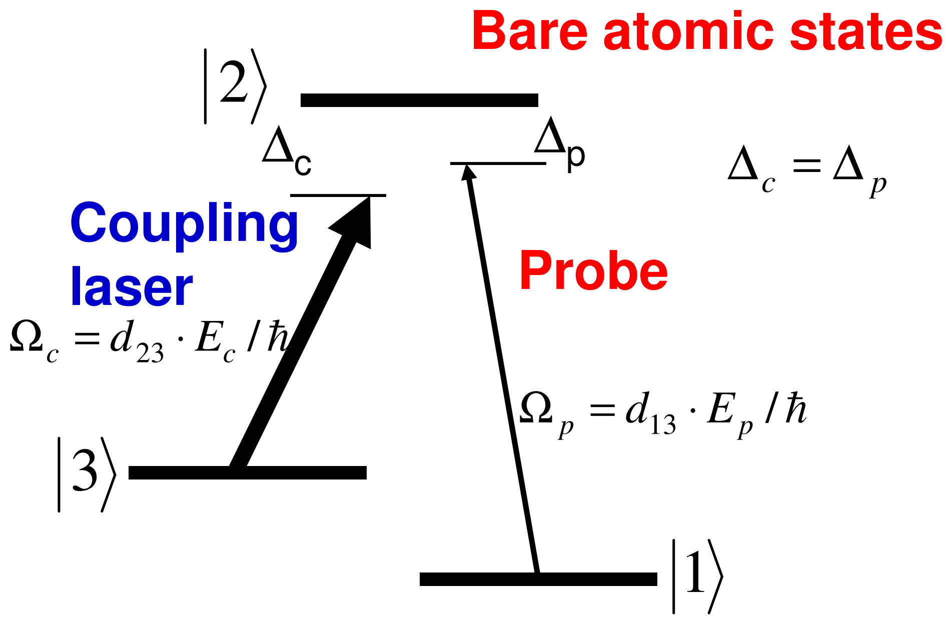


$$P = |C|^2 = |C_1 + C_2|^2 = P_1 + P_2 + P_{12}$$

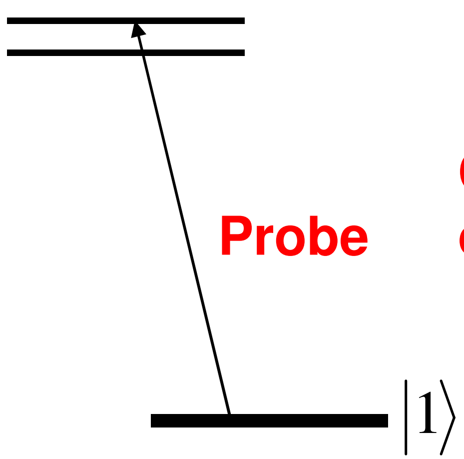
Parameters of the radiation field to control the interference term



Bare Atom vs. Dressed Atom



Dressed states



Laser-atom interaction

$$H = H_{atom} + H_{interaction}$$

$$H_{interaction} = d \cdot E \;, \quad \langle i | H_{atom} | j \rangle = E_i \delta_{ij}$$

Bare atomic states

Dressed states

$$|C\rangle = \frac{\Omega_p}{\Omega_T}|1\rangle + \frac{\Omega_c}{\Omega_T}|3\rangle, \quad \Omega_T = (\Omega_c^2 + \Omega_p^2)^{1/2}$$

$$|NC\rangle = \frac{\Omega_c}{\Omega_T}|1\rangle - \frac{\Omega_p}{\Omega_T}|3\rangle \qquad \langle 2 | d \cdot E | NC \rangle \to 0$$

Therefore

$$|1\rangle = \frac{\Omega_c |NC\rangle + \Omega_p |C\rangle}{\Omega_T}$$

When $\Omega_p << \Omega_c$, $|1\rangle \sim |NC\rangle$

Results of Dressed Level Spectroscopy

❑ **Probe absorption in presence of control laser:**

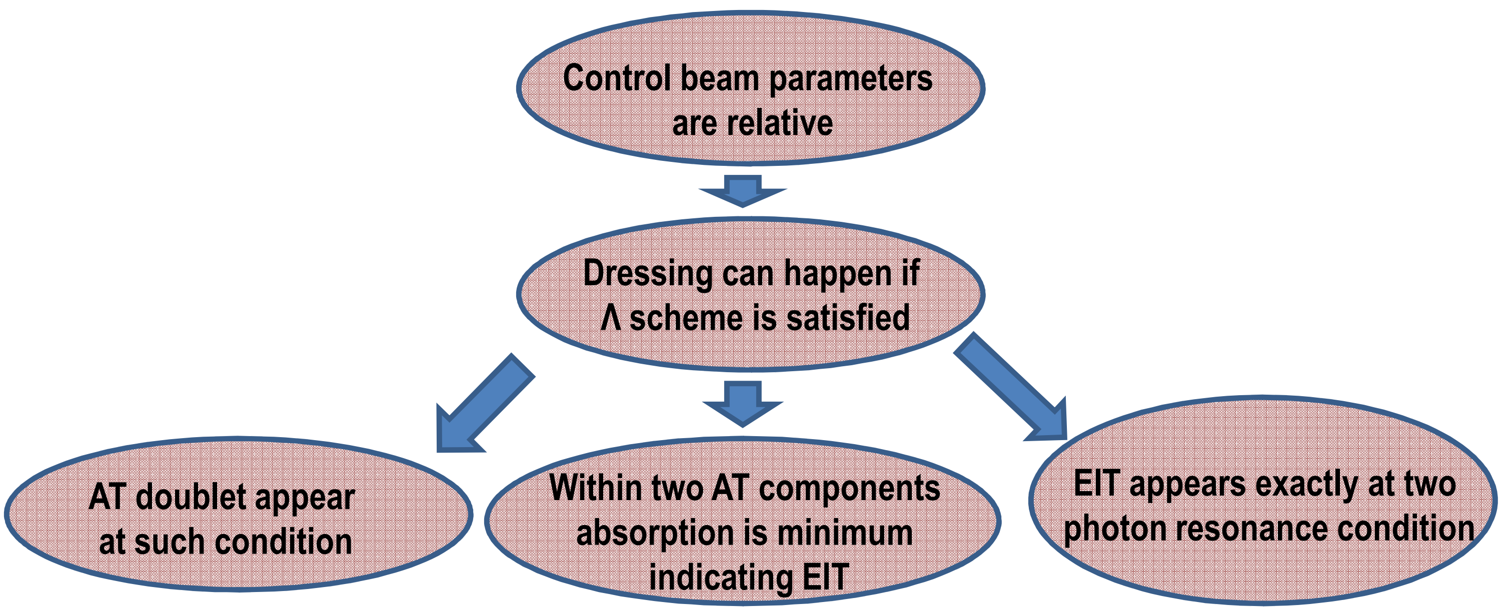
$$\rho_{21} = \frac{\Omega_{probe}(\Delta_{control} - \Delta_{probe})}{|\Omega_{control}|^2 - (\gamma_{probe} + \gamma_{control} - j\Delta_{control})(\Delta_{control} - \Delta_{probe})}$$

❑ **Autler –Townes Doublet :**

$$\delta_{\pm} = \left(\frac{\Delta_{control}}{2}\right) \pm \frac{1}{2}\sqrt{\Delta_{control}^2 + 4|\Omega_{control}|^2},$$

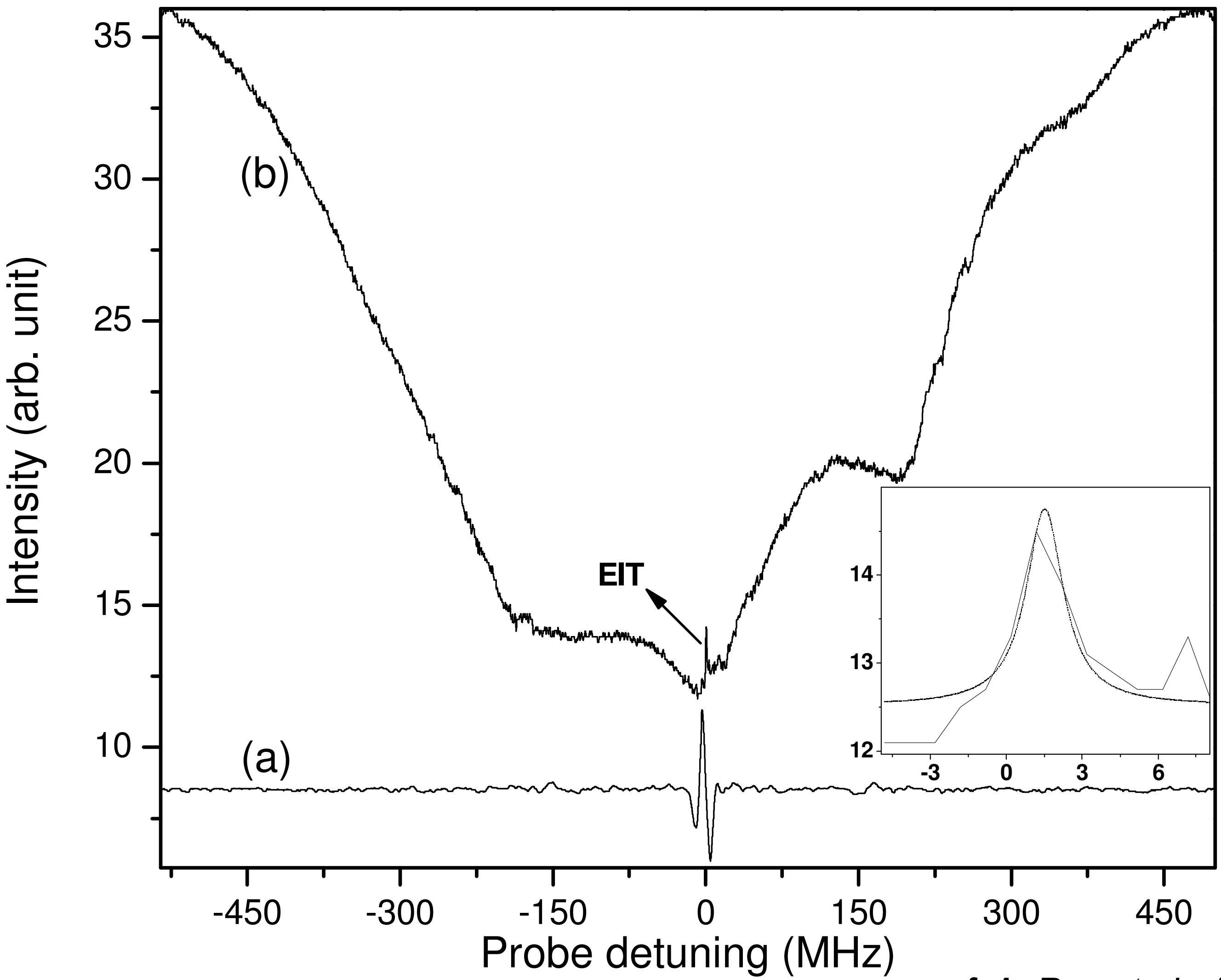
$$\alpha \pm = \frac{\gamma_{control} + \gamma_{probe}}{2}\left(1 \mp \frac{\Delta_{control}}{\sqrt{\Delta_{control}^2 + 2|\Omega_{control}|^2}}\right)$$

Chronology of events in dressed-atom picture



Towards novel type optical memory and photon switching

Subnatural EIT in an alkali vapour cell:



The Cs D_2 transition manifold is used to construct Λ scheme where $6S_{1/2}F=3,4 \rightarrow 6P_{3/2}$ F'= 4 are used. The fitted linewidth (FWHM) is < 2 MHz.

ref: A. Ray et al., Appl. Phys. B, ***100*** *(2010) 505*

Gain and loss mechanisms in a three level EIT medium

Absorption in dressed media: $$\mathrm{Im}\left\{\frac{\rho_{21}\times\Gamma_{21}}{\Omega_{\mathrm{probe}}}\right\}$$

Absorption in real atomic media: $$\int d(kv)\ \ f(kv)\ \ \mathrm{Im}\left\{\frac{\rho_{21}\times\Gamma_{21}}{\Omega_{\mathrm{probe}}}\right\}$$

Velocity distribution in atomic media: $$f(kv)=\frac{1}{\pi}\left(\frac{W_D}{W_D{}^2+(kv)^2}\right)$$

Absorption at two photon resonance: $$\frac{\Gamma_{31}}{\Gamma_{31}W_D+\Omega^2}\left(\frac{\sqrt{x}}{1+\sqrt{x}}\right)$$

