Coherence control of triple electromagnetically induced transparency and Autler-Townes effect using an atomic medium

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Abstract

In this contribution we analyze the interplay between the Autler-Townes phenomenon and the electromagnetically induced transparency in a five-level atomic system. This interplay is controlled by cyclically driving optical fields. The optical fields consist of two strong microwave, two strong optical-fields and a weak probe field. The comparison of both the effects in the system are studied with respect to the probe field transmission in the presence and in the absence of various decay processes.

OUTLINE

1. **Basics and first observation**

2. Electromagnetically induced transparency (EIT)

3**. Autler-Townes phenomenon**

4. The Model Formulation

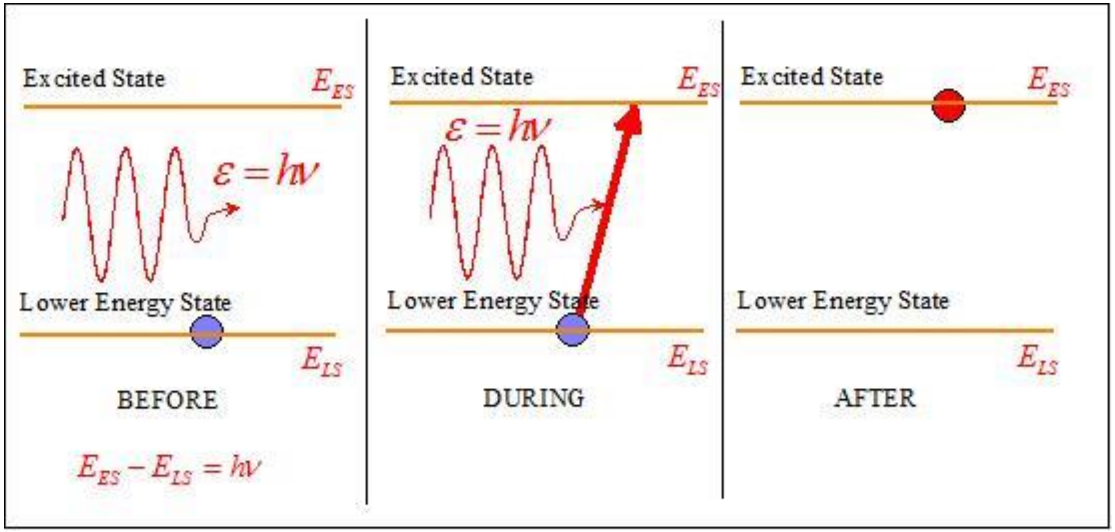
5. **EIT with single atom**

6. **Summary**

How the light is interacted with atom and molecules ?

Stimulated absorption

Stimulated Absorption: When a photon of energy equals to the energy difference between two atomic levels interacts with the atom. The atom in the lower energy state, absorbs the photon and jumps to the higher energy state (excited state).



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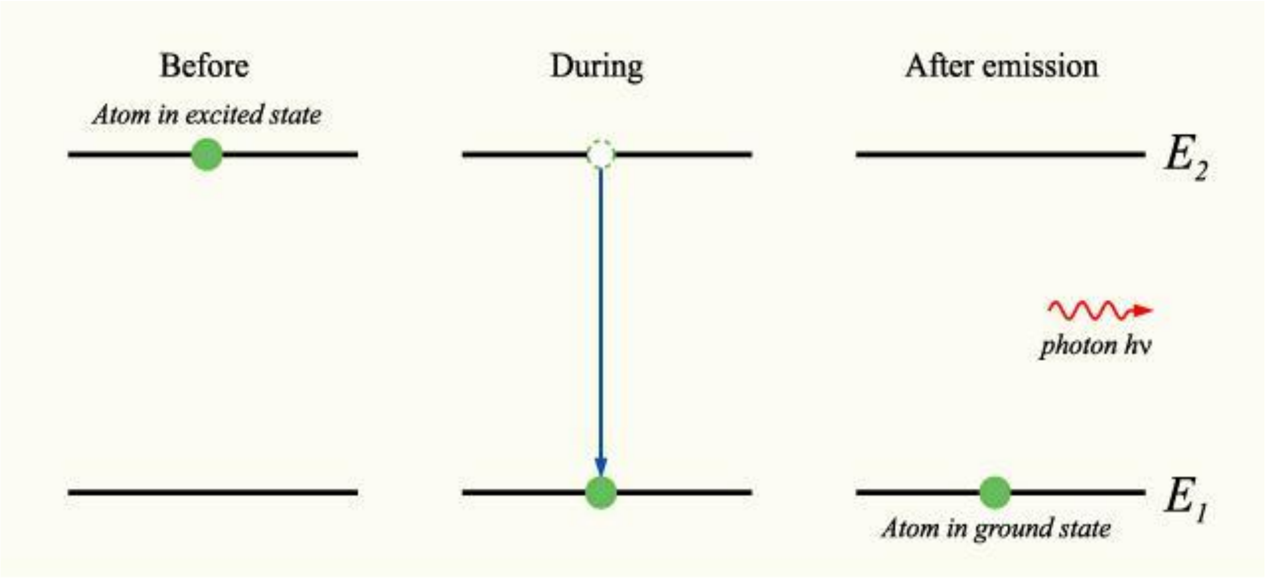
Spontaneous emission

Spontaneous emission: A process by which an atom in the excited state undergoes a transition to the lower energy state (ground state) and emits a photon.



