Quantum Control of Coherent Optical Phenomena in Gaseous and Solid Medium

[Literarure review presentation]

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Outline

Introduction

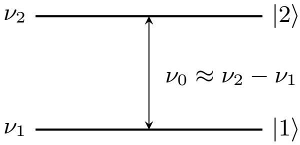
- Interaction of light with atomic system leads to various interesting **Coherent Optical Phenomena.**
- Coherent optical phenomena are based on quantum coherence and interference effect.
- In 1961, Fano first observed the coherent phenomena **Coherent Population Trapping**.
- Other such coherent phenomena includes
  - **Electromagnetically induced transparency**
  - **Electromagnetically induced absorption.**
- Study of coherent phenomena in solid medium like metamaterial and surface plasmon system also found increased research interest.
- Application: quantum memory, slow light, fast light, atomic clock, light storage, ion trapping, atom-photon entanglement etc.

Terminologies

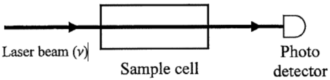
- Saturation Absorption Spectroscopy : SAS
- Coherent population trapping : CPT
- Electromagnetic Induced Transparency : EIT
- Negative Index Material : NIM
- Surface Plasmon Polariton : SPP

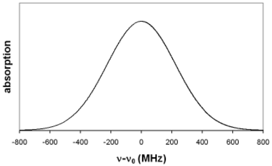
Atom-laser interacting system

- 2-level atomic system



- Absorption profile





Source: Ghosh, Pradip Narayan - Laser Physics and Spectroscopy (2018, CRC Press)

Saturation Absorption Spectroscopy (SAS)

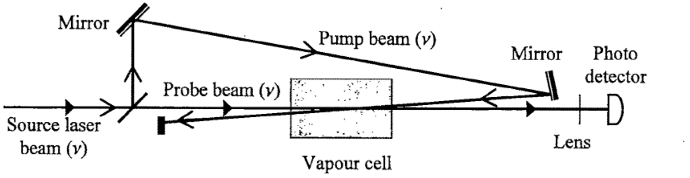


Figure: Basic experimental set up for SAS

- A technique to resolve narrow hyperfine transition.
- In 1970, Schawlow and Hansch first developed the technique known as laser-saturated absorption spectroscopy.

Source: Ghosh, Pradip Narayan - Laser Physics and Spectroscopy (2018, CRC Press)

SAS in 2-level atomic system

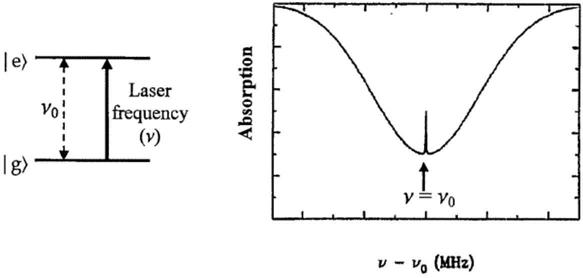


Figure: Absorption spectrum for 2-level atomic system under SAS configuration.

- Doppler free spectroscopy.
- Action of two counter propagating beams creates a sharp dip in velocity distribution curve.

Source: Ghosh, Pradip Narayan - Laser Physics and Spectroscopy (2018, CRC Press)

Crossover Resonance

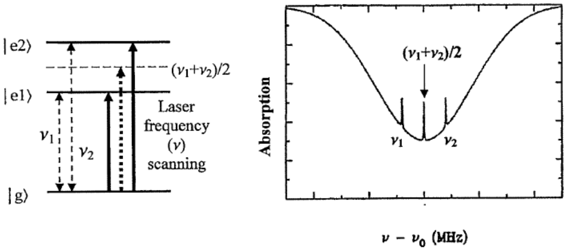


Figure: Probe absorption spectrum for 3-level atom under SAS configuration.

- Two dips on the left and right side are hyperfine transitions.
- Third dip in middle is crossover resonance dip.

