

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**HIGH RESOLUTION PUMP-PROBE IR LASER
SPECTROSCOPY OF RUBIDIUM ATOMIC VAPOR CELL**

MEHMET HÜSEYİN SEVİM

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF PHYSICS**

ADVISOR: ASSIST. PROF. DR. KAMİL ÇINAR

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GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**RUBİDYUM ATOMİK BUHAR HÜCRESİNİN YÜKSEK
ÇÖZÜNÜRLÜKLÜ POMPA-PROB KIZILÖTESİ LAZER
SPEKTROSKOPİSİ**

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*To my
beloved
mother...*

ABSTRACT

Today, research on atomic sensors is a rapidly developing field with a wide range of applications. High-resolution laser spectroscopy methods by using atomic vapor cells containing alkali metal atoms form the basis of high-precision metrological measurements based on the laser-atom interaction principle. One of the most important requirements for the precision and accuracy of these metrological measurements is the stabilization of the laser sources used in a stable and high-resolution manner.

This thesis examined the high-resolution spectroscopy of the 4x4x4 mm cubic rubidium atomic vapor cell produced in the TÜBİTAK National Metrology Institute (TÜBİTAK UME) Atomic Sensors Laboratory. The main reason for the preference of the rubidium atom is that it is in the alkali metal group of the periodic table and has a single electron in the valence band. Therefore, the observation of hyperfine structure of the rubidium atom can be obtained precisely. In this thesis, the $5S_{1/2}$ - $5P_{1/2}$ atomic transitions corresponding to the D_1 line at a wavelength of 795 nm of the rubidium atom are examined in detail.

The changes in the saturation absorption spectroscopy and atomic resonances at different atomic vapor cell temperatures, laser polarization states, and laser powers are systematically investigated in the experiments performed. The experimental setup is established according to the principle of overlapping two laser beams (pump and probe) of the same frequency, but different powers obtained from a single laser source in opposite directions in the atomic vapor cell to apply the Doppler-free spectroscopy technique. In this experimental technique, the more intense pump laser beam saturates the atoms and reduces the absorption of the probe light passing through the atomic vapor cell, thus making it possible to observe narrow resonance lines that exceed the Doppler broadening.

The obtaining of sub-Doppler resonances is carried out by the nonlinear saturation spectroscopy technique, which exceeds the resolution limits of linear absorption spectroscopy methods. With this technique, the sensitive hyperfine structure of the rubidium atom is obtained and analyzed in detail.

As a result, this thesis study includes a detailed investigation of the basic spectroscopic parameters, such as the amplitude and linewidth of the hyperfine structure in the D_1 line of rubidium atoms, in order to increase the sensitivity and resolution in spectroscopy-based atomic sensor applications.

Keywords: Laser Stabilization, Rubidium Spectroscopy, Laser-Atom Interaction, Atomic Vapor Cell, Doppler-Free Saturation Absorption Spectroscopy.

ÖZET

Günümüzde atomik sensörler üzerine yapılan araştırmalar hızla gelişmekte olan ve geniş bir uygulama alanına sahip bir çalışma alanıdır. Alkali metal atomları içeren gaz hücrelerinde yüksek çözünürlüklü lazer spektroskopisi yöntemleri, lazer-atom etkileşim prensibine dayalı olarak yüksek hassasiyetli metrolojik ölçümlerin temelini oluşturmaktadır. Bu metrolojik ölçümlerinin hassasiyet ve doğruluğu açısından en önemli gereksinimlerden biri, kullanılan lazer kaynaklarının kararlı ve yüksek çözünürlüklü biçimde stabilize edilmesidir.

Bu tez kapsamında TÜBİTAK UME Atomik Sensörler Laboratuvarında üretilen 4 mm boyutlarındaki kübik rubidium atomik gaz hücresinin yüksek çözünürlüklü spektroskopisi incelenmiştir. Rubidyum atomunun tercih edilmesinin temel nedeni, alkali metaller grubunda yer alması ve valans bandında tek elektron bulundurmasıdır. Bu durum, rubidyumun atomunun hiperince yapılarının belirgin ve net bir şekilde gözlemlenmesine olanak sağlamaktadır. Bu tez çalışmasında, rubidyum atomunun 795 nm dalga boyundaki D_1 hattına karşılık gelen $5S_{1/2}$ - $5P_{1/2}$ atomik geçişleri detaylı olarak incelenmiştir.