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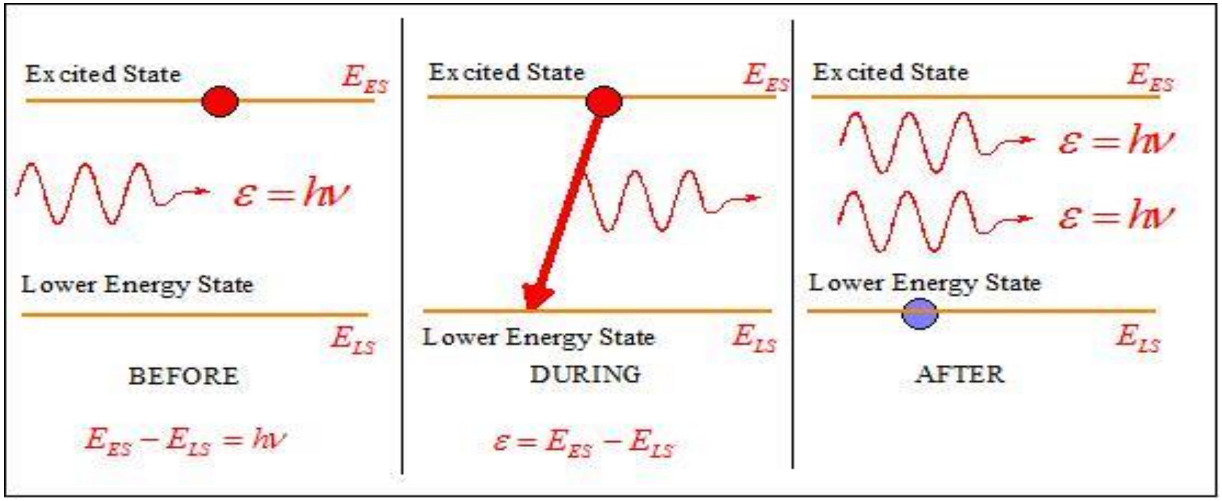
Stimulated emission

Stimulated emission: A process by which an atomic electron (in excited state) interacts with an electromagnetic wave drop to a lower energy level transferring its energy to that field



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Electromagnetically induced transparency

The concept of EIT was first given by Harris et. all in 1990. When a strong coupling laser field is used to drive a resonant transition in a three-level atomic system, the absorption of a weak probe laser field can be reduced or eliminated provided the two Resonant transitions are coherently coupled to a common state.

EIT was first observed in lambda type system of strontium vapors using high pulsed laser in 1991.