Source: Ghosh, Pradip Narayan - Laser Physics and Spectroscopy (2018, CRC Press)

Coherent optical phenomena in 3 level atomic system

Coherent Population Trapping

- Observed in 3-level system where both pump and probe laser beam acts simultaneously.
- Atomic population get trapped in coherent superposition state of two ground states $|1\rangle$ and $|2\rangle$.
- No absorption takes place from this state in presence of the field.
- First experimentally observed in a 3-level system by Alzetta *et al* in 1976.

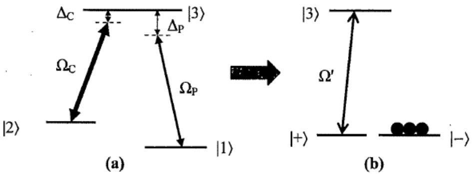


Figure: (a) Energy level diagram for 3-level lambda (Λ)-type system. (b) The population is pumped into a superstition state ($|-\rangle$) of the two ground states.

- Hamiltonian for 3-level atomic system is given by,

$$H = H_0 + H_I$$

- Eigenstates of H at resonance condition will be as follows:

$$|+\rangle = \frac{\Omega_p}{\Omega'}|1\rangle + \frac{\Omega_c}{\Omega'}|2\rangle$$
$$|-\rangle = \frac{\Omega_c}{\Omega'}|1\rangle - \frac{\Omega_p}{\Omega'}|2\rangle$$

  where $\Omega^{'} = (\Omega_c^2 + \Omega_p^2)$.

- The state $|-\rangle$ is nonabsorbing and it is called dark or trapped state.

Source: Ghosh, Pradip Narayan - Laser Physics and Spectroscopy (2018, CRC Press)

Electromagnetically Induced Transparency (EIT)

- A quantum mechanical phenomena which alters the optical properties of an atomic medium under the action of resonant electromagnetic field.
- Opaque medium exhibits high transparency at resonant frequency.
- Quantum destructive interference between 2 excitation pathways leads to nonabsorption of probe field.
- EIT was first observed in 3-level Lambda (Λ) type system.

Λ-type system

- Two ground hyperfine energy levels are coupled to a common excited level via pump and probe laser beam.

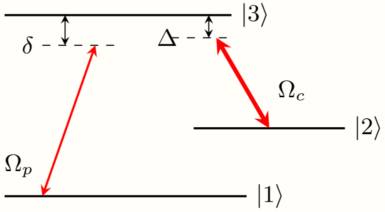


Figure: Lambda (Λ)- type atom-laser interaction system

OBEs for 3 level Λ type system

$$\dot{\tilde{\rho}}_{11} = \frac{i\Omega_p}{2}(\tilde{\rho}_{31} - \tilde{\rho}_{13}) + \Gamma_{21}(\tilde{\rho}_{22} - \tilde{\rho}_{11}) + \Gamma_{31}\tilde{\rho}_{33}$$
$$\dot{\tilde{\rho}}_{22} = \frac{i\Omega_c}{2}(\tilde{\rho}_{32} - \tilde{\rho}_{23}) - \Gamma_{21}(\tilde{\rho}_{22} - \tilde{\rho}_{11}) + \Gamma_{32}\tilde{\rho}_{33}$$
$$\dot{\tilde{\rho}}_{33} = \frac{i\Omega_p}{2}(\tilde{\rho}_{13} - \tilde{\rho}_{31}) + \frac{i\Omega_c}{2}(\tilde{\rho}_{23} - \tilde{\rho}_{32}) - (\Gamma_{32} + \Gamma_{31})\tilde{\rho}_{33}$$
$$\dot{\tilde{\rho}}_{21} = [i(\delta - \Delta) - \gamma_{21}]\tilde{\rho}_{21} + \frac{i\Omega_c}{2}\tilde{\rho}_{31} - \frac{i\Omega_p}{2}\tilde{\rho}_{23}$$
$$\dot{\tilde{\rho}}_{31} = [i\delta - \gamma]\tilde{\rho}_{31} + \frac{i\Omega_p}{2}(\tilde{\rho}_{11} - \tilde{\rho}_{33}) + \frac{i\Omega_c}{2}\tilde{\rho}_{21}$$
$$\dot{\tilde{\rho}}_{32} = [i\Delta - \gamma]\tilde{\rho}_{32} + \frac{i\Omega_c}{2}(\tilde{\rho}_{22} - \tilde{\rho}_{33}) + \frac{i\Omega_p}{2}\tilde{\rho}_{12}$$

