

**COHERENT LIGHT-MATTER INTERACTION
USING ZEEMAN SUBLEVELS IN ^{87}Rb VAPOR
FOR EIT, EIA, SLOW AND FAST LIGHT**

BHARTI



**DEPARTMENT OF PHYSICS
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**Coherent light-matter interaction using Zeeman
sublevels in ^{87}Rb vapor for EIT, EIA, slow and fast
light**

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BHARTI

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Dedicated to my loving parents.....

Certificate

This is to certify that the thesis entitled "**Coherent light-matter interaction using Zeeman sublevels in ^{87}Rb vapor for EIT, EIA, slow and fast light**", submitted by **BHARTI** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** in Physics is a record of the original, bonafide research work carried out by her under my supervision and guidance. The thesis has reached standards that meet the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

Prof. Joyee Ghosh

Associate Professor, Department of Physics

Indian Institute of Technology Delhi

New Delhi, 110016

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Abstract

In coherent light-matter interaction, especially in the scenario of a common or shared atomic level, the quantum interference between excitation pathways plays a crucial role. The constructive or destructive quantum interference between the transition amplitudes of excitation pathways can lead to remarkable modifications in the optical and dynamical properties of atomic systems. One such phenomenon is electromagnetically-induced transparency (EIT), resulting from the destructive quantum interference between excitation pathways driven by two fields known as the probe and pump/coupling beams. This leads to a strong suppression of probe absorption and substantial alteration of the medium's refractive index around resonance. In contrast, the another effect, known as electromagnetically induced absorption (EIA) emerges from the constructive quantum interference resulting in an enhancement of probe absorption under specific conditions. These phenomena illustrate the complexity of light-matter interactions within multi-level atomic systems and present opportunities for the manipulation of light propagation in atomic media. Alkali atoms, in particularly Rubidium, serves as an ideal candidate for the investigation of such phenomena due to its simple atomic structure, large oscillator strength, and capacity to achieve high atomic densities even at room temperature. These characteristics render them suitable for a wide range of applications in the classical as well as quantum domain, e.g., in Doppler-free spectroscopy, four-wave mixing, laser frequency stabilization, atomic clocks, cold atoms, slowing, delay and storage of light, and quantum memories, etc.

This thesis provides an extensive theoretical and experimental investigation of Electromagnetically Induced Transparency (EIT) by employing a semi-classical approach to describe light-matter interactions. The thesis also investigates coherent population oscillation (CPO) and Electromagnetically Induced Absorption (EIA). The work investigates the impact of atomic coherence, population dynamics, and laser parameters on the observed spectral features through comprehensive modeling and experimental validation taking into consideration the closed transitions of the D₂-line of ⁸⁷Rb vapor.

The chapters presented in the thesis investigate the impact of key beam parameters such as beam diameter, intensity and polarization in addition to other factors such as cell temperature and magnetic field on light matter interaction. We consider the interplay of

various relaxation mechanisms, such as Doppler broadening, spontaneous emission and transit-time effects in a three level Λ system. Atomic properties such as width of transmission profile, peak transmission and dispersive characteristics such as group delay are well explored using Rubidium vapor. The dependence of transmission and dispersive characteristics on applied magnetic fields plays a crucial role in applications such as vector magnetometry. An observable decrement in the group delay and a corresponding increment in the group velocity, indicating a transition from slow to fast light under the application of the magnetic field in a simple- Λ system. The research further extends to the double- Λ (tripod) system to illustrate the manipulation of optical characteristics through beam polarization and ellipticity, revealing a transition from slow to fast light propagation. Polarization-induced anisotropy in the atomic medium facilitates a tunable control over this transition, influenced by magnetic field and beam ellipticity. Experimental measurements are conducted utilizing Zeeman EIT and Zeeman EIA for various polarization configurations of the probe and coupling beams, emphasizing the polarization sensitivity of these phenomena. Zeeman EIT exhibits transmission windows originating either solely due to EIT or from the combined effect of EIT and CPO (coherent population oscillation), depending on beam polarizations. Interestingly, Zeeman EIA shows a transformation from its typical absorption feature to transmission feature as a result of AC Stark effects at high coupling beam intensities.

Ultimately, the experimental observation of slow light and the systematic measurement of group delay as a function of coupling intensity confirm the feasibility of controlling the propagation of light pulses within a coherently prepared atomic medium. These findings highlight the potential of EIT and EIA-based schemes in Rubidium vapor for applications in quantum information processing and optical storage, where precise control of delay, advancement, and reshaping of light pulses is an important asset.

