Induced Transparency effects in cyclic systems.

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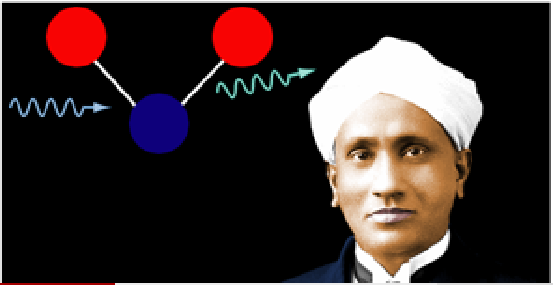
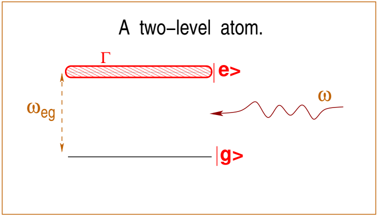
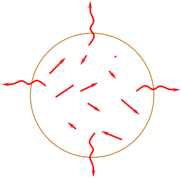


Outline

1. Two and three-level atomic systems.
2. A closed three-level Δ system
3. Conditions for non-linear processes with gain in atomic-Δ systems
4. Experimental demonstration of a novel $\chi^{(2)}$ non-linearity
5. Conclusions.

A two level atom interacting with an EM field.





$$\Delta = \frac{\omega_{eg} - \omega}{2}$$
$$\Gamma \ll \omega$$

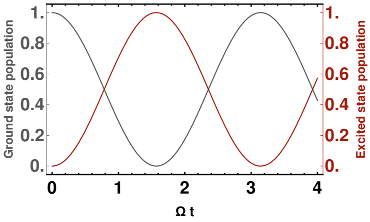
- The atomic state at any given time

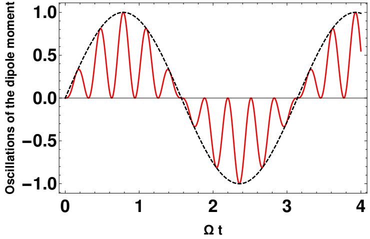
$$|\psi(t)\rangle = C_g|g\rangle + C_e|e\rangle$$
$$\langle\vec{M}\rangle = q\langle g|\vec{x}|e\rangle$$
$$\vec{d} = -(\sigma^-\vec{M}^* + \sigma^+\vec{M})$$
$$\langle d\rangle = \langle\psi|\vec{d}|\psi\rangle$$
$$\Omega_r = \frac{\vec{M}.\vec{e}_p}{2\hbar}E_0$$

- At resonance $\Delta = 0$,

$$\langle d\rangle = -\vec{M}\sin(2\Omega_r t)\sin(\omega_{eg}t)$$
$$|C_g|^2 = \cos^2(\Omega_r t)$$
$$|C_e|^2 = \sin^2(\Omega_r t)$$

Isolated two level system interaction with EM field.

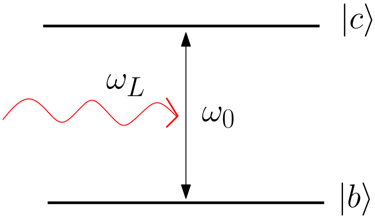




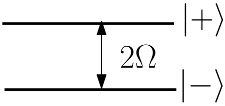
- Oscillations of populations in the excited and ground state. Note the total inversion for an isolated two-level atom.

- Rabi-oscillations of the electric dipole moment. The envelope frequency can be several orders less than the optical frequency of the light.

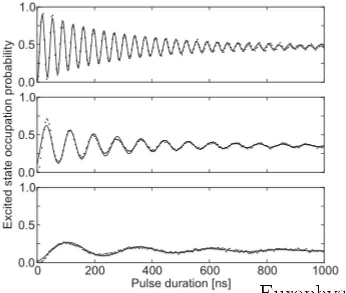
Experimental signatures of interaction with a bath.



$$P_c = \mathrm{A}\ \sin^2[(\sqrt{\Omega^2+\delta^2})\frac{t}{2}]$$



$$|\pm\rangle = \frac{1}{\sqrt{2}}(|b\rangle \pm |c\rangle)$$



Europhysics Letters **96**, 40012 (2011)

Two -level atoms interacting with EM bath.

$$\langle d \rangle = Tr[\rho d]$$

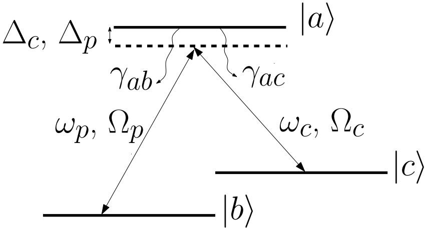
Assumption:
Linearity: Induced dipole oscillates as the same frequency as applied field.