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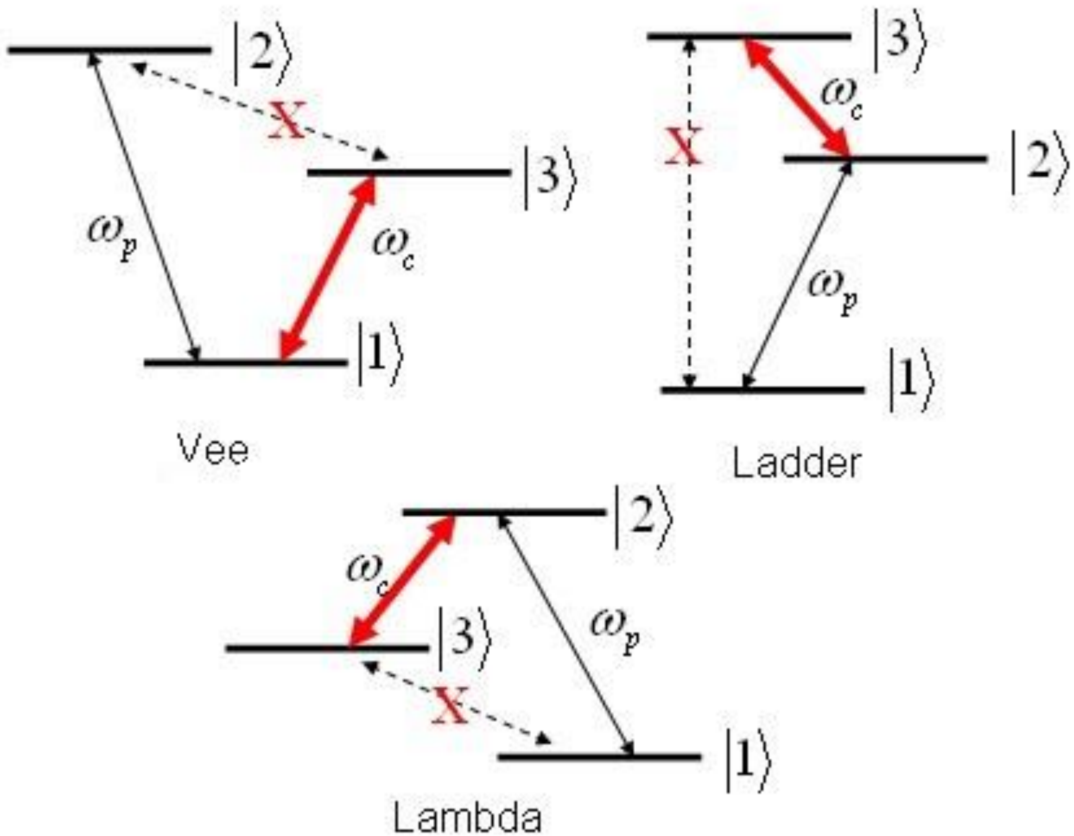
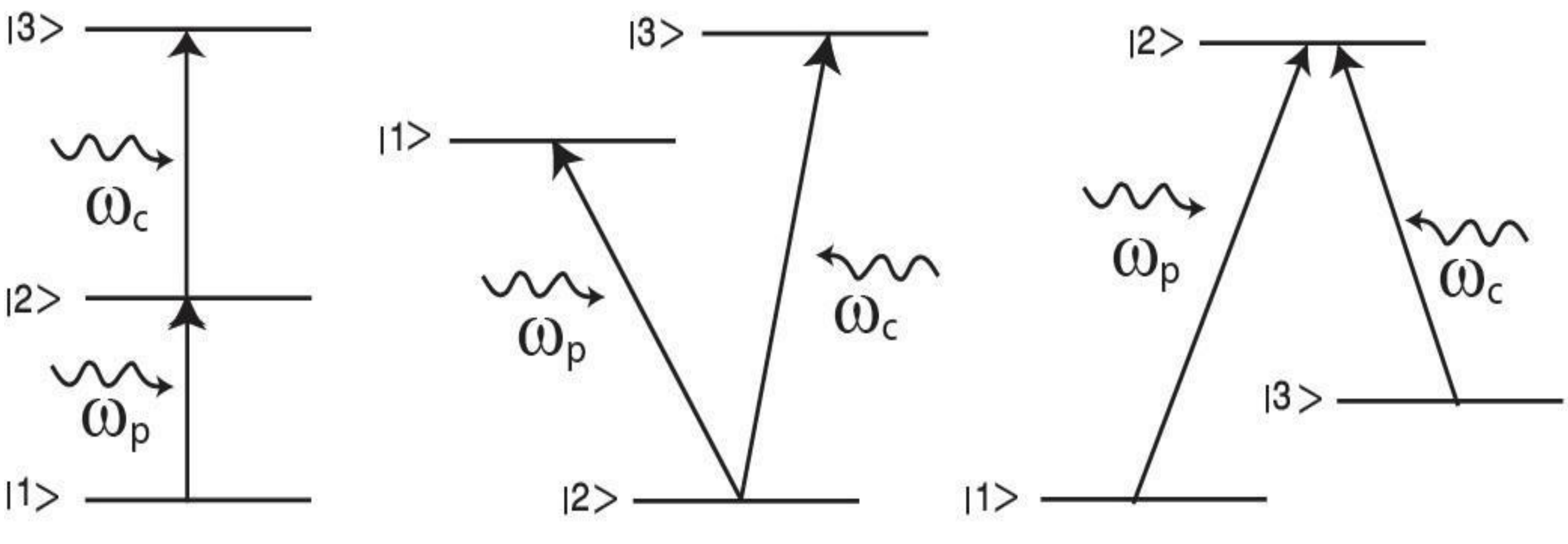
Electromagnetically induced transparency

EIT configurations:



Electromagnetically induced transparency

EIT configurations:



Ladder V-type Lambda-type

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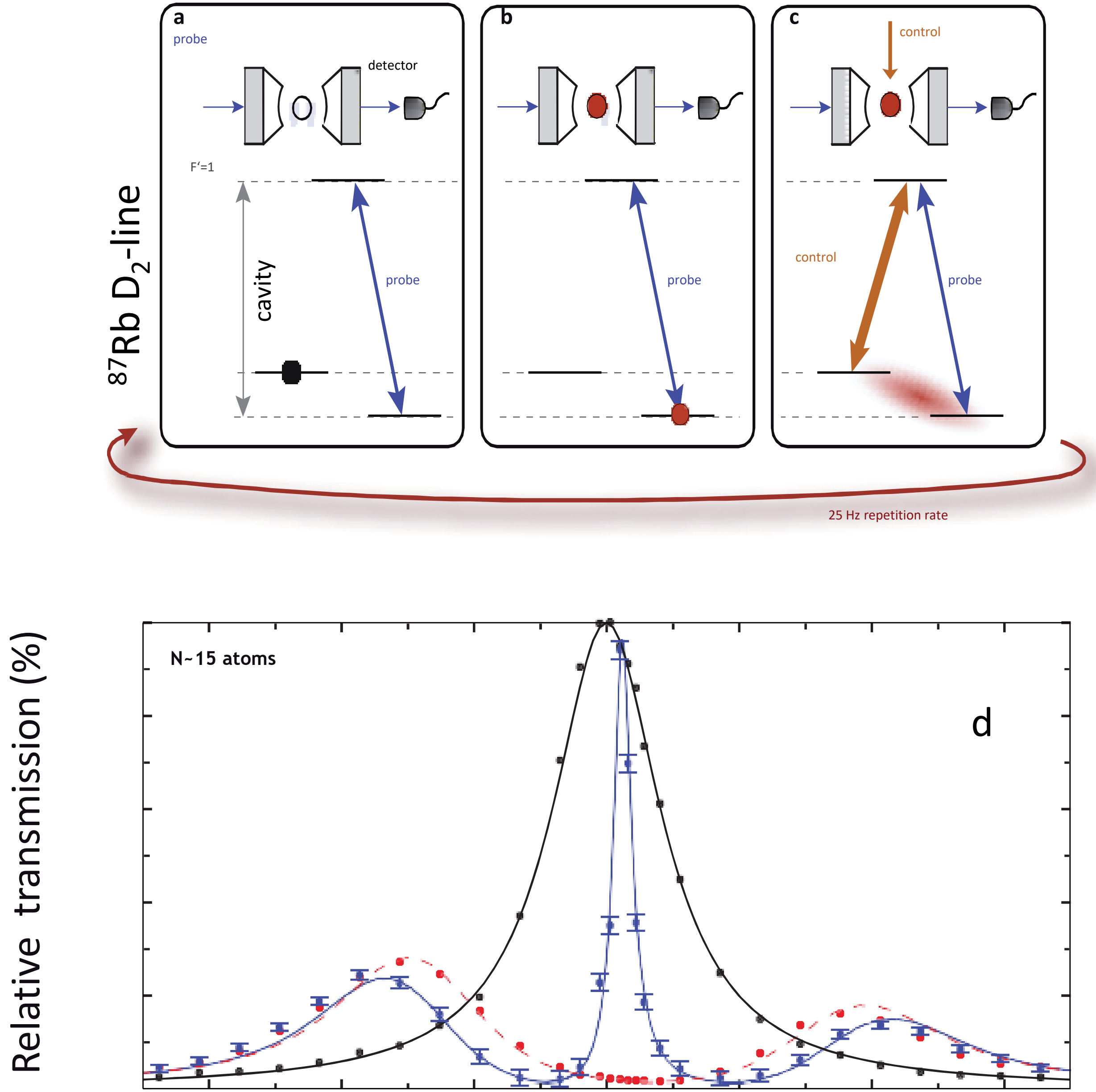


Martin Mucke et. all Max-Planck-Institut fur Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany, arXiv:1004.2442v1[quant-ph] 14 Apr 2010, EIT with single atoms in cavity

$$\frac{\Delta}{k}$$

The Model Formulation

The atomic Sodium Na^{23} D1 line
With $\lambda = 5895.93 A^{\circ}$ in a weak
static magnetic field