सार

सुसंगत प्रकाश-पदार्थ अंतःक्रिया में, विशेषकर उस स्थिति में जहाँ दो संक्रमण एक समान अथवा साझा परमाणु स्तर से जुड़े हों, उत्तेजना मार्गों के बीच उत्पन्न क्वांटम व्यतिकरण (quantum interference) अत्यंत महत्वपूर्ण भूमिका निभाता है। विभिन्न मार्गों के संक्रमण आयामों के बीच होने वाला रचनात्मक या विध्वंसात्मक व्यतिकरण परमाणु तंत्रों के प्रकाशीय तथा गतिशील गुणों में उल्लेखनीय परिवर्तन उत्पन्न कर सकता है। ऐसा ही एक प्रभाव है इलेक्ट्रोमैग्नेटिकली इंड्यूस्ड ट्रांसपेरेन्सी (EIT), जो दो क्षेत्रों-प्रोब तथा पम्प/कपलिंग-द्वारा प्रेरित उत्तेजना मार्गों के बीच विध्वंसात्मक व्यतिकरण के कारण उत्पन्न होता है। इसके परिणामस्वरूप प्रोब अवशोषण में तीव्र कमी तथा अनुनाद के निकट माध्यम के अपवर्तकांक में महत्वपूर्ण परिवर्तन देखा जाता है। इसके विपरीत, इलेक्ट्रोमैग्नेटिकली इंड्यूस्ड ऐब्जॉर्प्शन (EIA) रचनात्मक व्यतिकरण के कारण उत्पन्न होता है, जिससे विशेष परिस्थितियों में प्रोब अवशोषण में वृद्धि परिलक्षित होती है। ये प्रभाव बहु-स्तरीय परमाणु तंत्रों में प्रकाश-पदार्थ अंतःक्रिया की जटिलता को दर्शाते हैं तथा परमाणु माध्यम में प्रकाश प्रसार के नियंत्रण के लिए महत्वपूर्ण संभावनाएँ प्रदान करते हैं।

क्षारीय धातु परमाणु-विशेष रूप से रुबिडियम-ऐसे प्रकाशीय प्रभावों के अध्ययन हेतु अत्यंत उपयुक्त सिद्ध होते हैं, क्योंकि इनमें सरल परमाणु संरचना, उच्च दोलन शक्ति तथा कमरे के ताप पर भी उच्च परमाणु घनत्व प्राप्त करने की क्षमता होती है। ये गुण इन्हें डॉपलर-रहित स्पेक्ट्रोस्कोपी, फोर-वेव मिक्सिंग, लेजर फ्रीक्वेंसी स्थिरीकरण, परमाणु घड़ियाँ, कोल्ड ऐटम्स, प्रकाश के धीमेपन/विलंबन तथा क्वांटम मेमोरी जैसी विविध शास्त्रीय और क्वांटम अनुप्रयोगों के लिए अत्यंत उपयुक्त बनाते हैं।

यह शोध-प्रबंध इलेक्ट्रोमैग्नेटिकली इंड्यूस्ड ट्रांसपेरेन्सी (EIT) के गहन सैद्धांतिक तथा प्रायोगिक अध्ययन को प्रस्तुत करता है, जिसमें प्रकाश-पदार्थ अंतःक्रिया का विवेचन अर्द्ध-शास्त्रीय (semi-classical) ढाँचे में किया गया है। इसके अतिरिक्त, सुसंगत पॉपुलेशन ऑसिलेशन (CPO) तथा इलेक्ट्रोमैग्नेटिकली इंड्यूस्ड ऐब्जॉर्प्शन (EIA) का भी विस्तृत अध्ययन शामिल है। यह कार्य ^{87}Rb वाष्प की D_2 -लाइन के बंद संक्रमणों को ध्यान में रखते हुए परमाण्विक सुसंगतता, आबादी गतिकी तथा लेजर मापदंडों के प्रभाव का सैद्धांतिक मॉडलिंग और प्रायोगिक सत्यापन के माध्यम से विश्लेषण करता है।

शोध के विभिन्न अध्याय प्रकाश-पदार्थ अंतःक्रिया पर किरण व्यास, तीव्रता और ध्रुवण जैसे महत्वपूर्ण बीम मापदंडों के साथ-साथ सेल तापमान और चुंबकीय क्षेत्र जैसे कारकों के प्रभाव को व्यवस्थित रूप से जाँचते हैं। तीन-स्तरीय Λ तंत्र के संदर्भ में डॉपलर का विस्तार, स्वस्फूर्त उत्सर्जन तथा ट्रांजिट-टाइम जैसी शिथिलीकरण प्रक्रियाओं की संयुक्त भूमिका का अध्ययन किया गया है। रुबिडियम वाष्प के माध्यम से संचरण रूपरेखा की चौड़ाई, अधिकतम संचरण तथा प्रकीर्णकीय गुणों-जैसे समूह विलंब (group delay) का विस्तृत परीक्षण किया गया है। चुंबकीय क्षेत्र के साथ इन प्रकाशीय विशेषताओं का परिवर्तन वेक्टर मैग्नेटोमेट्री जैसी अनुप्रयोगों के लिए