Analytical solution for OBEs

$$\tilde{\rho}_{31} = \frac{-\frac{i\Omega_P}{2}}{(\gamma - i\delta) + \frac{\frac{\Omega_C^2}{4}}{\gamma_{21} - i(\delta - \Delta)}}$$

- Probe absorption profile

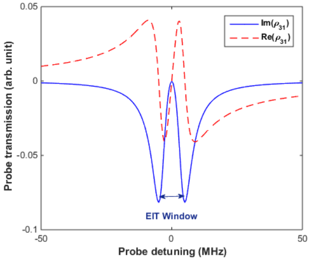
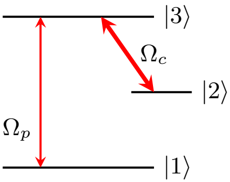
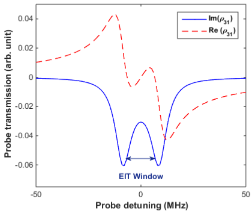


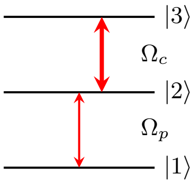
Figure: Real and imaginary part of $\tilde{\rho}_{31}$ vs probe detuning (δ) for Λ-type system

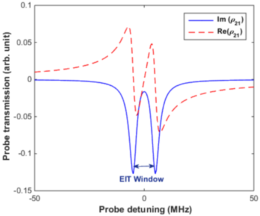
- **V-type system**





- **Cascade type system**





Negative Index Material (NIM)

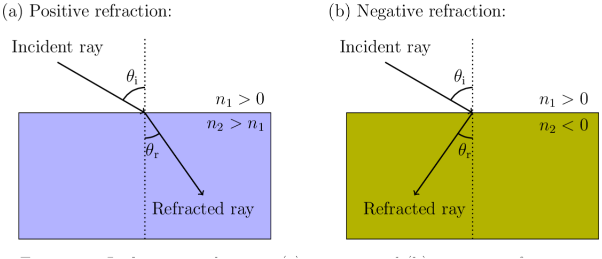


Figure: Positive and negative index material.

Source: https://www.semanticscholar.org/paper/The-Application-of-Negative-Refractive-Index-to-mm-Mohamed/57d7f5af72043c0e8d0e6d68ca7d7a89d37f6da9.

- An engineered material in which refractive index of material is negative.

NIM

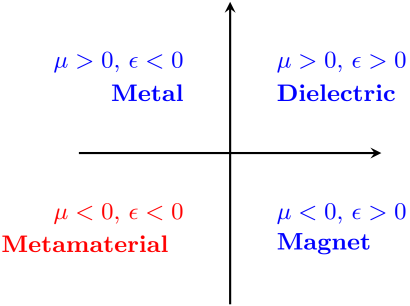


Figure: Permittivity and permeability diagram

- Both permittivity and permeability of the material is negative.
- Wave vector and Poynting vector are antiparallel.

Surface Plasmon Polariton

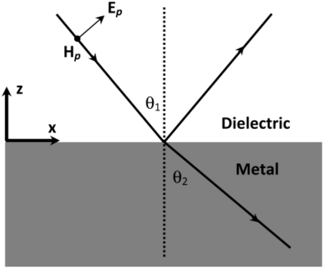
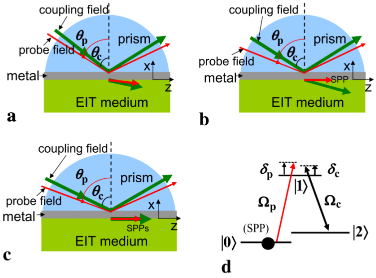


Figure 1. Representation of p-polarized electromagnetic radiation incident upon a planar interface between two media at an angle of incidence θ_1.