Gerçekleştirilen deneylerde farklı atomik gaz hücresi sıcaklığı, lazer polarizasyon durumları ve lazer güçlerinde doyum soğurum spektroskopisi ve atomik rezonansların değişimi sistematik olarak araştırılmıştır. Deney düzeneği, Doppler bağımsız spektroskopi tekniğini uygulamak amacıyla tek bir lazer kaynağından elde edilen aynı frekanstaki fakat güçleri birbirinden farklı iki lazer demetinin (pompa ve prob) atomik gaz hücresi içerisinde zıt yönlerde üst üste getirilmesi prensibine göre oluşturulmuştur.

Bu deney tekniğinde güçlü olan pompa lazer demeti, atomları doyuma ulaştırarak prob ışığının absorpsiyonunu azaltmakta ve böylelikle Doppler genişlemesini aşan dar rezonans çizgilerinin gözlenmesini mümkün kılmaktadır. Doppler altı rezonansların elde edilmesi, lineer absorpsiyon spektroskopisi yöntemlerinin çözünürlük sınırlarını aşan, lineer olmayan doyum spektroskopisi tekniğiyle gerçekleştirilmiştir. Bu teknik ile rubidyum atomunun hassas hiperince geçiş çizgileri elde edilmiş ve ayrıntılı olarak analiz edilmiştir.

Sonuç olarak bu tez çalışması, spektroskopi temelli atomik sensör uygulamalarında hassasiyet ve çözünürlüğü artırmak amacıyla rubidyum atomlarının D_1 hattındaki hiperince geçişlerinin genliği ve çizgi genişliği gibi temel spektroskopik parametrelerinin detaylı olarak incelenmesini içermektedir.

Anahtar Kelimeler: Lazer Stabilizasyonu, Rubidyum Spektroskopisi, Lazer-Atom Etkileşmesi, Atomik Gaz Hücresi, Doppler-Bağımsız Doyum Soğurum Spektroskopisi.

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LIST OF SYMBOLS AND ABBREVIATIONS

Rb	: Rubidium
K	: Kelvin
eV	: Electron volt
NIR	: Near Infrared
$^{\circ}C$	: Celsius degree
T	: Temperature
P	: Pressure
k_B	: Boltzmann constant
J	: Joule
N	: Number of atoms
m	: Meter
S	: Spin angular momentum
L	: Orbital angular momentum
I	: Nuclear spin
J	: Total angular momentum
n	: Principal quantum number
F	: Total angular momentum
h	: Planck constant
ν	: Frequency
γ	: Natural linewidth
s	: Second
τ	: Lifetime
Hz	: Hertz
v	: Velocity
$\hbar$	: Reduced Planck constant
ω	: Frequency
k	: Wave number
E	: Energy
t	: Time
FWHM	: Full width at half maximum
c	: Speed of light
m	: Mass
ω_D	: Doppler broadening
SAS	: Saturation absorption spectroscopy
DBR	: Distributed Bragg reflector
W	: Watt
dB	: Decibel
CW	: Continuous wave
A	: Ampere
Ω	: Ohm
V	: Volt
$\vec{E}$	: Electric field
$\vec{B}$	: Magnetic field
λ	: Wavelength
I	: Intensity

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1. INTRODUCTION

The development of the laser by Theodore Maiman at Hughes Research Laboratories in 1960 was a revolutionary achievement in physics and technology that paving the way for numerous scientific and practical applications [1]. The laser—an acronym for Light Amplification by Stimulated Emission of Radiation—was realized based on the foundational principles of stimulated emission first proposed by Albert Einstein in 1917. The coherence, high monochromaticity, and intensity of laser light quickly positioned lasers as indispensable tools across various fields, including atomic physics, spectroscopy, precision measurements, and quantum optics [2], [3]. After the success of the first laser, the development and experimental research about lasers have been accelerated. A variety of alternative laser types were demonstrated within the same decade, including helium-neon (He-Ne) gas lasers, semiconductor diode lasers, and CO₂ gas lasers, each have its own advantages for various fields [4], [5]. Among these fields, atomic spectroscopy significantly benefited from laser technology, enabling precise measurements of atomic structures and transitions that had previously been challenging or impossible to resolve clearly. The laser's coherence, narrow linewidth, and collimation properties made it an ideal tool for investigating atomic and molecular transitions with unprecedented accuracy.

Atomic spectroscopy, especially when it comes to alkali metals, has become very important for improving quantum technologies and precision measurements. Alkali metals have a single valence electron and show well-defined electronic transitions that make it easier to analyze and understand spectroscopic data [6]. Among the alkali metals, rubidium (Rb) is frequently chosen due to its suitable atomic structure, hyperfine splitting, and convenient optical transitions in the near-infrared (NIR) region of the electromagnetic spectrum. Specifically, D line transitions of rubidium at 780 nm (D₂ line) and 795 nm (D₁ line) are widely studied, as these transitions correspond to clearly distinguishable hyperfine levels [7], [8]. Therefore, rubidium atom spectroscopy has been extensively utilized in numerous fundamental research and technological developments, including atomic clocks, atomic magnetometers, gyroscopes, and various quantum sensing and communication technologies.