- Macroscopic susceptibility $\chi = \chi_R + i\chi_I$ is given by

$$\chi_R = -\frac{N|M|^2}{3\hbar\epsilon_0}\left(\frac{\Delta}{\Delta^2 + (\Gamma^2/4) + (\Omega^2/2)}\right)$$

$$\chi_I = \frac{N|M|^2}{3\hbar\epsilon_0}\left(\frac{(\Gamma/2)}{\Delta^2 + (\Gamma^2/4) + (\Omega^2/2)}\right)$$

A three-level atom interacting with a bi-chromatic field.



$|a\rangle \rightarrow |c\rangle$ and $|a\rangle \rightarrow |b\rangle$ are dipole allowed transitions. $|b\rangle \rightarrow |c\rangle$ is electric dipole forbidden.

$$\delta = \Delta_p - \Delta_c,\ \tan\theta = \frac{\Omega_p}{\Omega_c},\ \tan 2\phi = \sqrt{\Omega_p^2 + \Omega_c^2}$$

The eigen states are

$$|+\rangle = \sin\theta\sin\phi|b\rangle + \cos\phi|a\rangle + \cos\theta\sin\phi|c\rangle \quad (1)$$

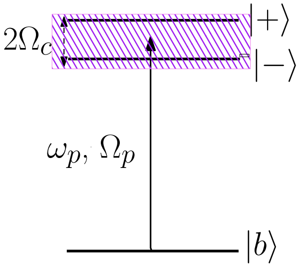
$$|-\rangle = \sin\theta\cos\phi|b\rangle - \sin\phi|a\rangle + \cos\theta\cos\phi|c\rangle \quad (2)$$

$$|DS\rangle = \cos\theta|b\rangle - \sin\theta|c\rangle \quad (3)$$

Rev. Mod. Phys., **77**, 633, (2005).

Dressed-state analysis.

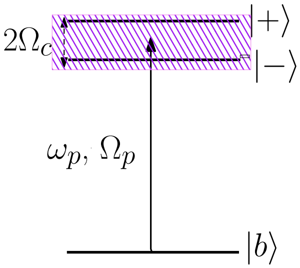
At single-photon $\Delta_c = 0$ and two-photon resonance $\delta = \Delta_c - \Delta_p = 0$, and for $\Omega_c \gg \Omega_p$ the atom is dressed by the coupling field.



$$|\pm\rangle = \frac{1}{\sqrt{2}}|c\rangle \pm |a\rangle$$

- For separation of Dressed states less than the decay related widths interference between de-excitation pathways in the common reservoir results in non-absorption of the probe. Electromagnetically Induced Transparency.

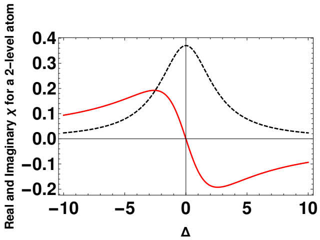
EIT as an environment induced effect.



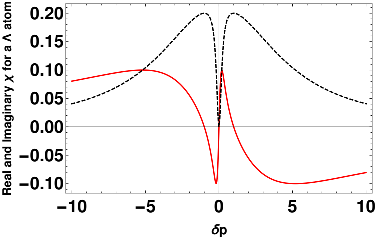
$$|\pm\rangle = \frac{1}{\sqrt{2}}|c\rangle \pm |a\rangle$$

- In the limit of $\gamma_{cb} = 0$, the dressed states couple destructively with the same dominant bath mode.
- For non-zero $\gamma_{cb} \neq \gamma_{ab}$, the decay rates and positions of dressed states drastically vary deciding whether or not the induced transparency exists.
  Journal of Modern Optics, **55**, 3159-3171 (2008)

Three-level Λ system interaction vs two-level.