- SPP is electromagnetic wave present at the interface between metal and dielectric.
- Surface electromagnetic wave consist of surface charges.
- When a p-polarized light is incident upon a metal surface at an angle beyond θ_c (critical angle), a spatially decaying field (evanescent wave) propagates in a direction normal to the surafce.
- At critical angle the decay length is infinite and beyond critical angle it is order of few wavelength.

Zhang et al. J.Phys.D: Appl. Phys. 45 (2012) 113001 (19pp)

EIT in SPP system



- EIT can be used for coherent control of light by excitation of SPP.
- EIT based SPR system consist of three layers among which the third level acts as EIT medium.
- In a SPR system the pump and probe beam can be considered as follows
  - The coupling or pump field is freely propagating field and the probe field is a SPP.
  - Or the coupling field is a SPP field.
- Choice of coupling field leads to different frequency spectra for reflectivity of probe beam.

Du *et al.*Physical Review A, 91(1):013817, 2015.

Literature Survey

Coherent optical phenomena (CPT and EIT)

- In 1976, Alzetta *et al.* first experimentally observed CPT.
- Three black lines in fluorescence of Na atoms were detected.

IL NUOVO CIMENTO   VOL. 36 B, N. 1   11 Novembre 1976

An Experimental Method for the Observation of R.F. Transitions and Laser Beat Resonances in Oriented Na Vapour.

G. ALZETTA, A. GOZZINI, L. MOI and G. ORRIOLS (*)
Laboratorio di Fisica Atomica e Molecolare del C.N.R. - Pisa

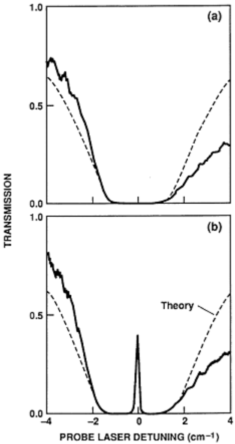
(ricevuto il 18 Agosto 1976)

Summary. — A method which allows a direct picture of phenomena involving line broadening, light shifts and many-photon transitions in the ground state of sodium atoms pumped by dye-laser is reported. A new phenomenon due to light beats between the different dye-laser axial modes has been easily evidenced by the method.

1976-1989

- In 1976, Arimondo gave the theoretical analysis of coherent phenomena in 3-level system.
- In 1984, Bright reviewed the use of EM field to create transparency.
- In 1986, Kocharovskaya and Khanin predicted the population trapping in two lower levels of Λ configuration .
- Also the foundations of EIT were laid by them in 1988.
- In 1989, Harris independently observed EIT.

- In 1991, Harris *et al.* first experimentally demonstrated EIT.
- This experiment was carried out in a Λ scheme in Strontium vapour using pulsed lasers.
- Result shows that the transmittance of the probe field, could be increased from e^{-20} to e^{-1}.
- They pointed out the importance of the quantum interference in this increment.
- For no interference process present, the transmittance would only have increased to e^{-7}.



1990-1999

- In the same year, Field *et al.* first observed EIT in a collisionally broadened resonance transition of Pb vapour.
- In 1992, Kasapi *et al.* experimentally demonstrated EIT in a cascade Ξ-type in Lead vapour.
- In 1994, Eberly and his group first observed spatial evolution of dressed field pulses. This result provided the information of EIT propagation.