Here $$x=\frac{\Omega_{\mathrm{pump}}^2}{\Omega_s^2}=\frac{\Gamma\ \ \Omega_{\mathrm{pump}}^2}{2\Gamma_{31}W_D^2}$$

See Javan et al., Phys. Rev. A, 66, 013805 (2002)

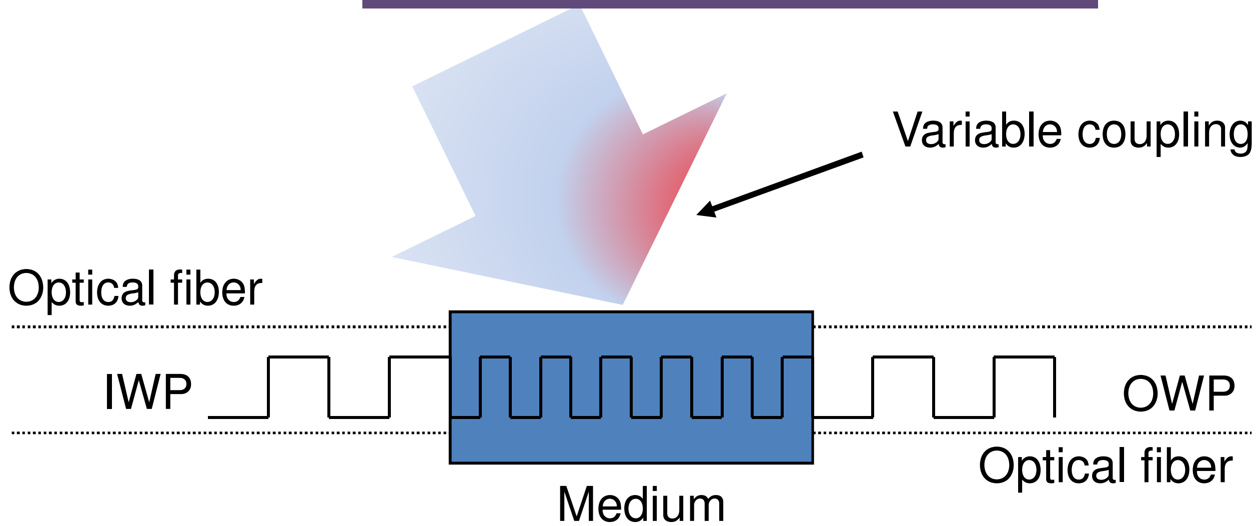
Contd.

Gain and loss mechanisms in a three level EIT medium

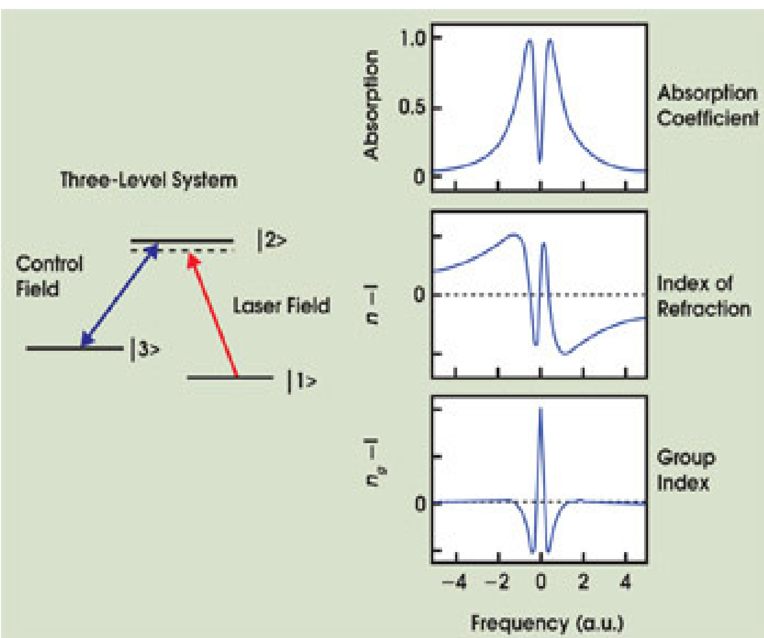
The EIT signal appears at the position of the absorption minimum. Contrast of EIT is determined by the mutual competition between (i) optical pumping and (ii) non radiative decay between ground states.

- **Optical pumping:** $\left(\frac{\Omega^2_{pump}}{\Gamma}\right)$ ⇒ Gain mechanism
- **Non-radiative decay:** Γ_{31} ⇒ Loss mechanism
- **Linewith of EIT:**
  $$\begin{cases} \Omega_{\mathrm{pump}}\sqrt{\dfrac{2\Gamma_{31}}{\Gamma}} \Rightarrow \Omega_{\mathrm{pump}} << \Omega_{\mathrm{s}} \\ \dfrac{\Omega^2_{\mathrm{pump}}}{W_{\mathrm{D}}} \Rightarrow \Omega_{\mathrm{pump}} >> \Omega_{\mathrm{s}} \end{cases}$$
- **Conditions of EIT:** $\Omega^2_{\mathrm{pump}} >> \Gamma\Gamma_{31}$ and $\Delta_{\mathrm{pump}} = \Delta_{\mathrm{probe}}$

Excerpts of the story



Results: (i) Slowing down the group velocity
(ii) The light is stored in the medium



http://www.photonics.com/Article.aspx?AID=24576

Kramers-Kronig relation (near resonance):

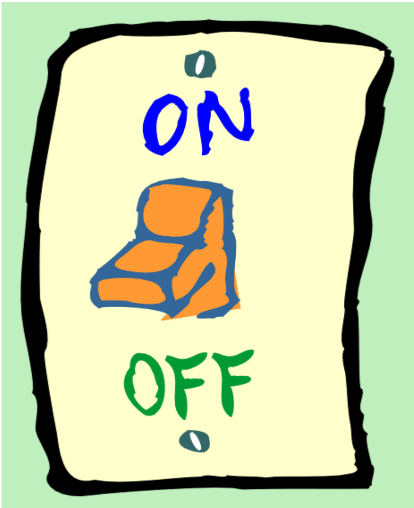
$$\alpha(\omega) \approx \frac{Ne^2}{4\varepsilon_0 mc}\frac{\gamma}{(\omega_0-\omega)^2+(\gamma/2)^2} \longrightarrow \text{Absorption}$$

$$n'(\omega) \approx 1+\frac{Ne^2}{4\varepsilon_0 m\omega_0}\frac{(\omega_0-\omega)}{(\omega_0-\omega)^2+(\gamma/2)^2} \longrightarrow \text{Dispersion}$$

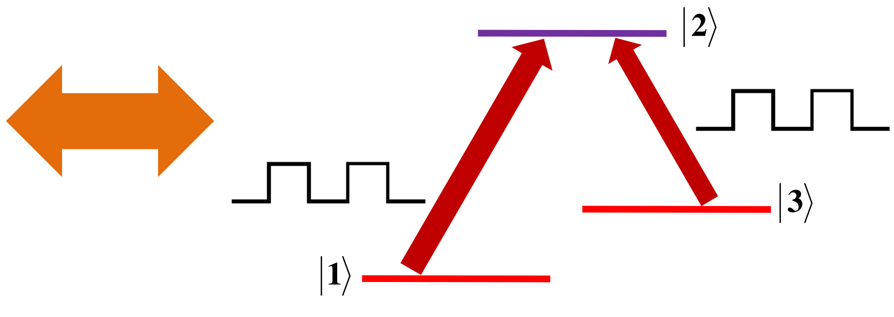
$$n(\omega) = n'(\omega) - i\frac{\alpha(\omega)}{2k_0} \longrightarrow$$

complex r . i

A ladder system in optical switching

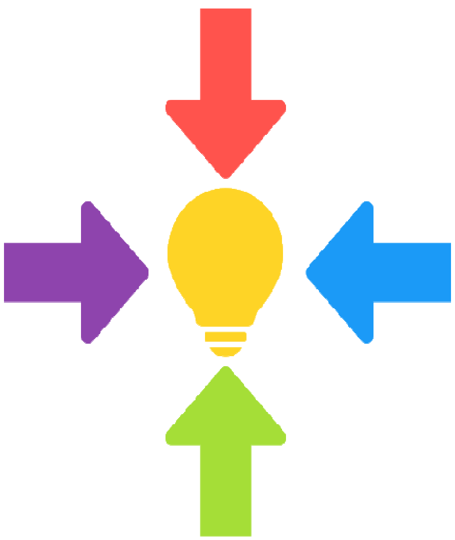


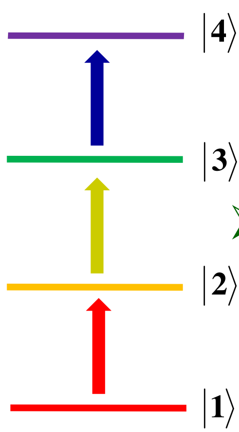
One way all optical switching: switching ON and OFF one light beam with another



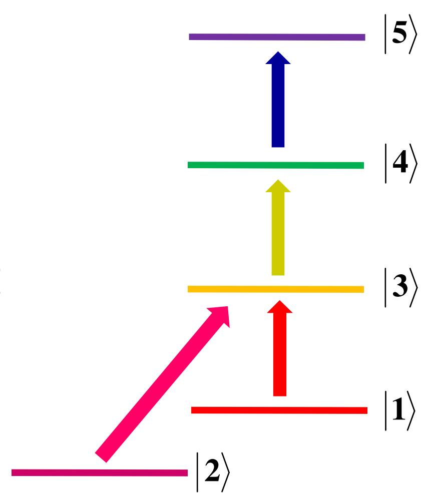
- Λ level coupling

Multiway all optical switching: switching ON and OFF two or more light beams with a single light beam



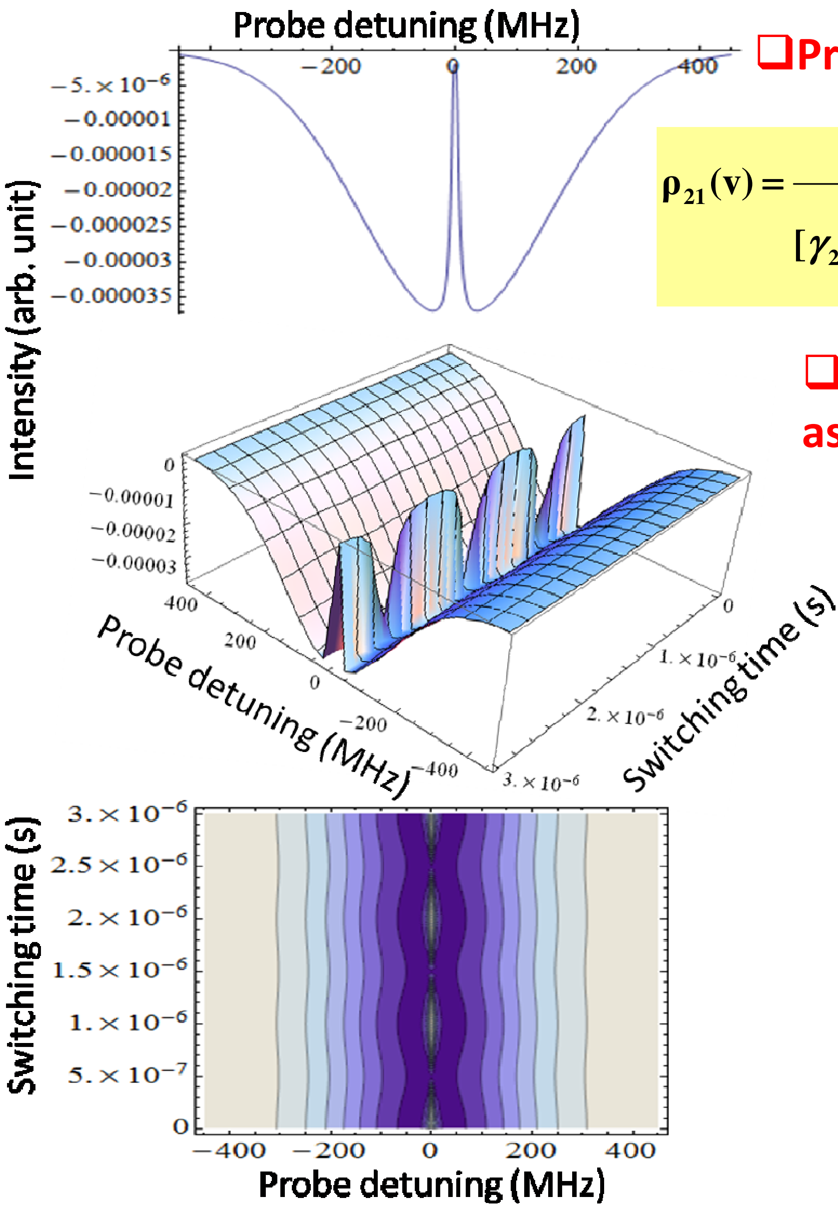


- multistep Ξ level coupling



- tripod level coupling

A simplistic view of Intensity Modulation transfer in a coherently prepared gas medium