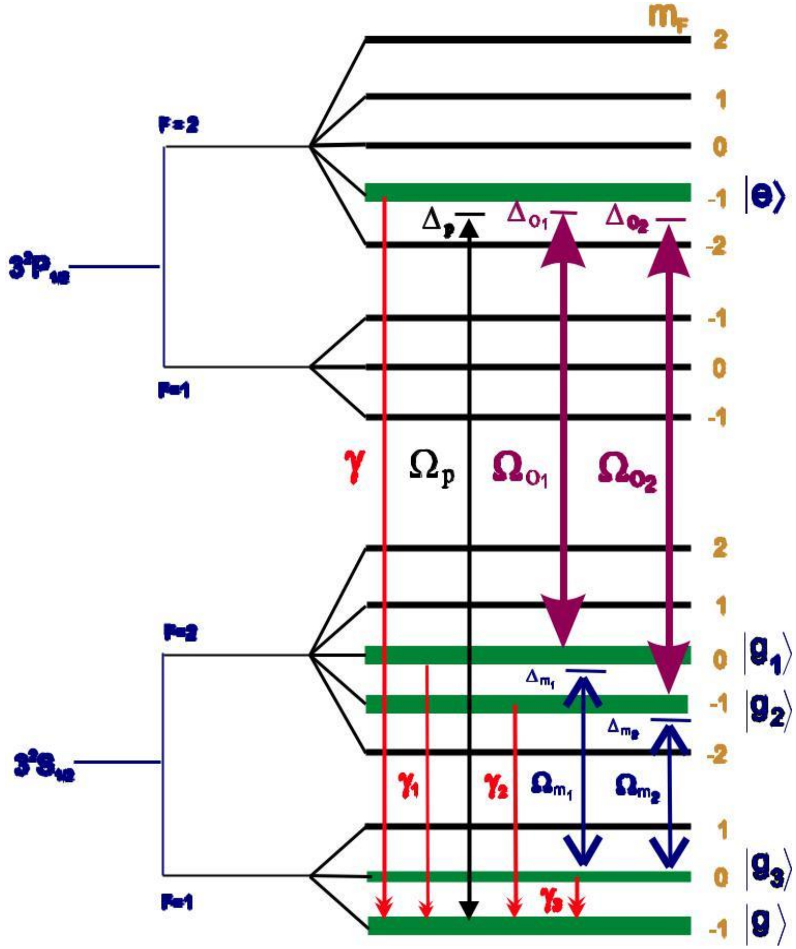


Fig. 1: (Color online) Schematics of the atomic system

The Model Formulation

$$3P^{2}_{1/2}$$

$$|e\rangle(|3P_{1/2}, F=2, m_F=-1\rangle)$$

$$3S^{2}_{1/2}$$

$$|g_1\rangle(|3S_{1/2}, F=2, m_F=0\rangle),$$

$$|g_2\rangle(|3S_{1/2}, F=2, m_F=-1\rangle),$$

$$|g_3\rangle(|3S_{1/2}, F=1, m_F=0\rangle),$$

$$|g\rangle(|3S_{1/2}, F=1, m_F=-1\rangle).$$

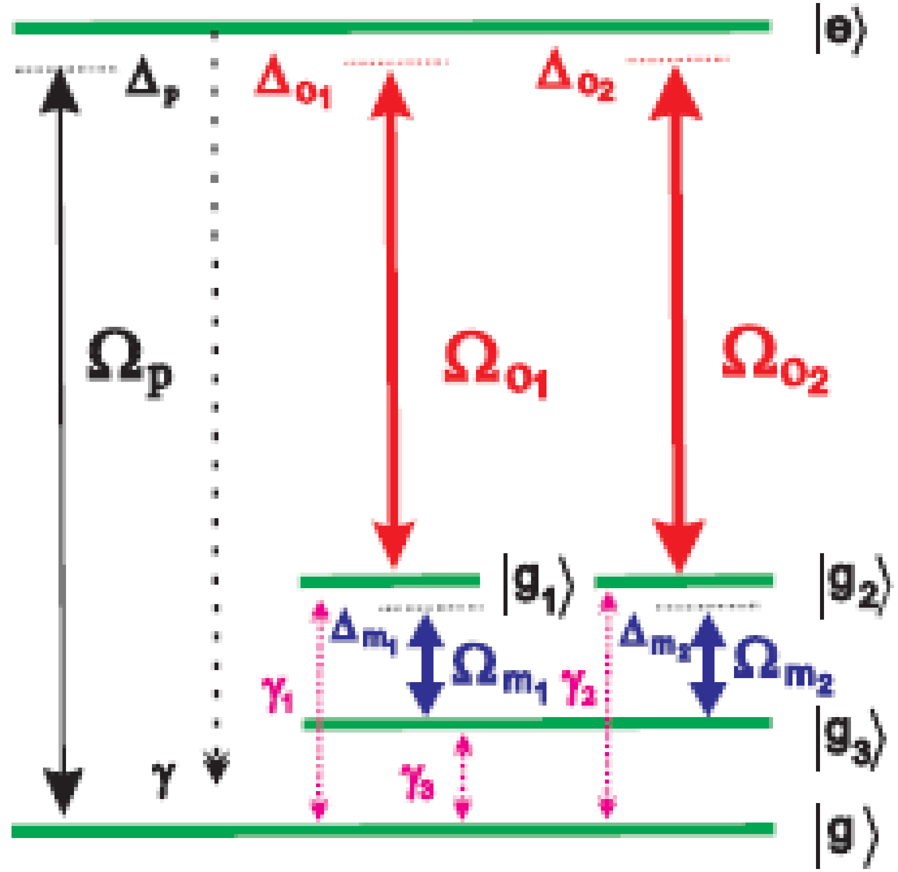


Fig. (Color online) Schematics of the atomic system

Where $\Delta_{01} = \omega_{eg_1} - \omega_{01}$ and $\Delta_{02} = \omega_{eg_2} - \omega_{02}$ are, respectively, The detunings of the optical fields with frequencies ω_{01} and ω_{02} whereas the detunings of the two microwave fields characterized by the frequencies ω_{m1} and ω_{m2}, are defined as $\Delta_{m1} = \omega_{g_1 g_3} - \omega_{m1}$ and $\Delta_{m2} = \omega_{g_2 g_3} - \omega_{m2}$, respectively.

However, $\Delta_p = \omega_{eg} - \omega_p$ represents the detuning of the probe field with the carrier frequency ω_p .

We consider that the excited atom decays radiatively to the ground energy levels $|g\rangle$ with the decay rate γ due to coupling of vacuum field modes.