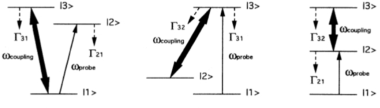
PHYSICAL REVIEW A VOLUME 52, NUMBER 3 SEPTEMBE

Continuous-wave electromagnetically induced transparency: A comparison of V, Λ, and cascade systems

David J. Fulton,* Sara Shepherd, Richard R. Moseley, Bruce D. Sinclair, and Malcolm H. Dunn
J. F. Allen Physics Research Laboratories, Department of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife KY16 9SS, Scotland, United Kingdom
(Received 27 February 1995)

A theoretical and experimental investigation has been carried out into the viability of V-type, Λ-type, and cascade systems within rubidium for the observation of electromagnetically-induced transparency (EIT). A Λ-type system is also discussed where EIT is induced on a two-photon transition. Continuous-wave single-frequency titanium sapphire lasers have been employed to provide the applied optical fields. It is found that systems that have a strong coupling field resonant with the $5S_{1/2}$ ground state suffer from complicating optical pumping mechanisms that tend to mask EIT windows. It is also found that wavelength matching of the applied optical fields enhances the observation of EIT since this results in a reduced residual Doppler linewidth of the atomic system.

PACS number(s): 42.50.Gy, 42.50.Hz, 32.80.Bx



(a) (b) (c)

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1050-2947/95/52(3)/2302(10)/$06.00 52 2302

- In 1995, Fulton *et al.* conducted theoretical and experimental investigations on continuous-wave EIT in Λ, and Ξ-type system in Rb atom.

- In 1996, Kasapi *et al.* applied EIT to isotope discrimination by adjusting the intensity of a coupling laser.
- In 1997, Hopkins *et al.* investigated EIT in laser cooled medium.
- In 1998, Azim *et al.*proposed a method to measure photon statistics of a quantized radiation field in an EIT set-up.
- In the year 1999,
  - Boon and his group experimentally observed of transparency on a transition in the blue spectral region in a V-type system.
  - Ying-Cheng Chen *et al.* experimentally detected fast and slow light using EIT.
  - Hau *et al.* reported an experimental demonstration of EIT in ultra cold Na atoms, where optical pulses propagated at twenty million times slower than the speed of light in vacuum.

2000-2009

- In 2000, Entin *et al.* experimentally demonstrated non degenerate four-level N-type scheme to observe EIT at the $^{87}Rb\ D_2$ line.
- In 2001,
  - Badger and his group investigated the role of hyperfine structure in EIT by studying the $5S_{1/2} - 5P_{3/2} - 5D_{3/2,5/2}$ cascade (Ξ)-type system in ^{85}Rb and ^{87}Rb.
  - Chen *et al.* first reported the observation of narrow and high contrast spectra in a Λ-type configuration.
  - In 2001, Wang and his group experimentally investigated EIT in a multi-level cascade (Ξ) type system of cold ^{85}Rb atoms and proposed Kerr nonlinearity in EIT windows.
  - In this year , Dogariu and Kim proposed dispersive properties if EIT.
- In 2002, Kozuma and his co workers reported an experimental investigation of group velocity reduction and light storage.

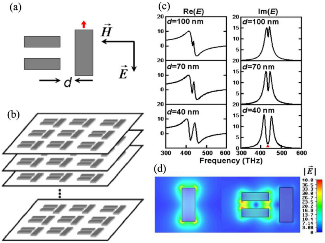
- In 2004, Carvalho led group measured the dependence of the linewidth of an EIT resonance on the angle between coupling and probe beams.
- In 2005, Chakrabarti *et al.* reported the additional absorption enhancement peak in a Λ-type system due to velocity selective optical pumping along with EIT.
- In 2006, Wang observed two-photon transparency.

Other type of atom-laser coupling scheme

- Inverted Y type system : Yan *et al.* explored EIT in an inverted-Y system of interacting cold atoms.
- N level system : In 2008, Anton *et al.* delved into optical switching in a five level atom through EIT. Chen *et al.* and Kong *et al.* explored the optical properties of an N-type system in Doppler broadened multilevel atomic media.
- Rydberg EIT : Naber *et al.* investigated EIT with Rydberg atoms across the Breit-Rabi regime. Tian *et al.* modeled EIT in a Y system with a single Rydberg state. Kara *et al.* studied Rydberg interaction induced enhanced excitation in thermal atomic vapor.