❑ **Probe absorption in presence of control laser:**

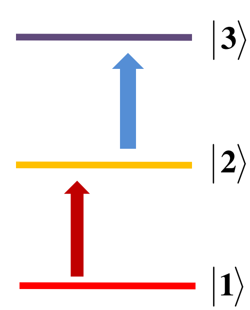
$$\rho_{21}(v) = \frac{i(\Omega_{pr}/2)}{[\gamma_{21} - i(\Delta_{pr} + kv)] + \dfrac{(\Omega_{pu}/2)^2}{\{\gamma_{31} - i(\Delta_{pr} + \Delta_{pu}) - i(\omega_{pr} - \omega_{pu})(v/c)\}}} G(v)dv$$

❑ **Introduction of external intensity modulation as deterministic flow:**

$$\Omega_{pu}^2 \rightarrow \Omega_0^2(c_1 + c_2 Cos\, \omega_m t)$$

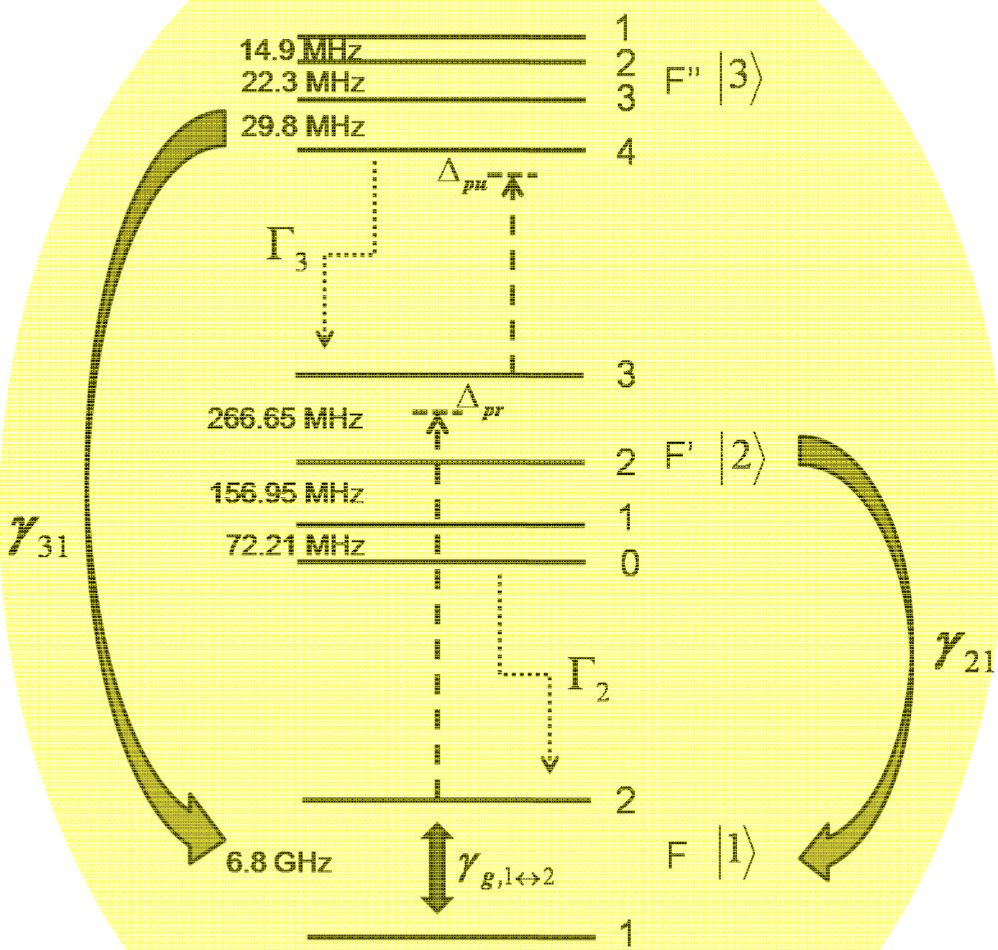
The system gets into:

Coherent Crosstalk

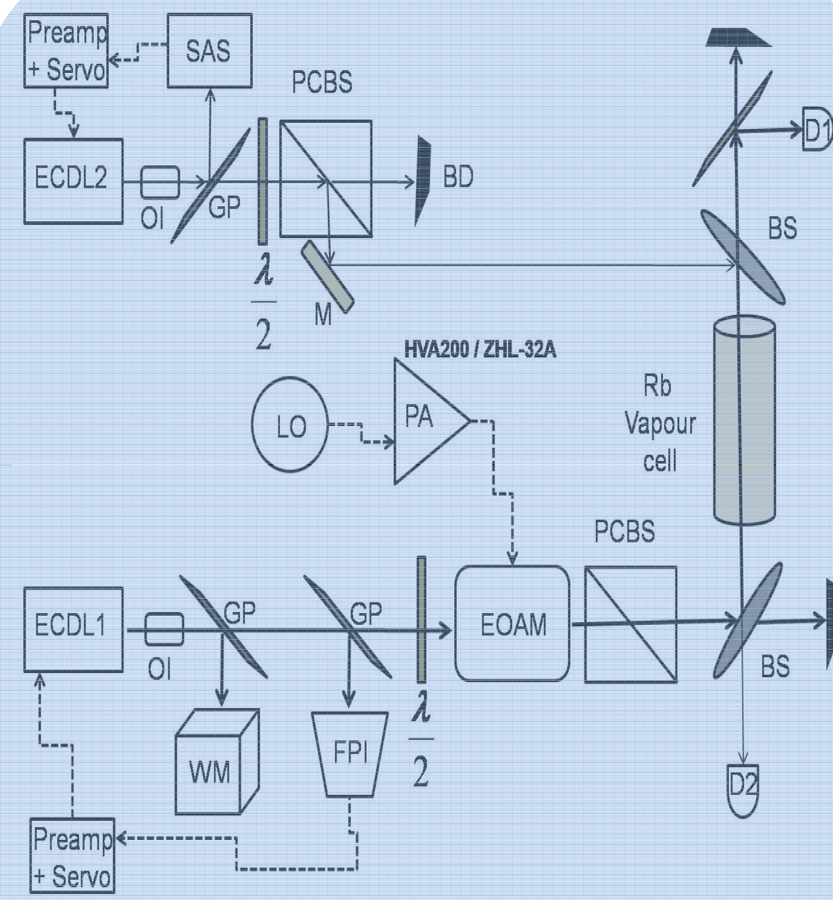


ref: A. Ray et al., Eur. Phys. J. D, ***67*** *(2013) 78*

Experiments in ^{87}Rb 5S-5P-5D ladder scheme

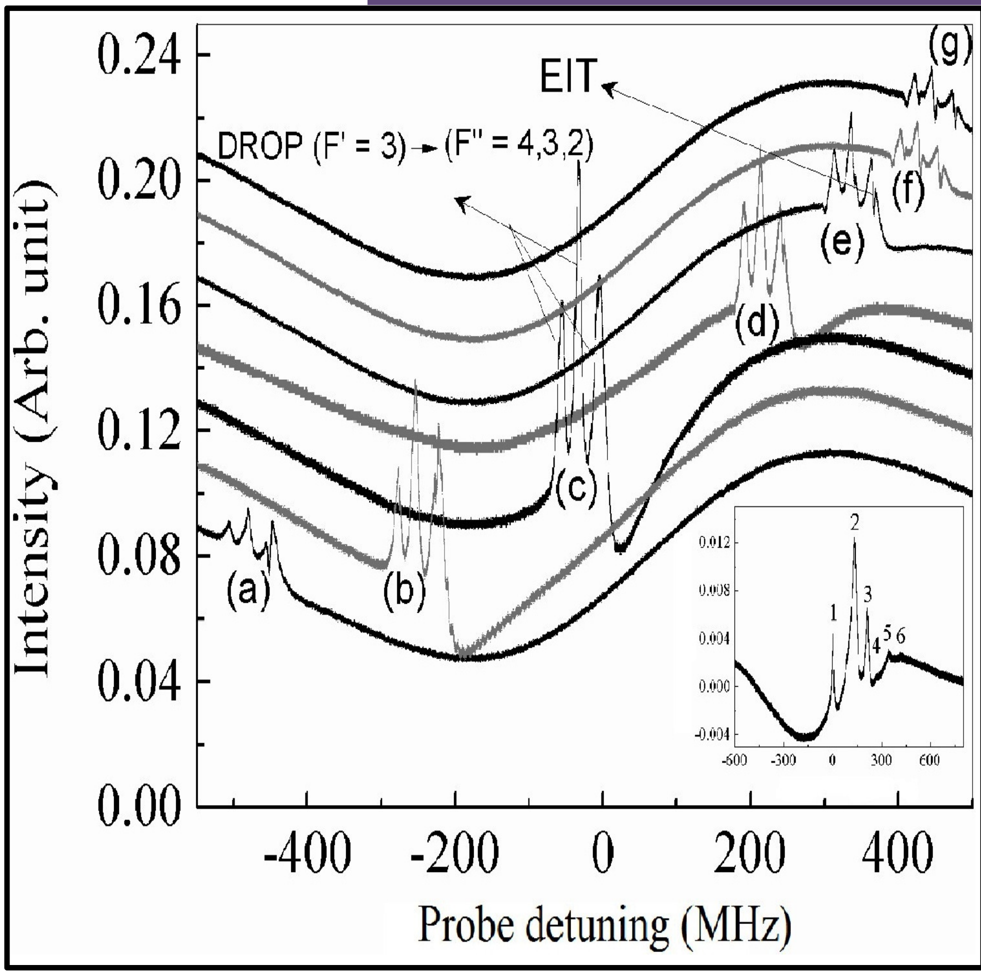


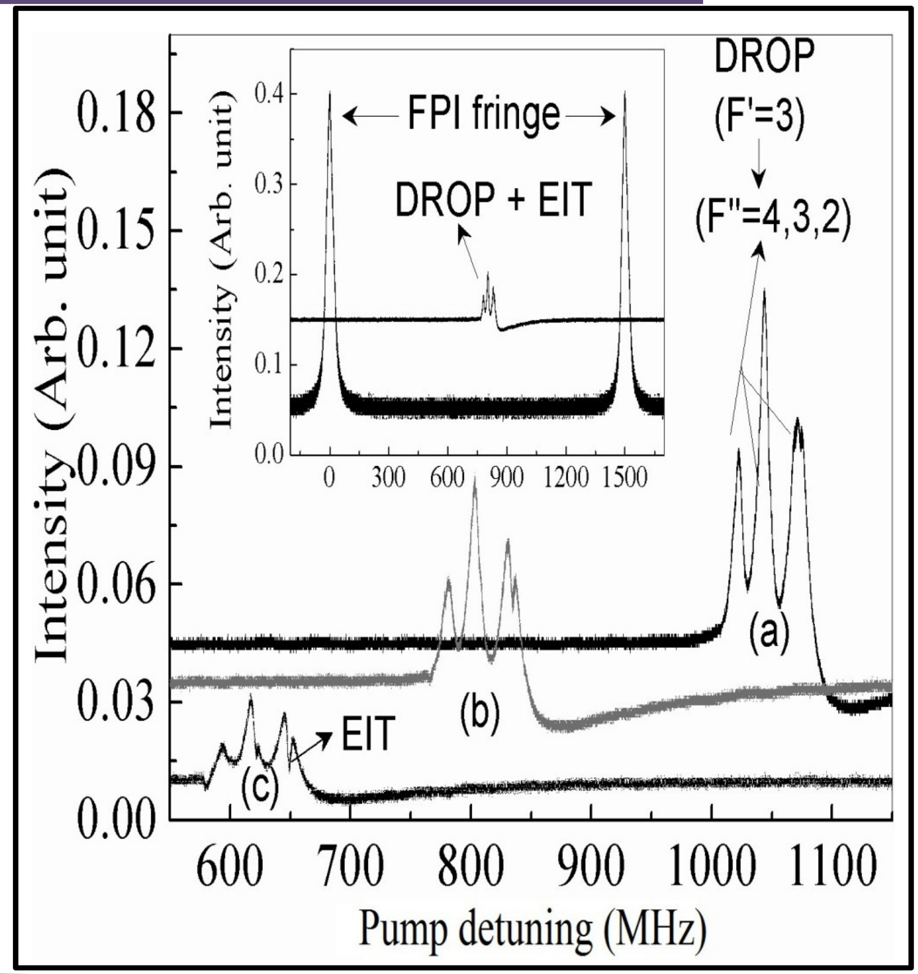
The level scheme



Experimental schematic

Spectroscopic results: two views

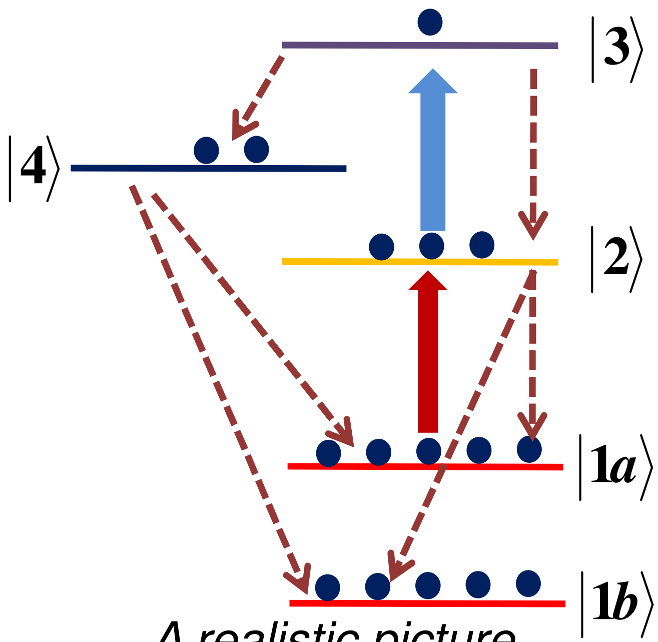




Results:
EIT appears within DROP (double resonance optical pumping profile) {ref: Moon et al., Opt. Express **16, 12163** (2008) Moon et al. } and differs from earlier result {ref: Xiao et al., Phys. Rev. A **51, 576 (1995)**}