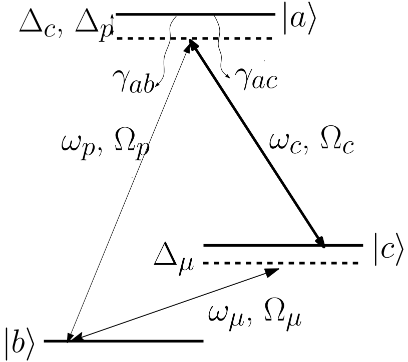


- Real and imaginary parts of susceptibility for a two-level atom showing absorption maximum and refractive index minimum at line center.



- Real and imaginary parts of susceptibility for a Λ atomic system interacting with a bi-chromatic light. At two-photon resonance both real and imaginary parts of the susceptibility vanish in the ideal case.

A closed three-level Λ system. (I)



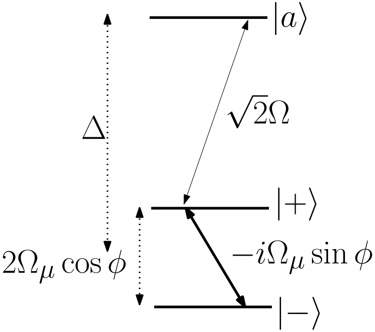
- Three atomic levels, two optical fields and a microwave field.
- Optical fields drive electric dipole transitions;
- Microwave field drives a magnetic dipole transition.

Conditions for steady-state populations and coherences.

- For time-independent solutions
- $\Delta_p = \Delta_c + \Delta_\mu$.
- To study EIT related effects, in addition
- Δ_p - $\Delta_c = 0$.
- For non-EIT scenarios where absorption of probe and coupling freely occurs,
- $\Delta_p = \Delta_c + \Delta_\mu$ & Δ_p - $\Delta_c \neq 0$.

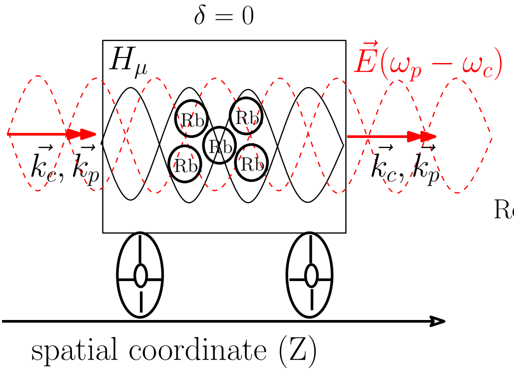
A closed three-level Λ system: (II)

- Induced dipole moments become relative-phase dependent.
  - $\phi = \phi_c - \phi_p - \phi_\mu$.
- For $\Delta_p = \Delta_c = \Delta$ and $\Omega_p = \Omega_c = \Omega$,



- At $\phi = 0, \pi, \ldots$ the system has a $|DS\rangle$, Ω_μ contributes only to level shifts.
- At other ϕ values no $|DS\rangle$

Experimental verification of phase dependence.



Hebin Li et. al., Phys. Rev. A **80**, 023820,(2009)

- ϕ was changed by translating the cavity with atoms along the propagation direction of ω_p and ω_c.
- EIT transmittance of ω_p showed a periodic variation with variation of ϕ.

Preeti T.M et. al, Europhysics Letters **94**, 30006, (2011)

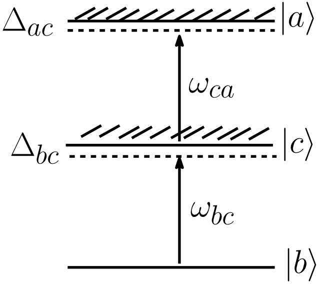
- At 300 K there are about 2500 thermal photons at 3.035 GHz.
- These cause phase-independent jumps of atom between both the ground states.
- For EIT systems this means despite microwave drive it is hard to get a better transparency signal just by using linearity of atomic-dipole responses.

What if we include non-linear responses?

- The coupling and microwave photon can give rise to a probe photon using a $\chi^{(2)}$ response.
- Gain at probe frequency due to parametric amplification.
- Squeezing of noise in one of the quadrature components of probe light :Amplifying signal and not noise.
- Noise transfer across frequency domains.