महत्वपूर्ण है। सरल- Λ तंत्र में चुंबकीय क्षेत्र लागू करने पर समूह विलंब में कमी तथा समूह वेग में वृद्धि के कारण धीमे प्रकाश से तेज प्रकाश की ओर संक्रमण का अवलोकन किया गया है।

शोध को आगे बढ़ाते हुए डबल- Λ (ट्राइपॉड) तंत्र का उपयोग कर ध्रुवण तथा एलीप्टिसिटी के माध्यम से प्रकाशीय गुणों के नियंत्रण को प्रदर्शित किया गया है, जिससे धीमे से तेज प्रकाश के समायोज्य संक्रमण स्पष्ट होते हैं। परमाणु माध्यम में ध्रुवण-प्रेरित ऐनिसोट्रॉपी इस नियंत्रण को चुंबकीय क्षेत्र तथा एलीप्टिसिटी के साथ संवर्धित करती है। प्रोब तथा कपलिंग किरणों की विभिन्न ध्रुवण संरचनाओं के लिए जीमान EIT तथा जीमान EIA के प्रायोगिक अवलोकन इन प्रभावों की ध्रुवण संवेदी प्रकृति को रेखांकित करते हैं। जीमान EIT में संचरण रूपरेखा-केवल EIT अथवा EIT+ CPO के संयुक्त प्रभाव-दोनों से उत्पन्न हो सकती हैं, जबकि जीमान EIA उच्च कपलिंग तीव्रताओं पर AC-Stark प्रभावों के कारण पारंपरिक अवशोषण से संचरण जैसी आकृति में परिवर्तित होता है।

अंततः, धीमे प्रकाश का प्रायोगिक अवलोकन तथा विभिन्न कपलिंग शक्तियों पर समूह विलंब के सुव्यवस्थित मापन यह सिद्ध करते हैं कि सुसंगत रूप से तैयार माध्यम के भीतर प्रकाश किरणों के प्रसार को प्रभावी रूप से नियंत्रित किया जा सकता है। यह शोध रुबिडियम वाष्प में EIT तथा EIA आधारित योजनाओं की उन संभावनाओं को उजागर करता है जो क्वांटम सूचना प्रसंस्करण तथा प्रकाशीय भंडारण जैसी अनुप्रयोगों में, प्रकाश के विलंबन, अग्रगमन तथा पुनःआकारण के सटीक नियंत्रण को संभव बनाती हैं।

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Abbreviations

NIR	N ear- i nfrared
EM	E lectromagnetic
FWHM	F ull W idth H alf M aximum
SAS	S aturated A bsorption S pectroscopy
PS	P olarization S pectroscopy
EIT	E lectromagnetically I nduced T ransparency
EIA	E lectromagnetically I nduced A bsorption
ECDL	E xternal C avity D iode L aser
HWP	H alf W ave P late
QWP	Q uarter W ave P late
PBS	P olarizing B eam S plitter
PD	P hoto- D iode
CCD	C harge- C oupled D evice
BS	B eam- S plitter
ND	N eutral D ensity
FG	F unction G enerator
SMF	S ingle- M ode F iber
PMF	P olarization- M aintaining F iber
AOM	A cousto- O ptic M odulator
EOM	E lectro- O ptic M odulator
DAVLL	D ichroic A tomic V apor L aser L ocking
PDH	P ound- D rever- H all
GUI	G raphical U ser I nterface
PID	P roportional- I ntegral- D erivative A nalysis
PZT	P iezo- E lectric T ransducer

Symbols

c	speed of light in vacuum
Γ	spontaneous emission
Γ_t	transit decay rate
ρ	density matrix
Ω	rabi frequency
N	atomic number density
χ	susceptibility
δ, Δ	detunings
α	absorption
W_D	doppler full width half maxima
τ_g	group delay
v_g	group velocity
k	wave vector in free space
ω	angular frequency
ω_{ij}	angular frequency separation between ground and excited state i , and j
λ	wavelength
\hbar	reduced Planck's constant
l	orbital angular momentum in units of $2\pi\hbar$
F	hyperfine quantum number
m_F	hyperfine magnetic quantum number