*ref: A. Ray et al., Eur. Phys. J. D,**67** (2013) 78*

DROP and EIT



A realistic picture

- Three level scheme is an experimenter's dream, which is hardly realizable.
- In a multilevel scheme certain effects (e.g. optical pumping, pump field saturation etc.) can play crucial role.
- Repeated optical pumping-decay cycles can populate the uncoupled component of the ground state, introducing 'Radiation Trapping' into picture.

Two photon absorption in a dressed medium:

$$R_{1\rightarrow 3} = \frac{2\pi}{\hbar}\left|\left(\frac{<3|\vec{d}.\overrightarrow{E_{pu}}|+><+|\vec{d}.\overrightarrow{E_{pu}}|1>}{\left(\omega_{21}+\frac{\Omega_{pu}}{2}\right)-\omega_{pr}}\right)+\left(\frac{<3|\vec{d}.\overrightarrow{E_{pu}}|-><-|\vec{d}.\overrightarrow{E_{pu}}|1>}{\left(\omega_{21}-\frac{\Omega_{pu}}{2}\right)-\omega_{pr}}\right)\right|^2 \times\delta(\omega_{31}-\omega_{pu}-\omega_{pr})$$

Agarwal et al., PRL, 77(1996) 1039

DROP, EIT (contd.)

- The DROP stems out of loss of atoms from |1>→|2>→|3> scheme.
- The EIT demands no loss of atoms from the same coupling domain.
- Both DROP and EIT arises at two photon resonance condition.
- EIT appears as a fine structure within DROP.
- EIT is more prominent when |1>→|2> shifts far from cyclic condition.

Inferences:

(1) DROP and EIT are counter-intuitive in nature.

(2) The loss of atoms even at exact cyclic resonance is so prominent that EIT is obscured from DROP background.

(3) The branching ratio plays the most vital role in populating the uncoupled component of ground state.

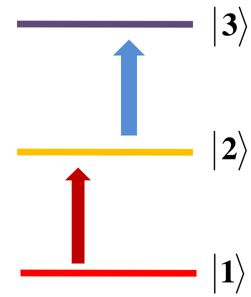
*ref: A. Ray et al., Eur. Phys. J. D,**67** (2013) 78*

EIT, DROP and Optical Switching

EIT (must) conditions in a Ξ system:

(1) $\Delta_{pu} + \Delta_{pr} \approx 0$ ➡ Two Photon resonance condition

(2) $\dfrac{\Omega_{pu}^{2}}{\gamma_{21}} >> \gamma_{31}$ ➡ Optical Pumping condition



Polarizability resembles Damped Harmonic Oscillator:

$$\rho_{21}(t) = \rho_{21}(0)\exp\left(-\frac{\gamma_{21}}{2}t\right)\left(\cos\frac{\Omega}{2}t + \frac{\gamma_{21}}{\Omega}\sin\frac{\Omega}{2}t\right)$$

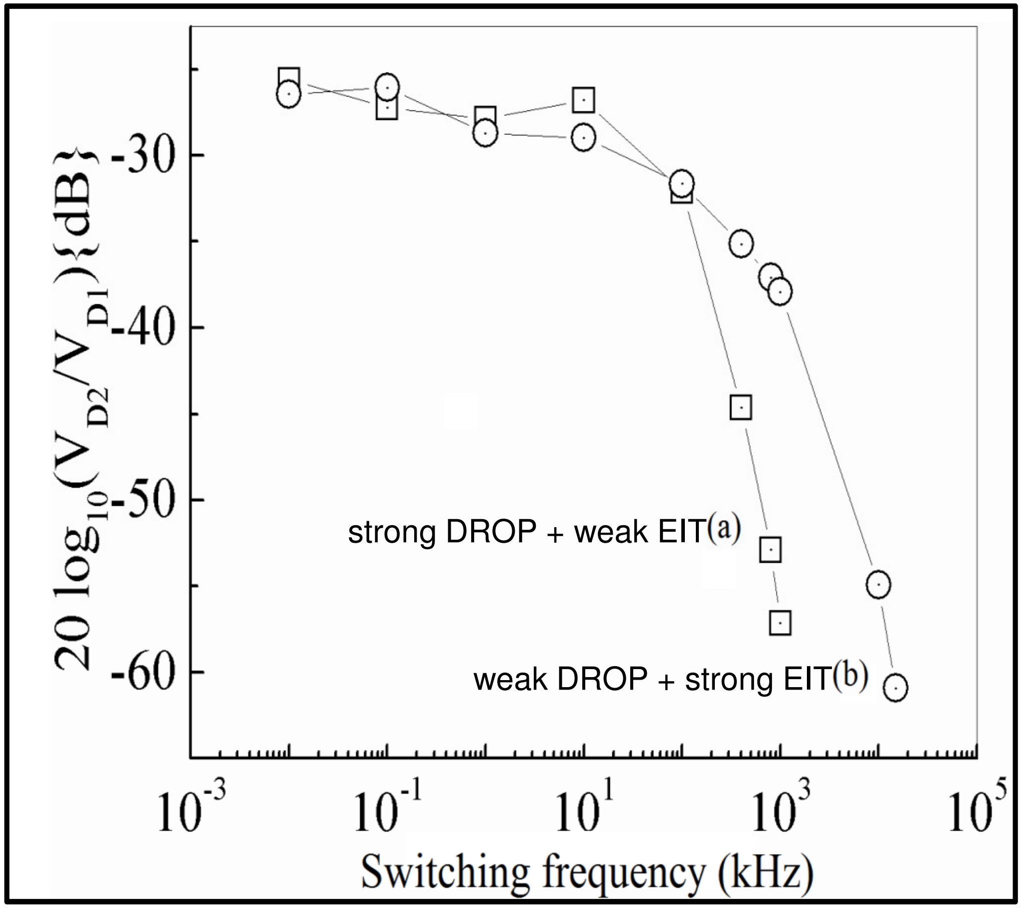
Xiao et al., Opt. Lett., 20(1995) 1489

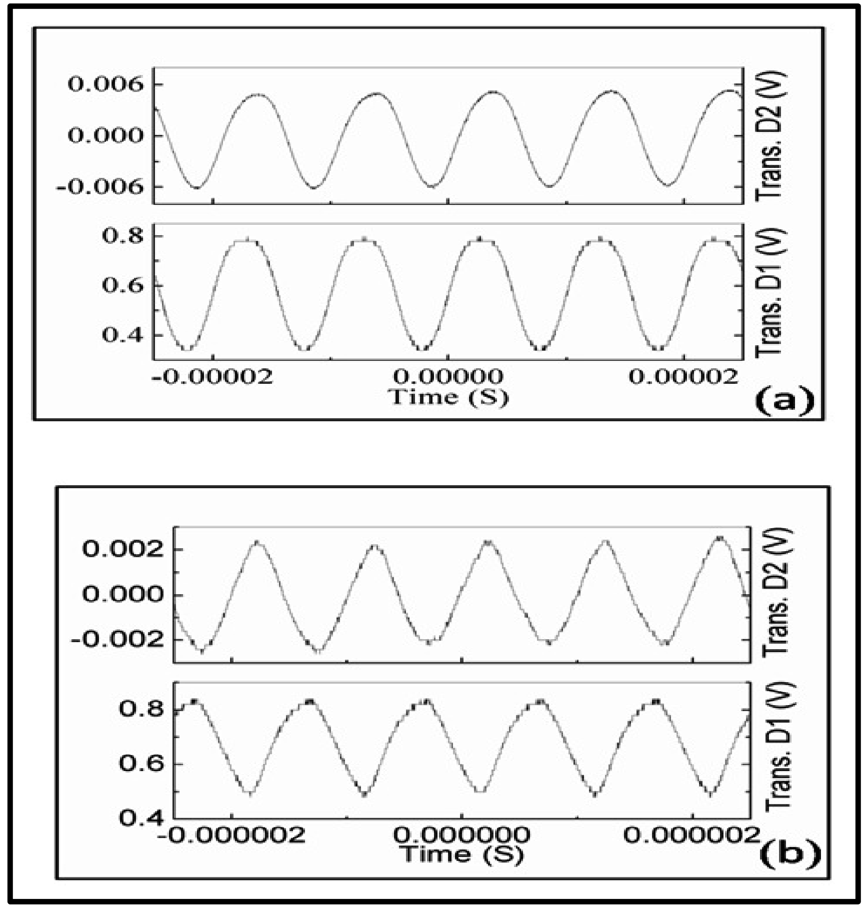
- For EIT the switching speed is determined by $\dfrac{\Omega_{pu}^{2}}{\gamma_{21}}$, at which the excursion of medium opaque ↔ transparent occurs.
- For DROP the switching speed is determined by decay rates.

As both DROP and EIT appear at two photon resonance, a bimodal slow-fast switch can be made out of it !!!