Non-linear response from atomic-EIT systems

Schmidt and Imamoglu, Opt. Lett., **21**, 1936, (1996)



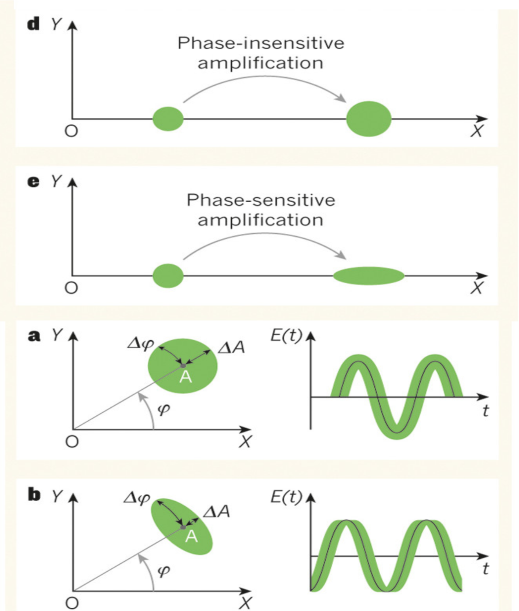
$$\mathrm{Re}[\chi^{(3)}(\omega_{bc})] \sim \frac{1}{\Delta_{bc}^2 \Delta_{ac}^2}$$

10^{-15} for $\mathrm{I}(\omega_{ca}) = 10^2 \, \frac{W}{cm}$

- Δ_{bc} cannot be very small, hence small value of Kerr non-linearity.
- Presence of unwanted self-phase modulation.
- EIT condition removes absorption at resonance hence $\Delta_{bc} = 0$, large non-linearity.

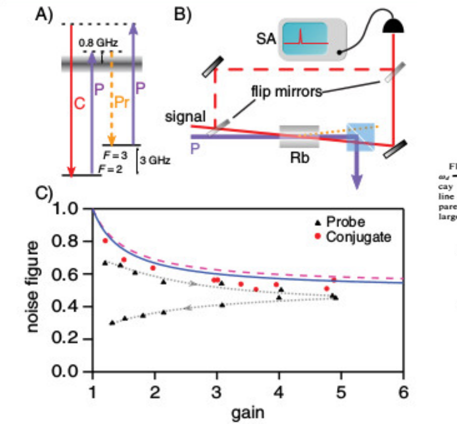
Amplifying without noise

- A phase-insensitive amplifier which amplifies the noise in both quadratures.
- A phase-sensitive amplifier.
- A coherent state with equal uncertainties in both quadratures.
- An amplitude-squeezed state which squeezes the amplitude of the Electric field going below SQL.



Closed atomic systems as noise-less-amplifiers.

PRL **103**, 010501 (2009) PHYSICAL REV



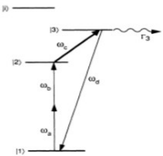


FIG. 1. Energy-level diagram for the sum frequency process $\omega_d = \omega_a + \omega_b + \omega_c$. State $|3\rangle$ is lifetime broadened with a decay rate Γ_3. When a strong field at frequency ω_c is tuned to line center of the $|2\rangle$-$|3\rangle$ transition, the media becomes transparent on the $|1\rangle$-$|3\rangle$ resonance transition. This allows much larger nonlinear $\chi^{(3)}L$ products than are normally possible.

$$\hat{\chi}_D^{(3)}(-\omega_d,\omega_a,\omega_b,\omega_c) = \hat{\chi}_D^{(3)}(-\omega_a,\omega_d,-\omega_b,-\omega_c) = \hat{\chi}_D^{(3)}(-\omega_b,\omega_d,-\omega_a,-\omega_c).$$

- Harris et. al., (Phys. Rev. Lett. **64**, 1107 (1990), showed a suppresion of $\chi^{(1)}$ and an enhancement of $\chi^{(3)}$.

Theoretical calculations for probe transmittance in a Δ system of ^{85}Rb.

- Hamiltonian in the interaction and rotating wave picture

$$\hat{H}(\boldsymbol{r},\boldsymbol{v}) = \delta'_{\mathrm{p}}(\boldsymbol{v})|1\rangle\langle 1| + (\delta'_{\mathrm{c}}(\boldsymbol{v}) - \delta'_{\mathrm{p}}(\boldsymbol{v}))|2\rangle\langle 2| + \Omega_{\mu\mathrm{w}}(\boldsymbol{r})|1\rangle\langle 2| + \Omega_{\mathrm{p}}(\boldsymbol{r}_{\perp})|1\rangle\langle 3| + \Omega_{\mathrm{c}}(\boldsymbol{r}_{\perp})|2\rangle\langle 3| + \mathrm{h.c.} \quad (4)$$

- Unlike a Λ system, we have to chose detunings carefully to satisfy

$$\delta_{\mathrm{p}} - \delta_{\mathrm{c}} - \delta_{\mu\mathrm{w}} = 0, \quad (5)$$

to ensure steady state.