The Model Formulation

The losses-free Hamiltonian in the interaction representation and rotation wave approximation becomes as

$$H_I = \frac{\hbar}{2}[\Omega_{m1} \exp[i(\Delta_{m1} t + \phi_{m1})] |g_1\rangle\langle g_3| + \Omega_{m2} \exp[i(\Delta_{m2} t + \phi_{m2})] |g_2\rangle\langle g_3|$$

$$+ \Omega_{O1} \exp[i(\Delta_{O1} t + \phi_{O1})] |e\rangle\langle g_1| + \Omega_{O2} \exp[i(\Delta_{O2} t + \phi_{O2}) |e\rangle\langle g_2|]$$

$$+ \Omega_p \exp[i(\Delta_p t + \phi_p)] |e\rangle\langle g|] + H.c$$

Equations of Motion and Transition Matrix Element of the Probe Field

Focus of this section is to study the response of the medium when the atomic system interacts with two strong optical and microwave field, and a weak probe field. The system is treated with perturbation up to first order due to the weak probe field and up to all orders due to the strong two optical and two microwave field. The evolution of the transition density matrix element is determined in steady-state limit using master density matrix equation.

$$\dot{\rho} = -\frac{i}{\hbar}[H_I, \rho] - \frac{1}{2}\Gamma \sum \left(\sigma^{+}\sigma\rho + \rho\sigma^{+}\sigma - 2\sigma\rho\sigma^{+}\right)$$

where, σ and σ^{+} are the lowering and raising operators associated with the atomic radiative and dephasing decay rates in the atomic medium in vapor cell.

We further use the transformations

$$\rho_{eg} \to \tilde{\rho}_{eg} \exp[i\Delta_p t]$$

$$\rho_{g_2 g} \to \tilde{\rho}_{g_2 g} \exp[i(\Delta_p - \Delta_{O2})t]$$

$$\rho_{g_3 g} \to \tilde{\rho}_{g_3 g} \exp[i(\Delta_p - \Delta_{O2} - \Delta_{m2})t]$$

$$\rho_{g_1 g} \to \tilde{\rho}_{g_1 g} \exp[i(\Delta_p - \Delta_{O1})t]$$

Of the slowly and fast varying amplitudes of the atomic transitions. The coupled rate Equations in terms of slowly varying amplitudes under the conditions

$\tilde{\rho}_{gg} = 1, \tilde{\rho}_{g_3e} = \tilde{\rho}_{g_2e} = \tilde{\rho}_{g_1e} = \tilde{\rho}_{g_3e} \cong 0$, becomes as

$$\frac{dR}{dt} = MR + Q$$

$$R = \begin{pmatrix} \tilde{\rho}_{eg} \\ \tilde{\rho}_{g_2g} \\ \tilde{\rho}_{g_3g} \\ \tilde{\rho}_{g_1g} \end{pmatrix}$$

and

$$Q = \begin{pmatrix} \frac{i}{2}\Omega_p \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Matrix M

$$M = \begin{pmatrix} \gamma + i\Delta_p & -\frac{i}{2}\Omega_{02}e^{i\Phi_{02}} & 0 & -\frac{i}{2}\Omega_{01}e^{i\Phi_{01}} \\ -\frac{i}{2}\Omega^*{}_{02}e^{-i\Phi_{02}} & \gamma_2 + iS_{22} & -\frac{i}{2}\Omega_{m2}e^{i\Phi_{m2}} & 0 \\ 0 & -\frac{i}{2}\Omega^*{}_{m2}e^{-i\Phi_{m2}} & \gamma_3 + iS_{33} & -\frac{i}{2}\Omega^*{}_{m1}e^{-i\Phi_{m1}} \\ -\frac{i}{2}\Omega^*{}_{01}e^{-i\Phi_{01}} & 0 & -\frac{i}{2}\Omega_{m1}e^{i\Phi_{m1}} & \gamma_1 + iS_{44} \end{pmatrix}$$

Where, $S_{22} = (\Delta_p - \Delta_{O2}), S_{33} = (\Delta_p - \Delta_{O2} - \Delta_{m2})$ and $S_{44} = (\Delta_p - \Delta_{O1})$

$$\tilde{\rho}_{eg} = \mathrm{Re}[\tilde{\rho}_{eg}] + i\,\mathrm{Im}[\tilde{\rho}_{eg}],$$ with

$$\mathrm{Re}[\tilde{\rho}_{eg}] = \frac{2\Omega_p}{(D^2{}_1 + D^2{}_2)}[D_2\{4\gamma_1 D - 4(\Delta_p - \Delta_{O1})E + \gamma_2 \Omega^2{}_{m1}\}$$

$$- D_1\{4\gamma_1 E + 4(\Delta_p - \Delta_{O1})D + (\Delta_p - \Delta_{O2})\Omega^2{}_{m1}\}]$$

$$\mathrm{Im}[\tilde{\rho}_{eg}] = \frac{2\Omega_p}{(D^2{}_1 + D^2{}_2)}[D_1\{4\gamma_1 D - 4(\Delta_p - \Delta_{O1})E + \gamma_2 \Omega^2{}_{m1}\}$$

$$+ D_2\{4\gamma_1 E + 4(\Delta_p - \Delta_{O1})D + (\Delta_p - \Delta_{O2})\Omega^2{}_{m1}\}]$$