ref: A. Ray et al., Eur. Phys. J. D, ***67*** *(2013) 78*

Experimental demonstration

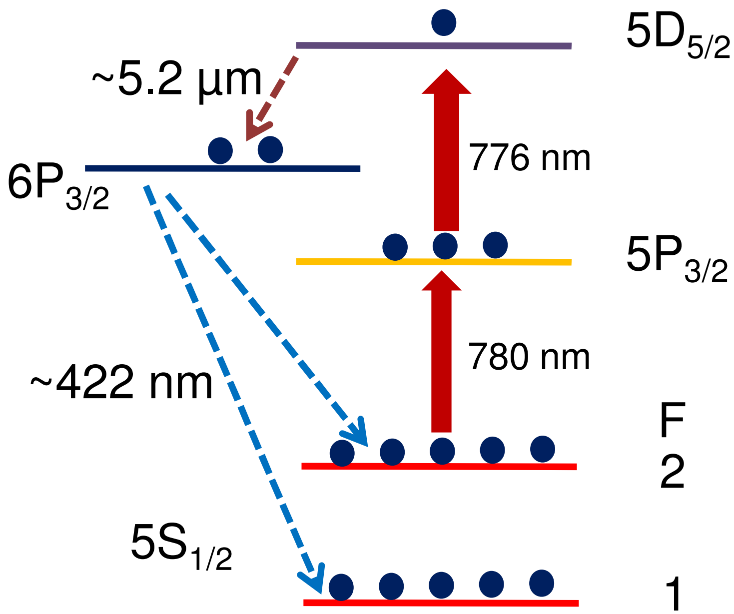


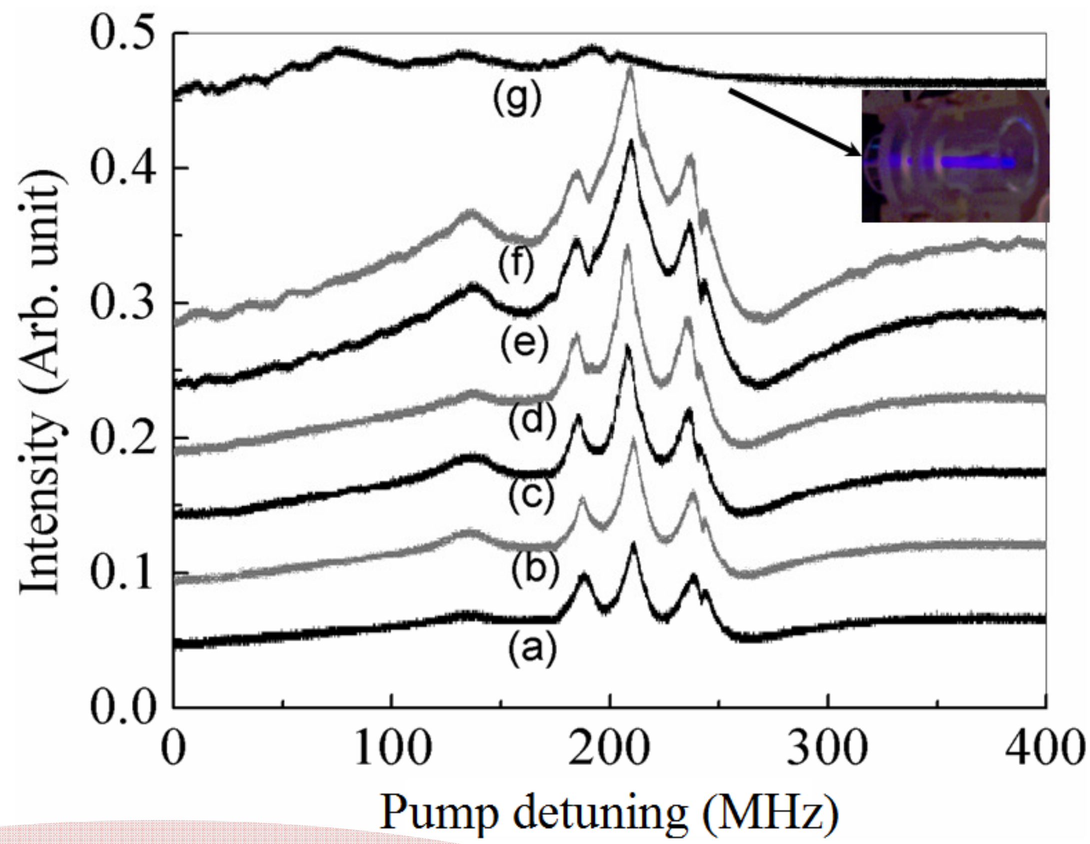


➢**The Bandwidth for dominant EIT condition extends to one order higher compared to the strong DROP condition. It requires a strong limiting control to hover between two regions.**

ref: A. Ray et al., Eur. Phys. J. D, ***67*** *(2013) 78*

A possible limit in DROP-EIT medium





If it hadn't been for Cotton-Eye Joe
I'd been married long time ago....

$$\rho_{21} = \frac{-i\Omega_{pr}}{2\gamma_{21}}\left[1-\frac{\Omega_{pu}^2}{4\gamma_{21}\gamma_{31}}-\frac{\Omega_{pr}^2}{\Gamma_2\gamma_{21}}+\frac{\Omega_{pr}^2\Omega_{pu}^2}{2\Gamma_2\gamma_{21}^2\gamma_{31}}\right]$$

Gaeta et al., PRA **58** (1998) 2500 .

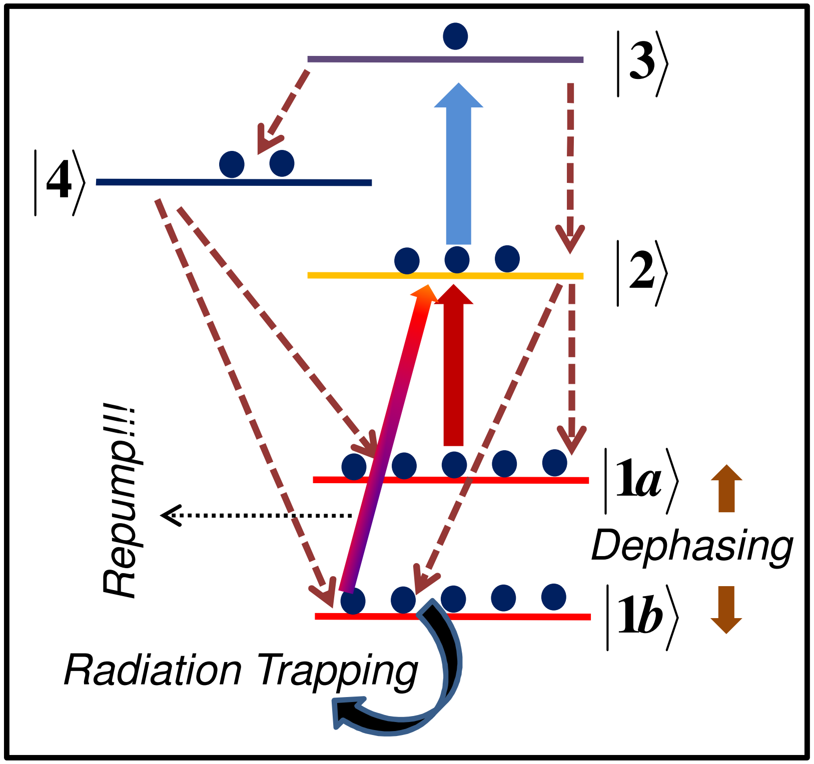
*ref: A. Ray et al., Eur. Phys. J. D,**67** (2013) 78*

Controlling the coherence in a Ξ system (1)

Physical understandings:

(i) EIT demands no population loss from |1a>→|2>→|3> channel.

(ii) DROP is prominent when |1b> is more populated.



Facts in hand:

(i) Atoms are radiation trapped at |1a>.

(ii) Slow Dephasing is present at |1a>↔|1b>.

A more complicated problem: coherence control in open Ξ system?

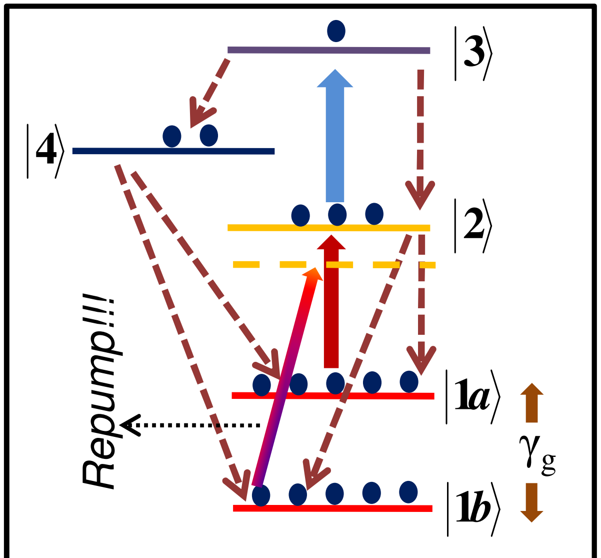
Possible controlling methods:

(i) Repumping back Radiation Trapped population.

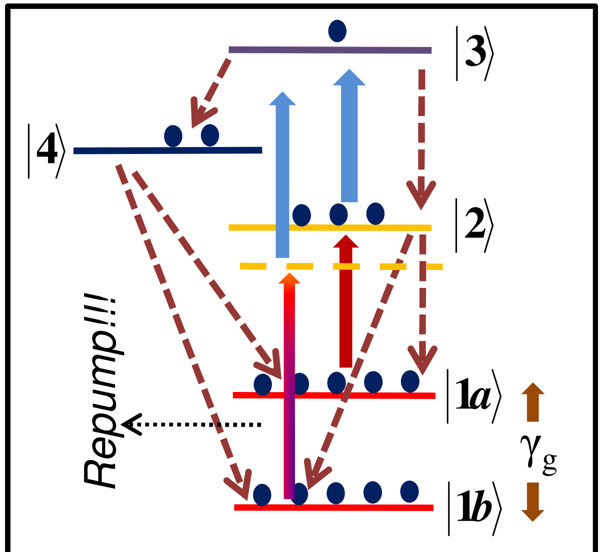
(ii) Using of Double Dark Resonance (!!!).

Controlling the coherence in a Ξ system (2)

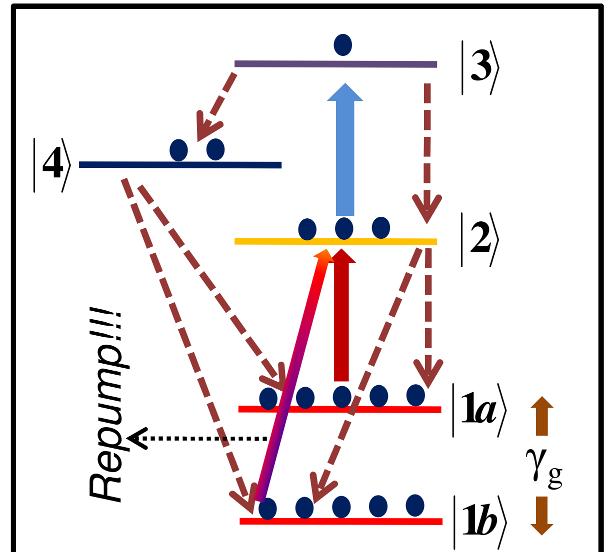
Possible admixture of level schemes under repump action:



Tripod



Double Ladder



Double Dark Resonance (DDR)

Addition of an additional laser (repump) in the system to restore ***'Radiation Trapped'*** population by using optical pumping appears to be easy but it radically changes system response (e.g. $\chi_{tripod} \approx \chi_{ladder} + \chi_{lambda}$).

However DDR can not be written as incoherent sum of two subsystems.

Figure of merit to decide efficacy of coherence control

$$\Gamma_{EIT} \approx \Gamma_{diff} + \frac{\Omega_c^2}{\left(\gamma + \frac{\delta_c^2}{\gamma}\right)}$$

Linewidth of EIT in Ξ system

γ is the total decay rate from 5D state including the decay to neighboring 6P *state (acting as temporary reservoir)*

In a Doppler broadened medium: $\gamma_{31} < \Gamma_{EIT} < (\Omega_c^2/\Delta\omega_D)$

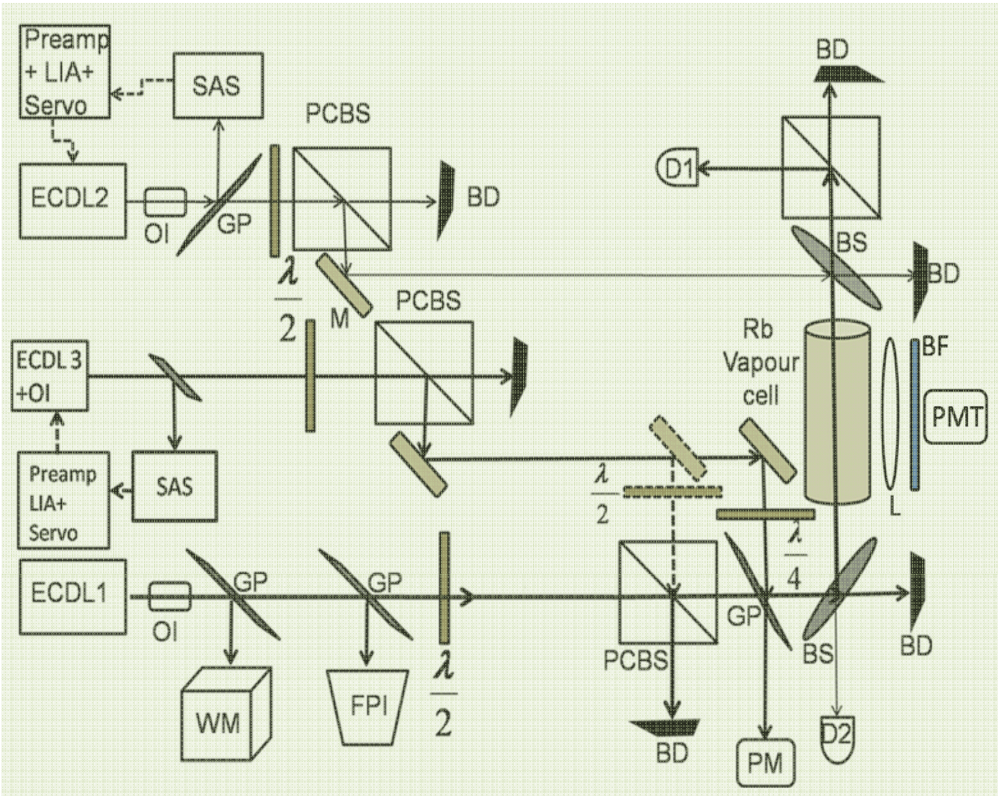
$$\xi_{EIT} = \frac{A_{k(EIT)}}{\sum_{k=1\to 3} A_k}$$