- The relative phase between all three fields is

$$\phi(z) = z(k_{\mathrm{p}} - k_{\mathrm{c}}) + \phi_{\mu\mathrm{w}}. \quad (6)$$

Theoretical calculations continued ...

- The dynamical evolution of density matrix elements is given by the master equation

$$\dot{\rho}(\boldsymbol{v}, z) = -i[\hat{H}(\boldsymbol{v}, z), \rho(\boldsymbol{v}, z)] + \sum_{k=1}^{5} \mathcal{L}(\hat{c}_k)\rho(\boldsymbol{v}, z) \tag{7}$$

- The $\mathcal{L}(\hat{c}_k)$ being the Lindblad super-operator

$$\mathcal{L}(\hat{c})\rho := \hat{c}\rho\hat{c}^\dagger - \frac{1}{2}\{\rho, \hat{c}^\dagger\hat{c}\} \tag{8}$$

acting on operators

$$\begin{aligned}
\hat{c}_1 &= \sqrt{(\bar{n}+1)\gamma_{12}}\ |1\rangle\langle 2|, \\
\hat{c}_2 &= \sqrt{\bar{n}\gamma_{12}}\ |2\rangle\langle 1|, \\
\hat{c}_3 &= \sqrt{\gamma_{13}}\ |1\rangle\langle 3|, \\
\hat{c}_4 &= \sqrt{\gamma_{23}}\ |2\rangle\langle 3| \\
\hat{c}_5 &= \sqrt{\gamma_c}\ (|1\rangle\langle 1| - |2\rangle\langle 2|)
\end{aligned}$$

Theoretical calculations cont...

- We solve for steady-state values of $\rho(v)$ which is then averaged over the Maxwell-Boltzmann velocity profile at some temperature T

$$\bar{\rho} = \frac{\int_{-\infty}^{\infty} \rho(v) e^{-\left(\frac{v}{v_{\mathrm{mp}}}\right)^2} \mathrm{d}v}{\int_{-\infty}^{\infty} e^{-\left(\frac{v}{v_{\mathrm{mp}}}\right)^2} \mathrm{d}v} \tag{9}$$

- The steady-state value of the density matrix element $\bar{\rho}_{31}$ is incorporated in the propagation equation of the probe as

$$\frac{\partial \Omega_{\mathrm{p}}}{\partial z} = -i\eta\bar{\rho}_{31}. \tag{10}$$

Phase diagram

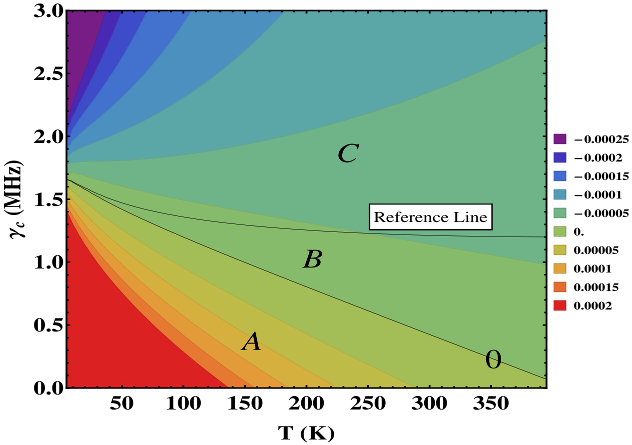


Figure: Contour plot showing the change from probe-field input intensity to transmitted intensity for temperatures $T = 0$ K to $T = 400$ K and for γ_c ranging from 0.001 MHz to 3.000 MHz. The Rabi frequencies are fixed at $\Omega_c = 6.4$ MHz, $\Omega_p = 1.0$ MHz, and $\Omega_{\mu w} = 0.8$ MHz.