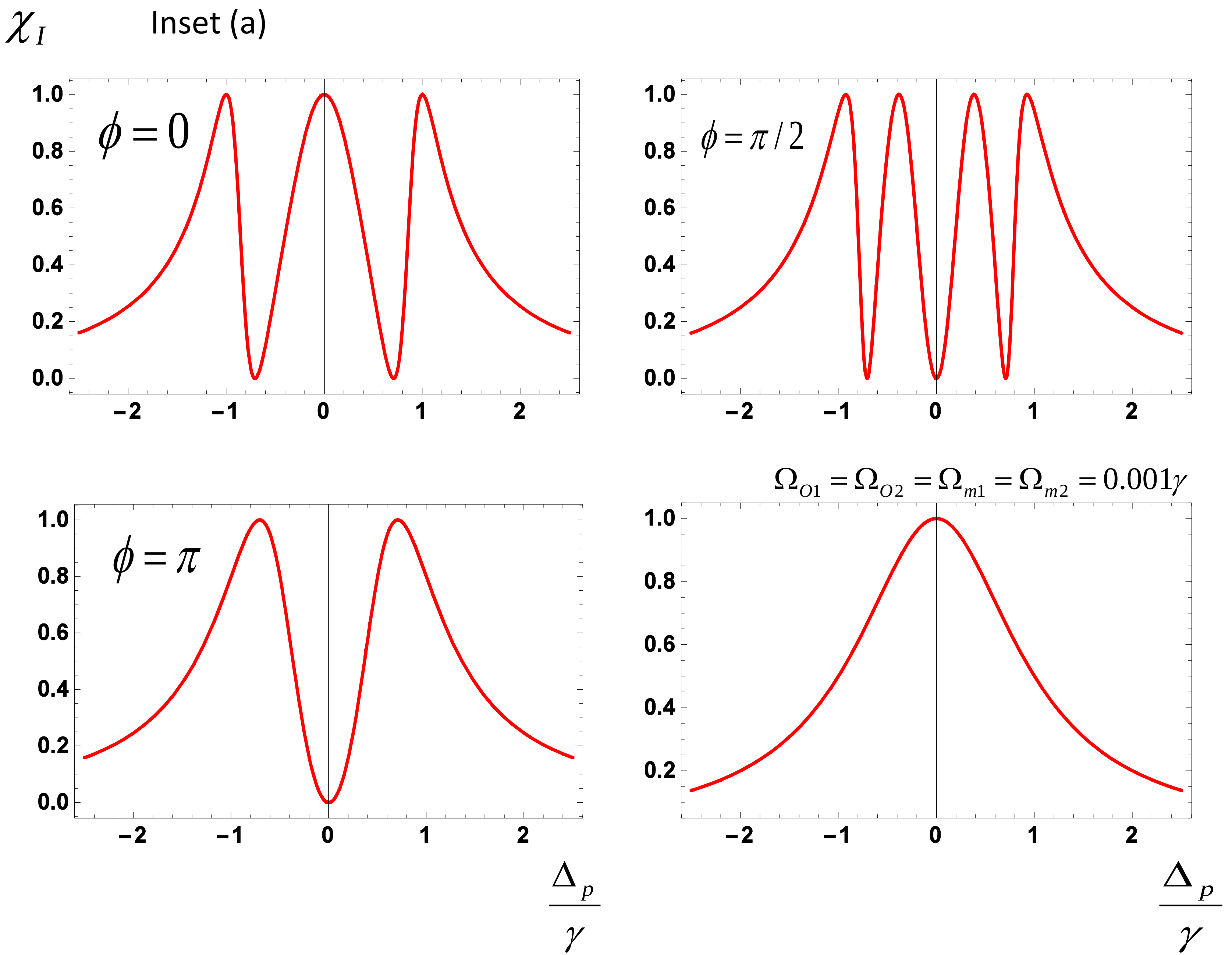
STATIONARY ELECTRIC SUSCEPTIBILITY

Response of the absorption and dispersion of the probe field is represented by the Imaginary and real parts of the electric susceptibility of the atomic system, respectively.

$$\mathrm{Im}\left[\chi(\Delta_p)\right] = \frac{2N\left|\alpha_{eg}\right|^2}{\varepsilon_0 \hbar \Omega_p} \mathrm{Im}\left[\tilde{\rho}_{eg}\right]$$ Absorption