Relative intensity of EIT in Ξ system

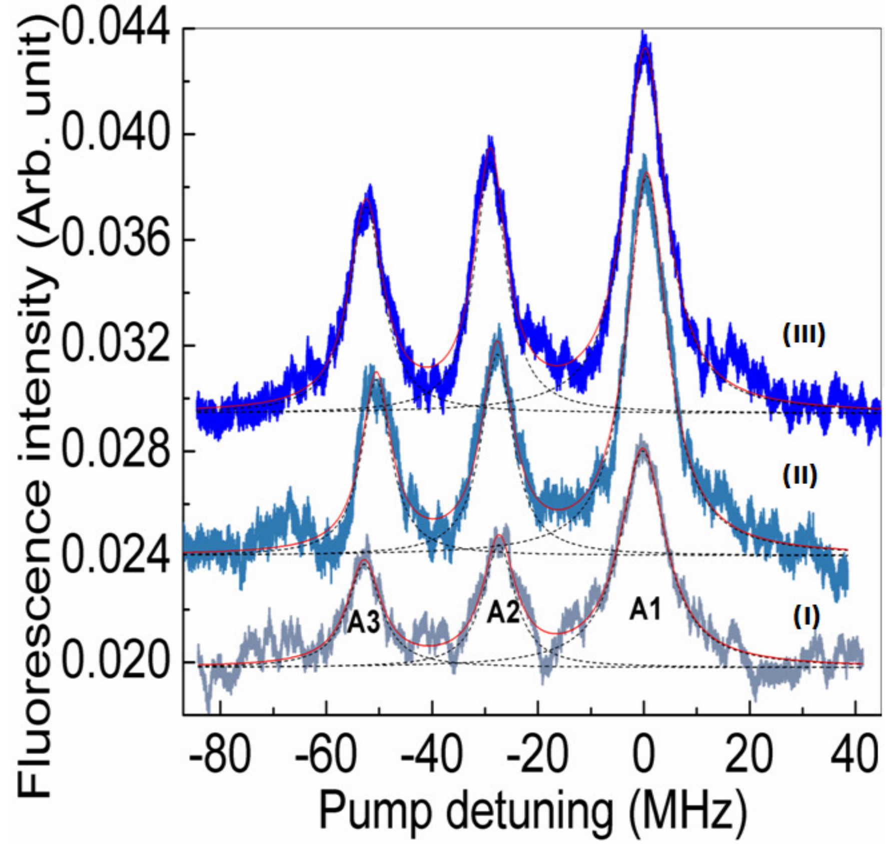
A_k stands for all peaks indicating EIT fine structure within DROP profile. Standard multi-peak fit program may be used.

Optimization of trade-off between Γ_{EIT} & ξ_{EIT}

Experiment with controlling the coherence



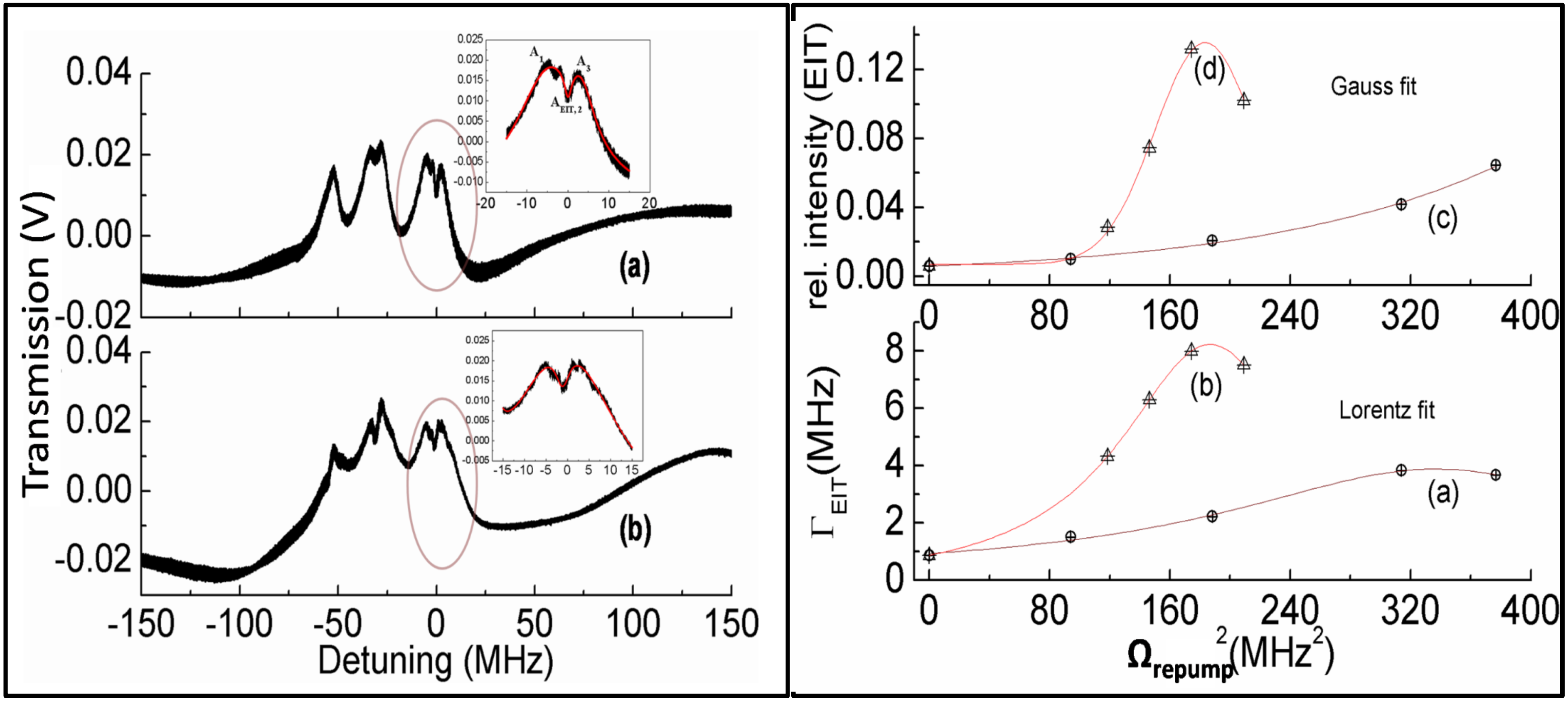
Experimental Schematic



Fluorescence diagnostic

The 5D→6P→5S channel acts as the monitor for population distribution in 2-nd excited state (5D) under various conditions. Of Particular interest is the Blue transition.

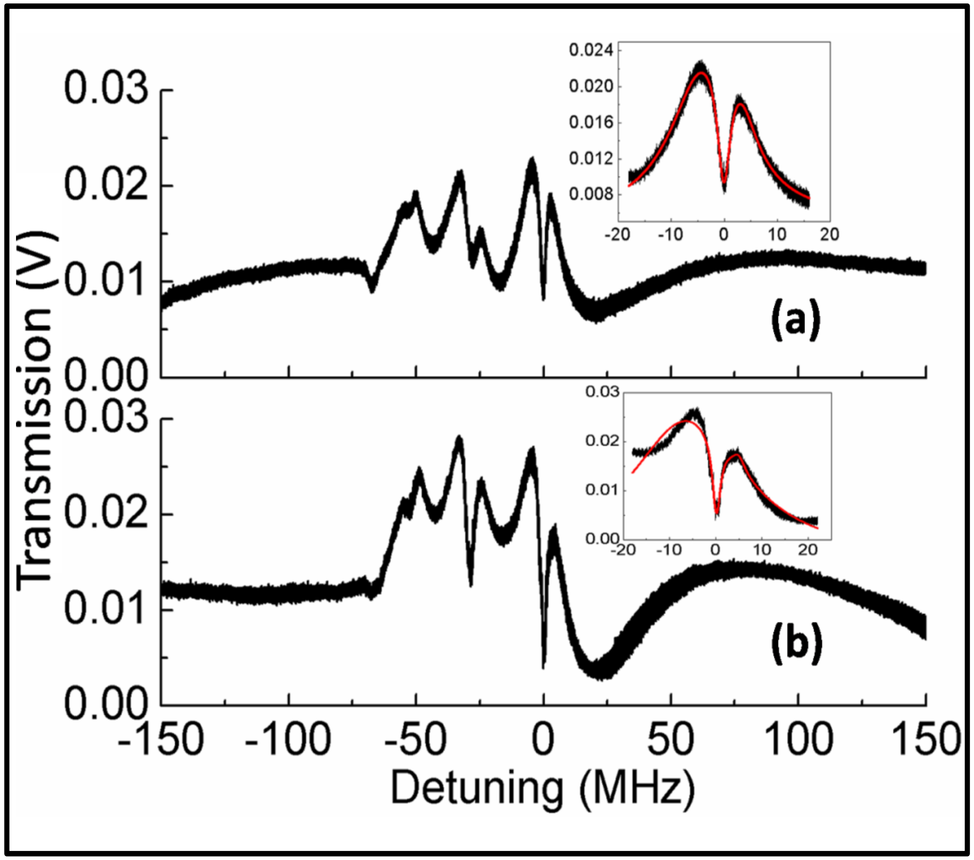
Repump Control of EIT window (1, closed system)

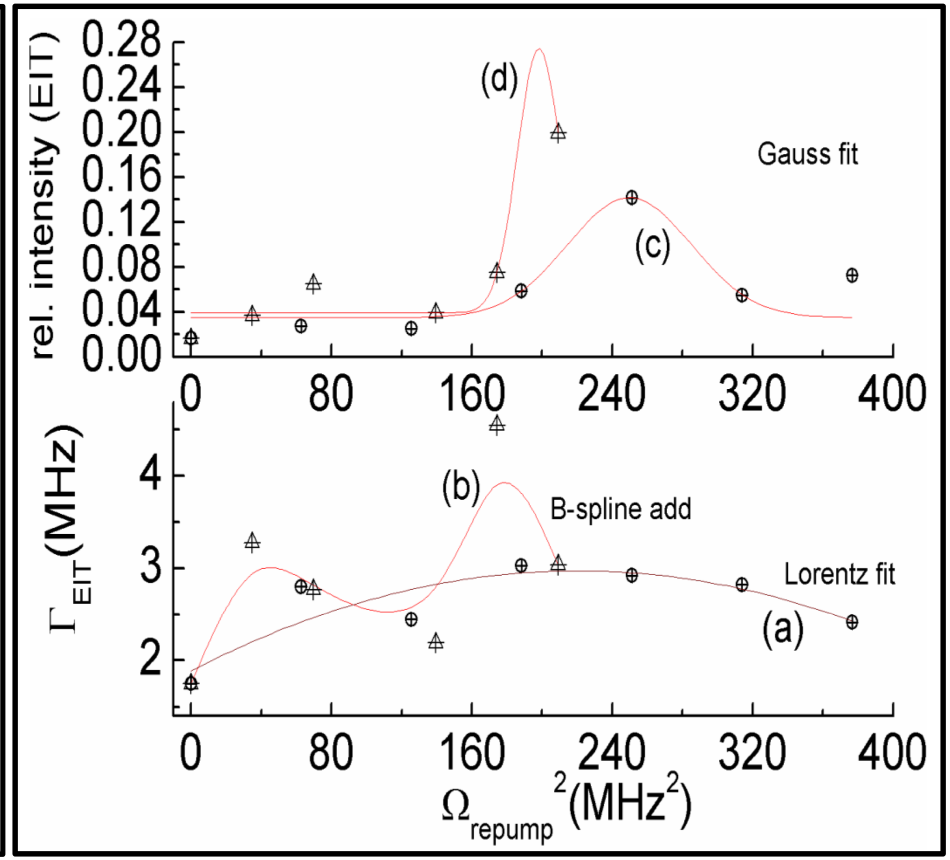


Result of control for on-resonance condition *(F=2 → F′=3 → F″=4)*.

The Lorentzian fitting ensures homogeneous broadening character of EIT while Gaussian fitting indicates role played by Maxwell-Boltzmann velocity distribution of atoms .