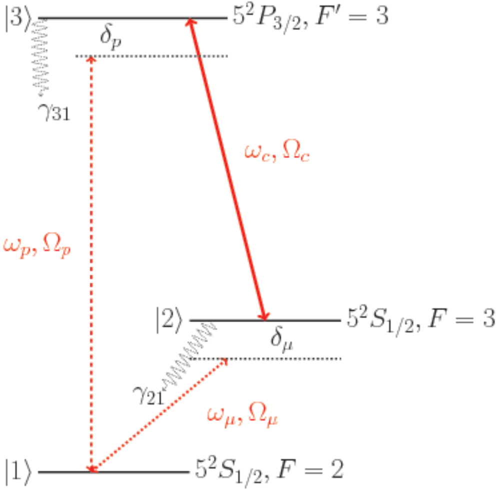
Conclusions from theoretical study

M. Manjappa et. al, Phys. Rev. A **90**, 043859 (2014)

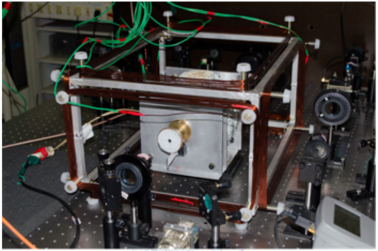
- A linear response of the Δ system to microwave and coupling fields will not produce gain at room temperature.
- A high intensity for the microwave field is required to mediate a χ^2 interaction between the optical coupling and the microwave drive field.
- This non-linearity will possibly convert some microwave energy to optical facilitating gain.

Experiment to bring out non-linearity in Δ systems.

Level scheme for our experiment.



Second generation microwave cavity.



Megha



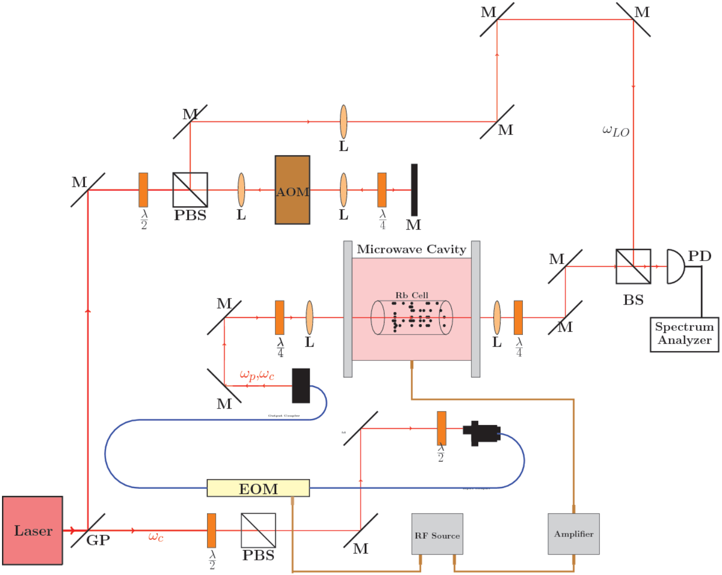
Ayyappan


Fabien


Barry

- The magnetic dipole coupling is weaker than electric dipole coupling.
- A high Q cavity for microwaves at 3.0357 GHz was built to enable stronger coupling.
- Appropriate cavity mode was chosen to produce an anti-node at the center.
- Unloaded Q $\sim$ 14000. Loaded Q $\sim$ 7000.

Experimental layout



Phase-sensitive probe enhancement and absorption.

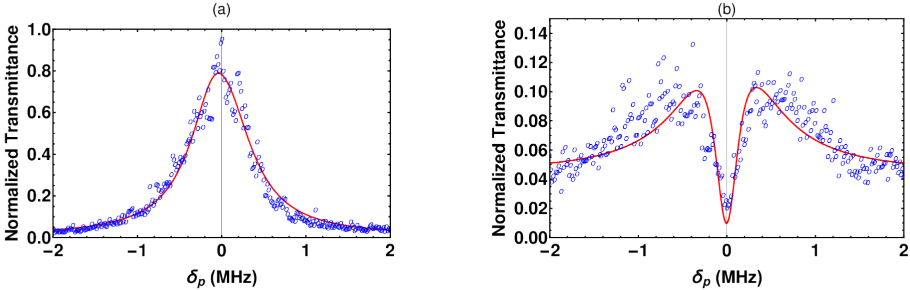


Figure: (Color online) Probe transmittance as a function of detuning δ_p is plotted for ϕ values differing by π. Experimental data points are denoted by circles. In plots (a) and (b) the probe transmittance is shown when the sample is irradiated with coupling, probe and drive fields for $\phi = 0$ and $\phi = \pi$ respectively. The continuous (red) lines in all the plots are theoretical fit to experimental points.

Intensity dependent probe transmission.