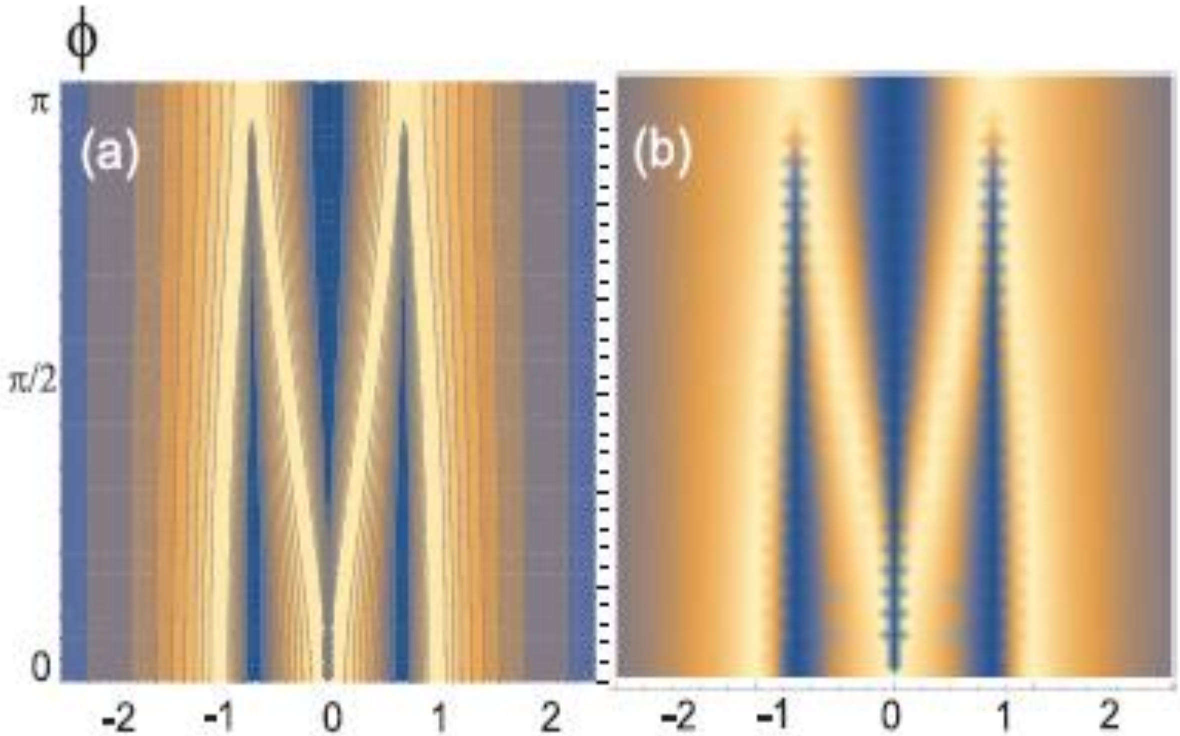
$$\mathrm{Re}\left[\chi(\Delta_p)\right] = \frac{2N\left|\alpha_{eg}\right|^2}{\varepsilon_0 \hbar \Omega_p} \mathrm{Re}\left[\tilde{\rho}_{eg}\right]$$ Dispersion

Here, α_{eg} is the matrix element of the electric dipole moment.
N –is atom number – density,
$\tilde{\rho}_{eg}$ is the density matrix element of the atomic transition between states $\left|e\right\rangle$ and $\left|g\right\rangle$



χ_I
Inset (a)
$\phi = 0$
$\phi = \pi / 2$
$\phi = \pi$
$\Omega_{O1} = \Omega_{O2} = \Omega_{m1} = \Omega_{m2} = 0.001\gamma$
$\frac{\Delta_p}{\gamma}$

Absorption $\operatorname{Im}\chi(\Delta_p)$ contour (a) and density (b) versus $\frac{\Delta_p}{\gamma}$ and ϕ is shown using $\gamma_1 = \gamma_2 = \gamma_3 = 0$ and $\Omega_{01} = \Omega_{02} = \Omega_{m1} = \Omega_{m2} = \gamma$



$$\frac{\Delta_p}{\gamma}$$

$$\operatorname{Im}[\chi(\Delta_p)] = \frac{N|\wp_{eg}|^2}{\epsilon_0 \hbar G}[\Delta_p^2(\gamma+\gamma_1) - \gamma_1(\Delta_p^2 - \gamma\gamma_1 - \Omega_{O1}^2/4)],$$

Applications of EIT

1. Fundamental and commercial applications of EIT in atomic physics and quantum optics include,
2. Lasing without inversion,
3. Reduction of the speed of light,
4. Quantum memory,
5. Optical switches,
6. All optical wavelength converters for telecommunications,
7. Quantum information processing.

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CONCLUSION

In this contribution, we have shown coherence control of triple color electromagnetically induced switching (EIS) of a weak probe field using a five- level atomic medium coupled cyclically with two strong optical – and microwave - field. The atom – field interaction, like Λ-, Ξ and V- type three-level atomic systems with coupling of a strong field and unlike four-level atomic systems with coupling of strong microwave – and optical – field, becomes independent of Doppler broadening and wave vectors mismatch when the coupling are incorporated collinearly. As a result, the resonance and switching phenomena can be demonstrated with simple probability loss and hot temperature medium.

This system with the ability, for example, to close and open the single through triple EIT window to the probe transmission in combination to suitable beam splitters set-up may be usable for logic and functional operations such as OR, NOT, and AND, and the other derived photonics -gates using the relative phase of the coupling fields as the controller.