Repump control of EIT window (2, closed system)

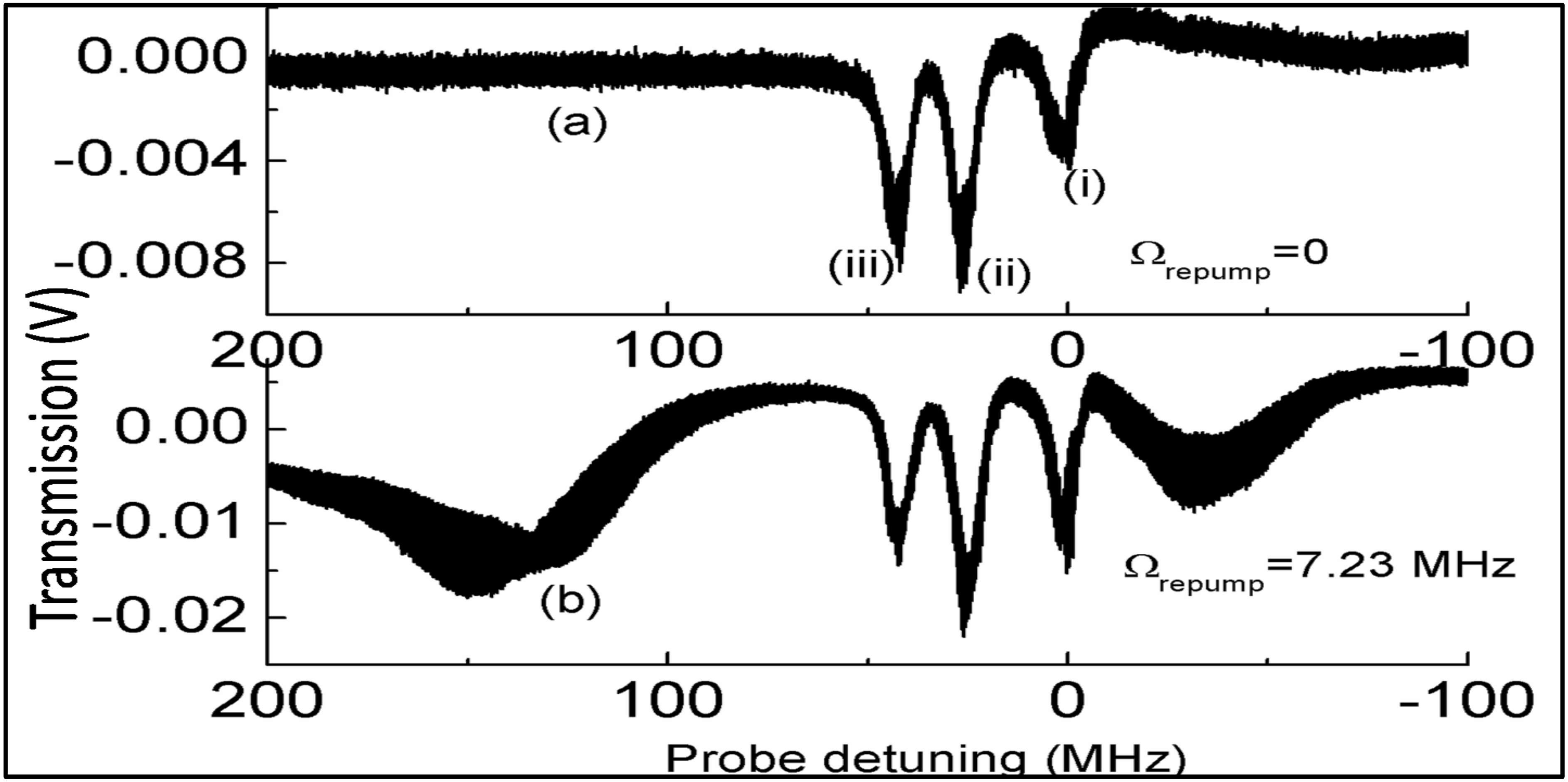




Result of control for off-resonance condition *(F=2 →F′=3,1 →F″).*

The Lorentzian fitting ensures homogeneous broadening character of EIT under σ^+ repumping only while Gaussian fitting shows better velocity selection for the same.

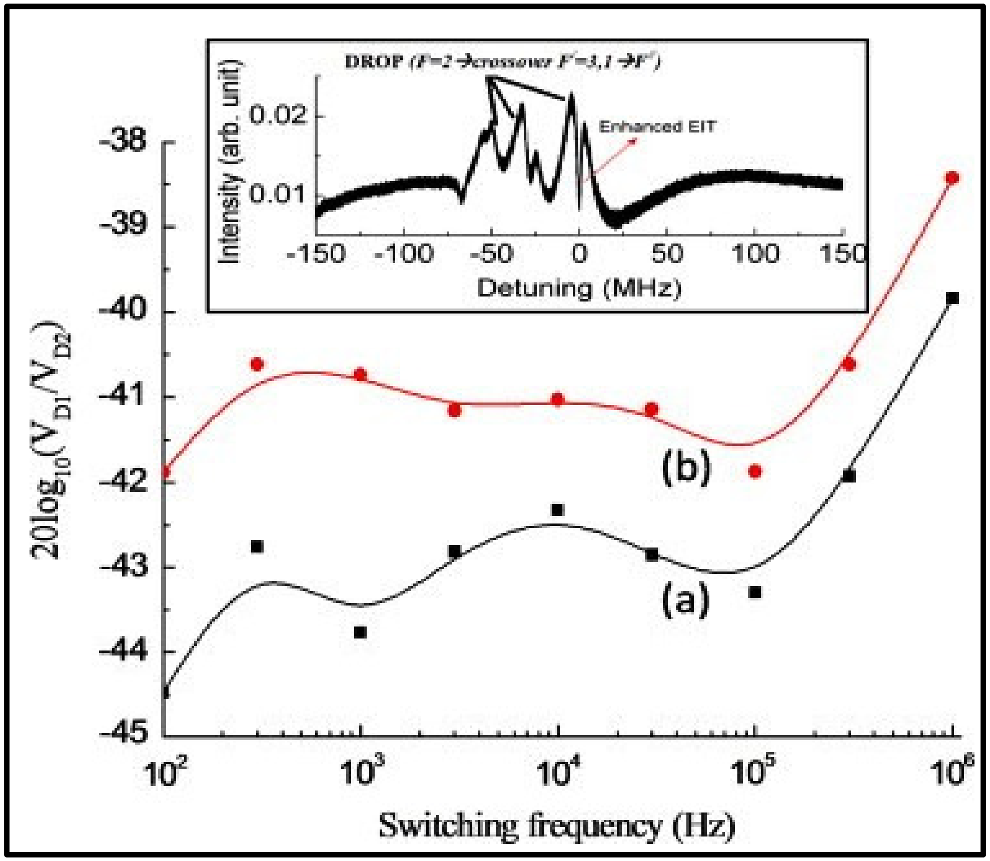
Repump control of open system

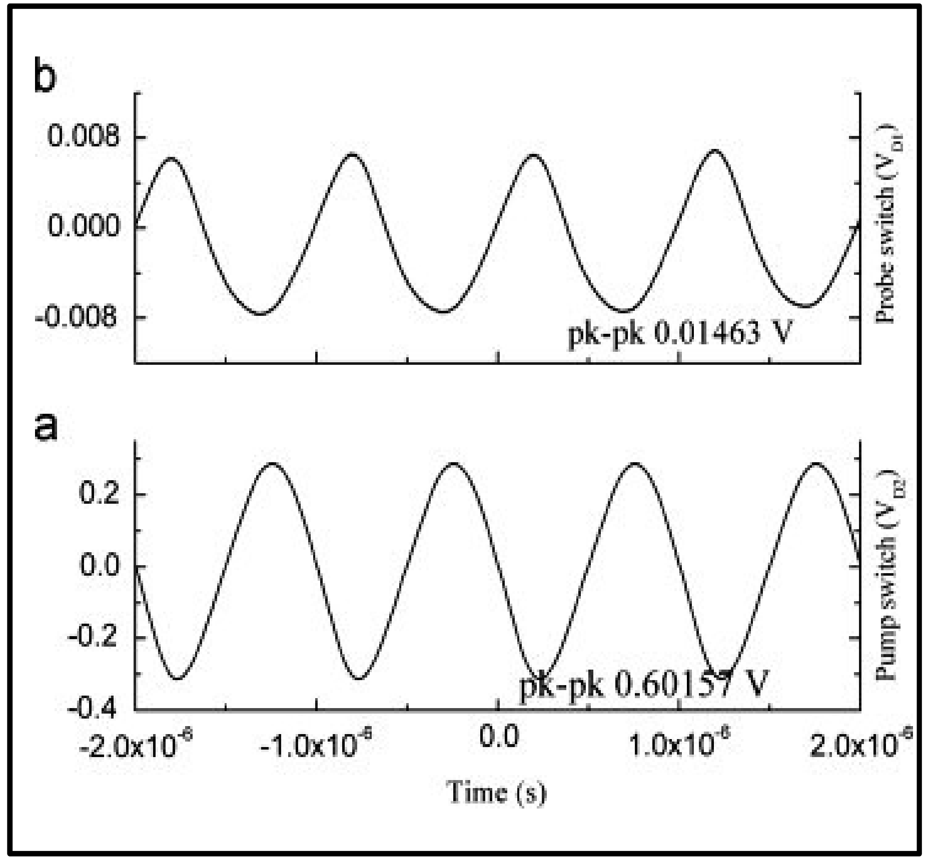


Result of control for on-resonance condition ***(F=1 →F$^{/}$=2 →F$^{//}$).***

The Repump control of F=1 →F$^{/}$=2 →F$^{//}$ appears to be more complex due to more complicated role played by Branching ratios (η). Higher pump power may help !!!

Repump control of optical switching





➢ **Plots (a) and (b) show the gain–bandwidth response of the switch without and with σ^+ repumping. An overall increment of ~4 dB in the gain parameter of the coherence assisted switching is observed with repumping control.**

The σ^+ repumping helps attaining higher Modulation Depth.

ref: A. Ray et al., Opt. Las. Technol, ***60*** *(2014) 107*

Domain of Repump control

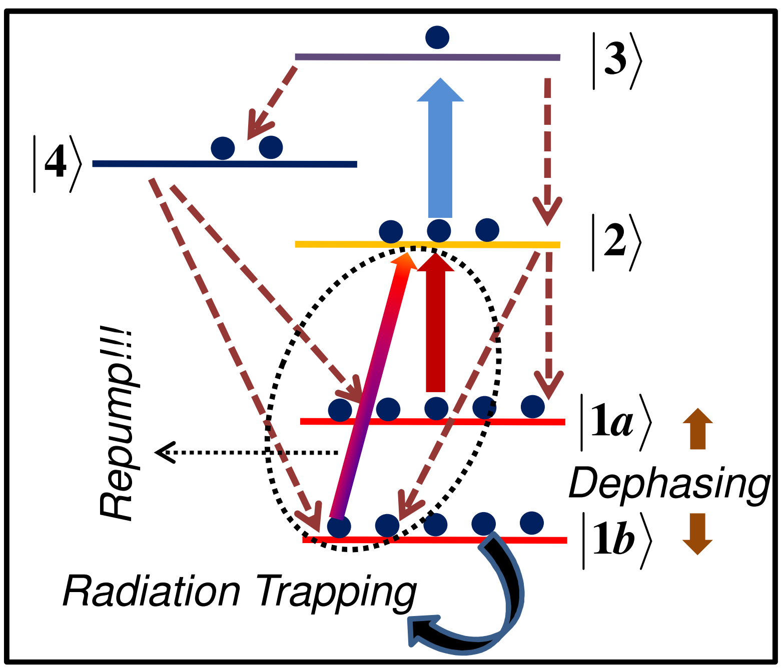
Hyperfine level repumping: e.g. F=1→F$^{/}$=2; efficient, good velocity selection but de-excites through many channels

Zeeman sublevel repumping: e.g. F=1,m_F=+1→F$^{/}$=2, $m_F^{/}$=+2; more efficient, better velocity Selection and de-excites through selective channels

Velocity selection by Raman transition

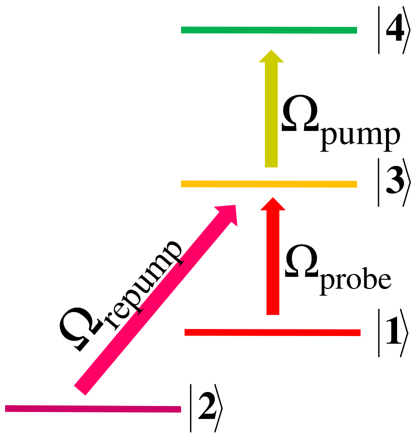
The counter propagating set of probe-repump laser combination provides finer velocity selection through Raman transition: $2kv = \omega_{1b1a} - (\omega_{L1b} - \omega_{L1a})$.

{Atomic Spectroscopy, Chris Foot, Oxford Univ. Press}



In an almost matched coupling scheme the Raman technique is twice more velocity selective than its single photon counterpart.