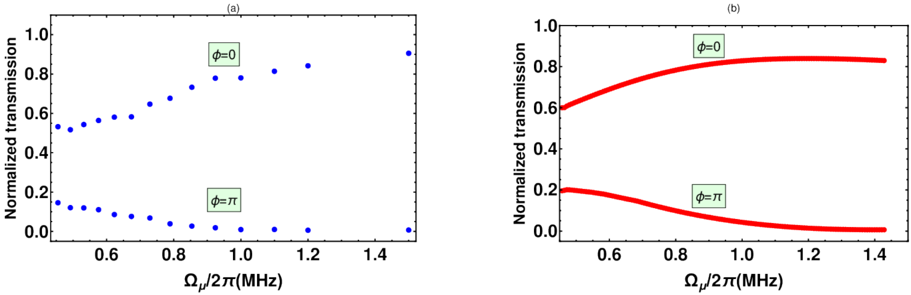


Figure: Experimental (a) and theoretical (b) plots of probe transmission as a function of Rabi frequency of the microwave field for two different ϕ values which differ by π. (a) Experimental intensity transmission of the probe field for phases $\phi = 0$ and $\phi = \pi$. (b) Corresponding numerically evaluated transmission values from our density matrix calculations.

Megha G. et. al., Accepted for publication in J.Phys, B (2017)

Demonstration of a high contrast switch.

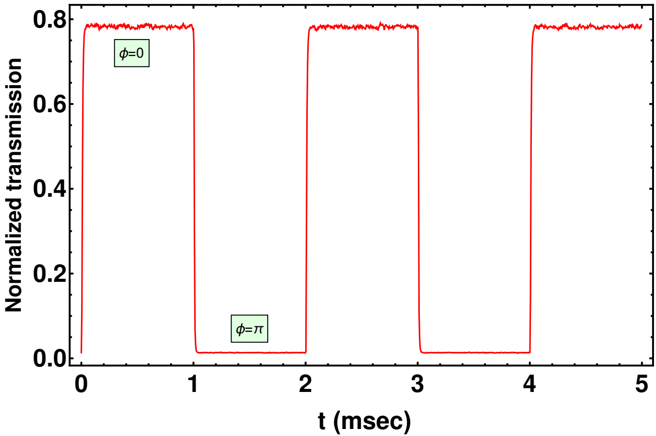


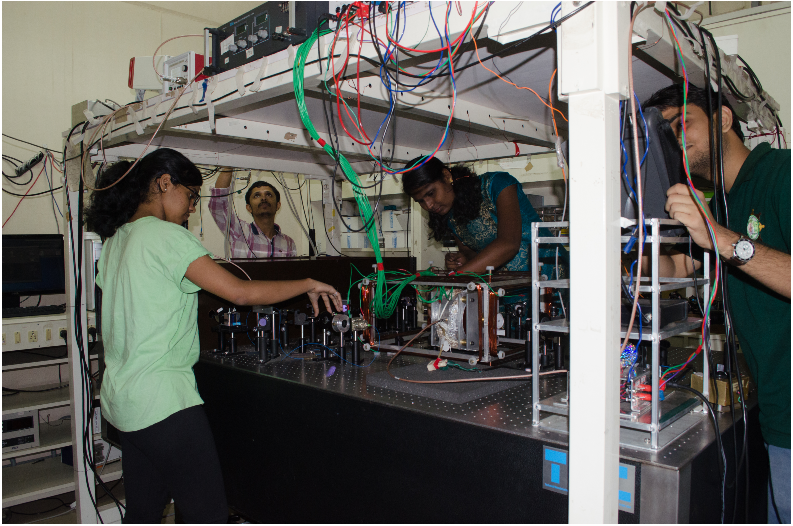
Figure: The microwave phase switches between values $\phi = 0$ and $\phi = \pi$ with a 1 ms switching cycle.

Thanks to M.S. Meena our technical in-charge in making this fast switch.

Closed interactions in an open environment.

- Cyclic and coherent atom-optical-microwave interactions suffer de-coherence in steady state.
- System has tremendous potential to show transient gain and noise-less amplification at room temperature.
- Vastly different regimes of EM spectrum and associated noise features can be studied in a single system.
- Quantum atom-optical experiments are proof-of-principle examples.
- They are natural systems to study the effect of environment. Separated timescales in the environment can be accessed with similar tools.
- The knowledge gained from this has a wide reach: EIT in its various avatars has been the most exploited effect for quantum storage so far.
- So let us back to the lab!

The group and the lab.



Thanks for your attention.