- In 1967, Veselago first predicted about negative index material.
- In 1999, Sir John Pendry first paved the way to develop a NIM. He showed that a sub wavelength metalic structure called split ring resonator can produce negative permeability at certain frequency.
- In 2000, Smith *et al.* demonstrated the first metamaterial with a negative refractive index at microwave frequencies using split-ring resonators (SRRs) and wire structures.
- 2003-2005: During this time researcher focused on developing NIM within various frequency range.
    - Yan *et al.* achieved negative permeability at 1 THz.
    - An alternative technique,used by Zhang *et al.* led to achieve resonance frequency up to 60THz.
    - Linden and his group found that magnetic response of a material can be achieved at 85 THz.

- 2005-2007: Several theoretical and experimental works carried out to achieve negative refractive index at optical wavelength.
- In 2008, Zhang *et al.* first designed EIT metamaterial with a working frequency of 428.4 THz.[1]



- In next decade significant progress has been made in the field of EIT in meatmaterial. In this era, a lot of microstructures and methods to realize plasmonic EIT effects have been proposed.

[1] Shuang Zhang, Dentcho A Genov, Yuan Wang, Ming Liu, and Xiang Zhang. Physical review letters, 101(4):047401, 2008.

SPP

- SPPs were first observed by Wood in 1902. He found unexplained features in optical reflection measurements on metallic gratings
- The term **plasmon** was first introduced by Pines in 1956.
- In the same year, Fano first used the term **polariton** for the coupled oscillation of bound electron.
- Ritchie in 1957 investigated electron energy losses in thin films and gave first theoretical description of **surface plasmons**. It was found that plasmon modes could exist near the surface of metals.
- In 1968 Otto and Kretschmann first proposed optical excitation of surface plasmons on metal films in their work differently.
- Surface plasmon properties of gold and silver were described by Kreibig and Zacharias in 1970.
- In 1974 Cunningham and co-workers introduced the term surface plasmon polariton (SPP).

SPP

- In 1997, Barren *et al.* studied the propagation of surface plasmon polaritons on textured surfaces, specifically on a grating surface.
- In 1998, Kano *et al.* calculated the electric field intensity distribution on a silver surface which is caused by the excited surface plasmon polaritons.
- In the same year, elastic scattering of SPP was first modeled by Bozhevolnyi *et al.* by considering isotropic point like scatterers whose responses to the incident SPP field are phenomenologically related to their effective polarizabilities.
- In 2003, near field imaging of scattering, reflection, interference and localization of surface polaritons are reviewed by Zayats and Smolyaninov.

SPP

- In 2004, Krenn and Weeber investigated various properties of SPP such as propagation length, mode field profile and reflection or scattering at metal dielectric interfaces.
- In 2010, Lu *et al.* showed that magnetic plasmon resonance play a vital role in plasmonic EIT.

- In 2015, Du *et al.* first proposed a way to excite SPPs resonantly by lights without using any coupler and a surface-plasmon-resonance (SPR) system.
- In the same year Meng *et al.* theoretically studied EIT in reflection spectra of V-type system at the gas-solid interface. In addition to finding a narrow dip arising from the EIT effect, they also explored the other particular saturation effect induced by pump field, which does not exist in Λ or Ξ -type system.

SPP

- Asgarnezhad *et al.* in 2017 investigated the possibility of the direct excitation of surface polaritons (SPs) by the free-space laser fields at the interface of negative-index metamaterial (NIMM) layer and a bottom layer of cold double Λ-type atomic medium.
- 2018 : In the following year, the same group investigated the excitation and propagation of the surface polaritonic rogue waves by proposing a coupler free optical waveguide that consists of a transparent layer, middle negative index metamaterial layer and bottom layer of the cold four level atomic medium.

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Future outlook

- Designing theoretical model for both atom-laser coupled system and SPP-laser coupled system to present coherent optical response in both medium.

- To investigate optical response at metal-dielectric interface from the reflected probe beam.

- To explore the probe beam's optical responses by tuning different parameters of laser lights.

- To design experimental set up to investigate the above-mentioned phenomena.

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Thank You !