Double Dark Resonance for coherence control

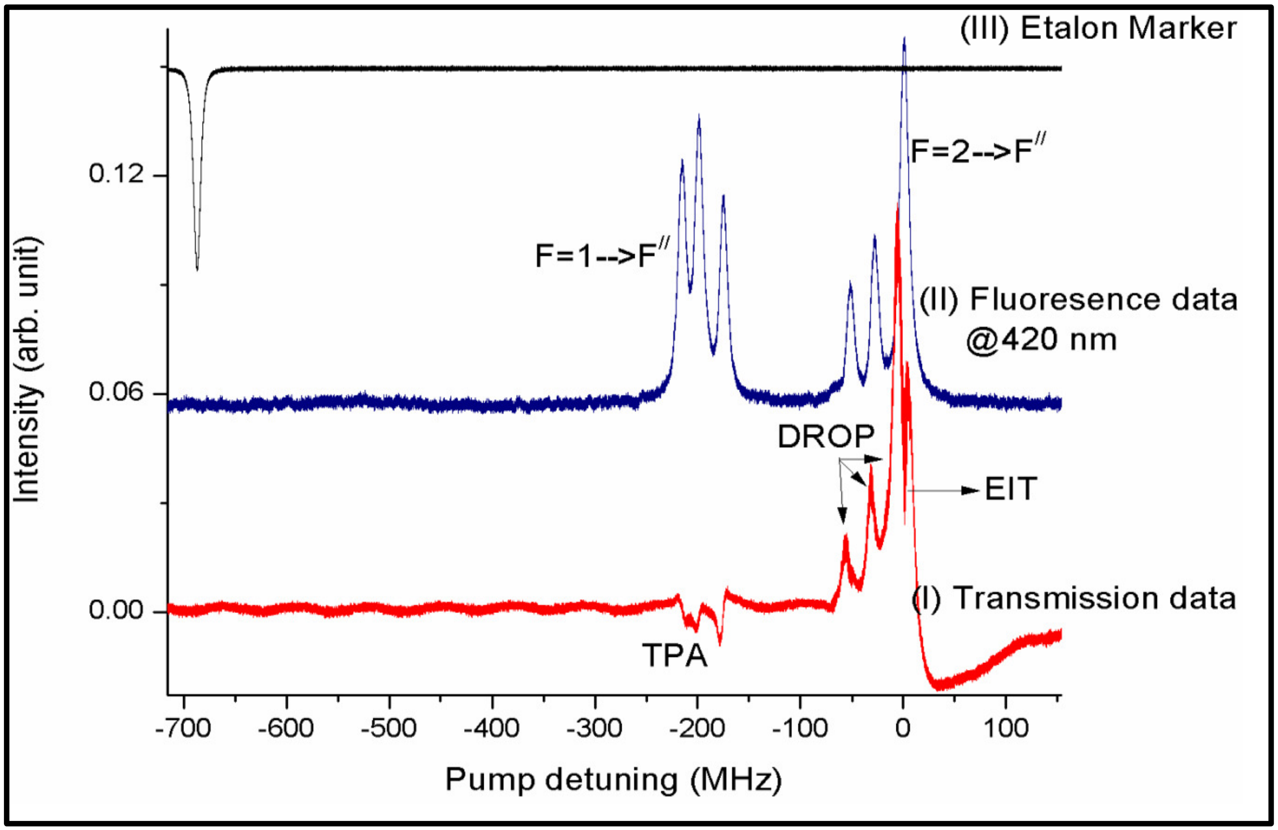


What happens if Dark states for both Λ and Ξ systems superpose? Can it be used in switching?

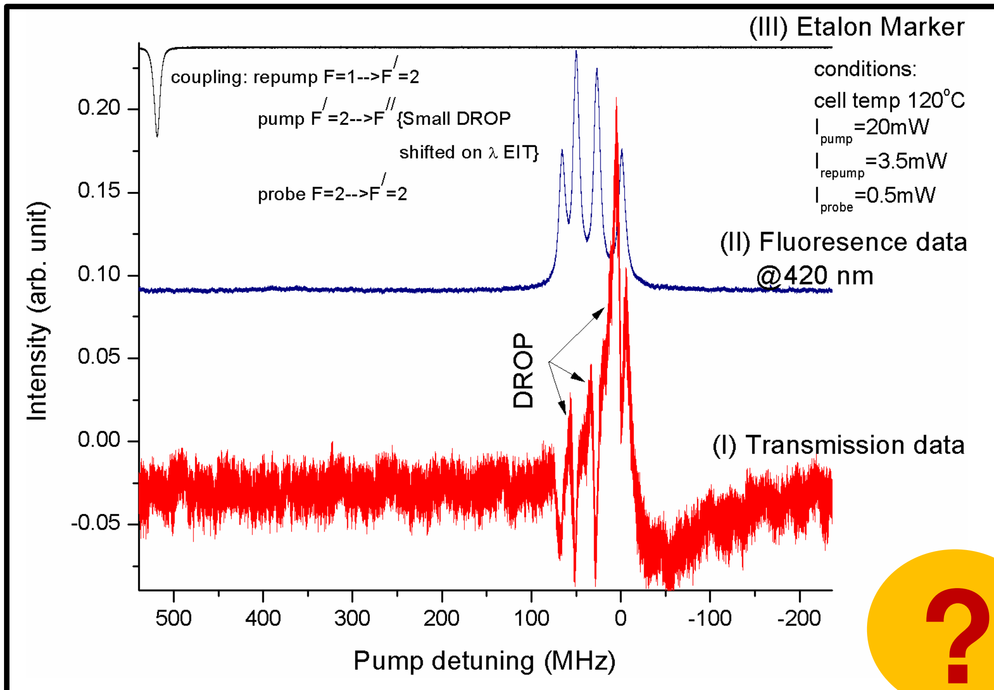
Case study for 5S-5P-5D [87]Rb atom: To make repump-probe combination co-propagating to make a sub-natural Λ EIT tweaking around DROP-EIT combination of Ξ system. Simultaneously the 420 nm transition is monitored.

➢**Starting point:**

The decoupled system



Double Dark Resonance for coherence control

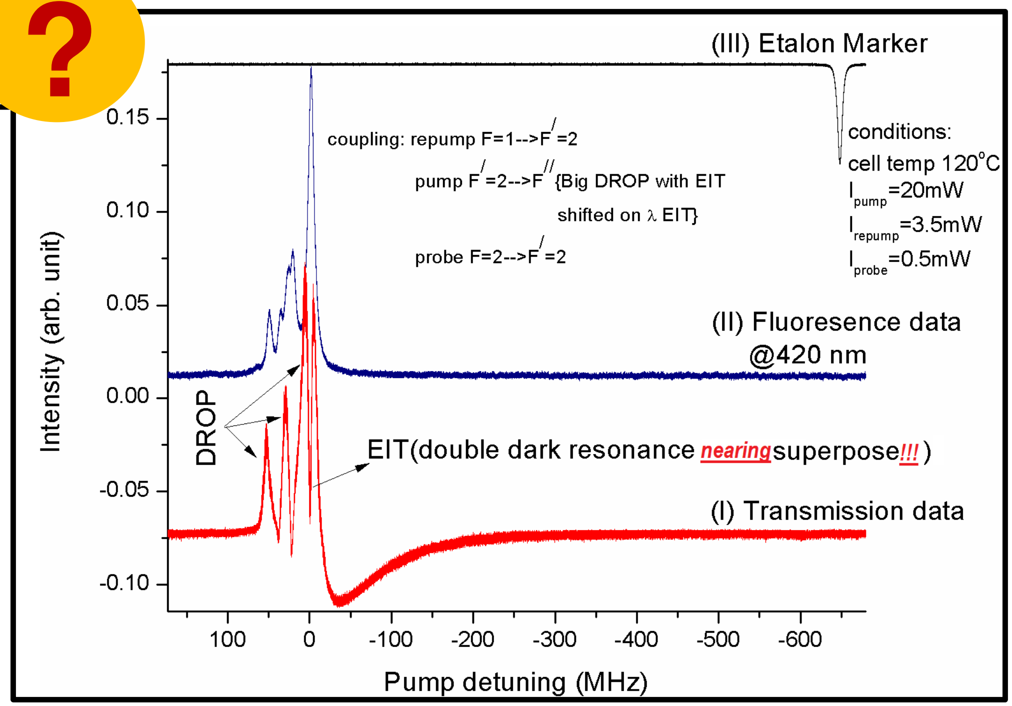


$$\rho_{tripod} \approx \rho_{\Xi} + \rho_{\Lambda}$$

see Joshi and Xiao, Phys. Lett. A, 317(2003)370

Missing Link!!!

?



The evolution of the complete system from incoherent sum of two subsystems to a new coupled system is more subtle and rapid than we expected

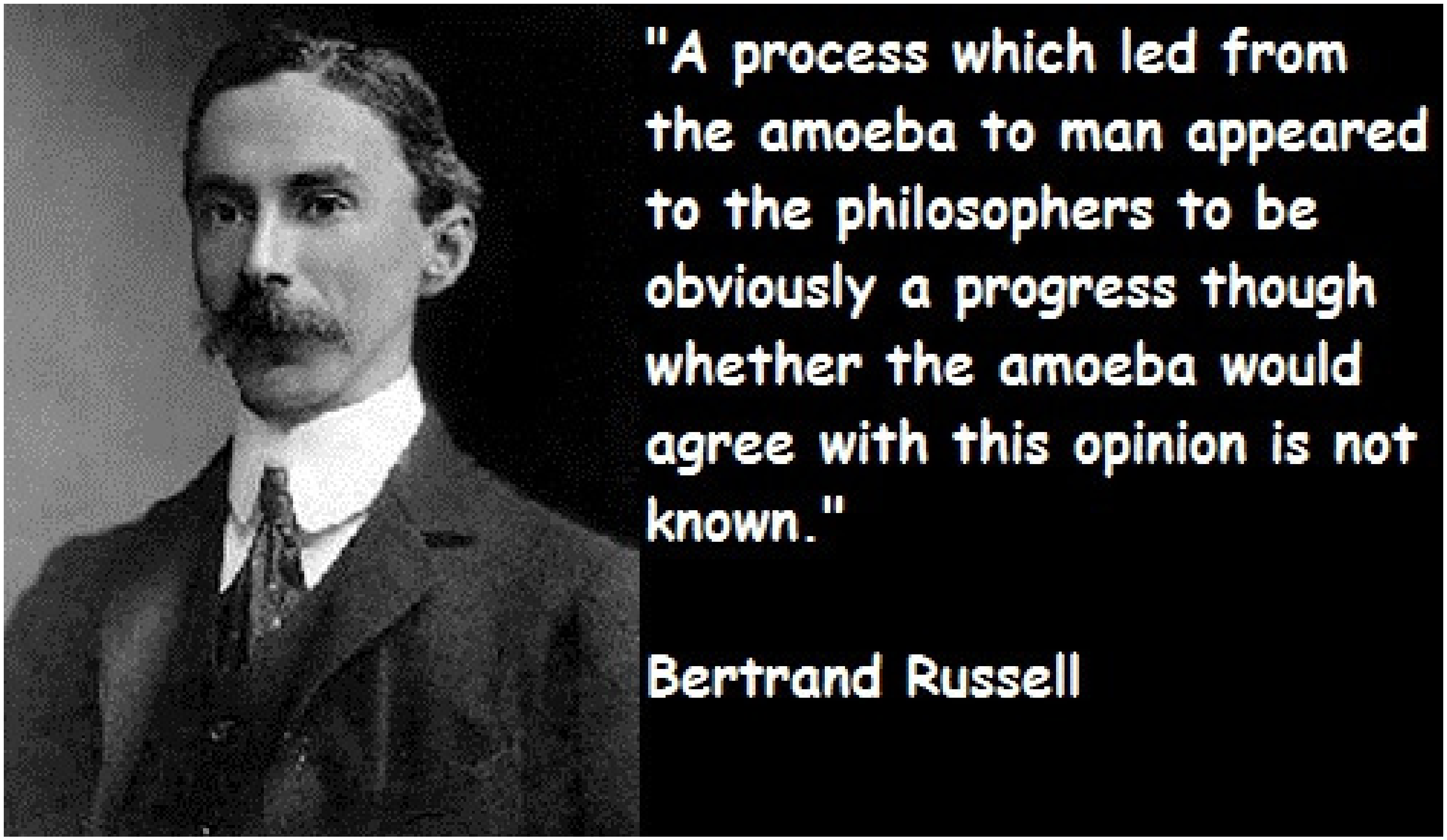
And

it may fit our interest !!!

ISOL facility @RIB.VECC; Now

Ref: A. Ray, Md. S. Ali, A. Bandyopdhyay, V. Naik and A. Chakrabarti, VECC News Letter, August, 2012.

Epilogue


"A process which led from the amoeba to man appeared to the philosophers to be obviously a progress though whether the amoeba would agree with this opinion is not known."
Bertrand Russell

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Initial review &suggestions: Dr. Matt Pearson (TRIUMF, Canada)

Thank You

Have a good day!

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