The interaction of laser radiation with atoms is fundamental to understanding and implementing precision spectroscopic techniques. When lasers interact with atoms, they can induce numerous phenomena such as absorption, stimulated emission and saturation [9], [10]. In laser spectroscopy, the atomic response depends on parameters like the intensity, frequency, and polarization of the laser light. These parameters determine the nature and strength of the interaction, allowing precise control over atomic excitation processes [11], [12]. Absorption occurs when atoms absorb photons matching the energy difference between atomic energy levels, leading to transitions from lower to higher energy states. However, stimulated emission describes atoms emitting photons in response to incident photons of matching frequency and phase, amplifying coherent radiation. Additionally, saturation effects increase at high intensities where a significant proportion of atoms transition to the excited states, diminishing further absorption [13]. However, the stability of lasers is not sufficient for many studies such as atomic clocks or frequency standards. Therefore, the frequencies of the lasers must be stabilized to the energy transitions of the atoms.

Laser-atom interactions form the foundation of modern atomic spectroscopy, if only eliminates the Doppler broadening effect which occurs due to thermal motion of atoms. Doppler broadening significantly reduces spectral resolution by broadening the atomic transition frequencies over a range due to different velocities of atoms in a medium relative to the laser source [14]. In addition, at room temperature, linewidths of atomic transitions are in the range of 100 - 1000 MHz whereas with the saturation absorption technique, the linewidths of very thin transitions are in the range of a few MHz [15].

In order to overcome this limitation, Doppler-free spectroscopy techniques were developed such as saturation absorption spectroscopy (SAS). In the SAS technique, two counter-propagating same frequency laser beams selectively interact with atoms. Therefore, this interaction forms sharp and narrow linewidth Doppler-free resonances that leads to enhanced laser stabilization [16]. In multi-level energy transitions, alkali metal vapors such as caesium, rubidium and potassium are widely used in frequency locking [17], [18], [19].

Various spectroscopy studies are done to investigate the atomic structures and transitions. For example, the study of sub-Doppler atomic transitions was made possible by the saturation spectroscopy research [20]. In the 1960s, theoretical

analyses of the Doppler broadening that occurs in atomic transitions were made by studying the caesium and xenon atoms [21], [22]. In the 1970s, hyperfine transitions were observed using the saturated absorption spectroscopy without the Doppler broadening effects in the non-linear laser and atom interaction [23], [24], [25]. In another study, it has been shown that the detected signal is a function of the interaction of both lasers, using a non-linear spectroscopy technique that surpasses the limitations of the Doppler broadening, which allows the measurement of fine transition lines of the excited states of the rubidium atom, by using two laser beams in opposite directions [26]. Another saturation absorption spectroscopy experiments are done by using rubidium atomic vapor cell [27], [28]. Locking to the atomic transitions obtained using Doppler free absorption spectroscopy in the frequency locking technique will increase frequency stability [29]. Therefore, high resolution spectroscopy is widely used at atomic frequency standards.

Investigations on atomic transitions of alkali vapor cells at different laser polarizations configurations and intensities and atomic vapor cell temperatures have been carried out in many different studies [30], [31], [32], [33]. Another study shows that the effects of temperature and power broadening of two isotopes of rubidium were investigated, and it allowed the determination of the velocity and line density of the atoms from the linewidths that changed with temperature [34], [35]. Measurement of line shapes of the rubidium D₂ transition are examined by variation of temperature of vapor cell and laser [36]. In another study, the atomic transitions of the caesium element, the optical pumping effect of the atoms and the absorption spectroscopy were investigated at different laser powers and polarizations and the experimental studies were compared with theoretical data [37]. As a result, the results obtained were used in frequency locking or different applications [38].

In this study, the effects of temperature of the atomic vapor cell, laser power and polarizations on the rubidium D₁ atomic transitions are studied. How spectral lines form and broaden around the resonance frequencies by Doppler effect are investigated by changing laser and temperature of vapor cell parameters.

Rubidium element is widely used in various precision measurement applications in the field of atomic sensors. Rubidium-based atomic gyroscopes can measure rotation rate with high precision, which is of critical importance especially in military and navigation systems [39]. In addition, rubidium atomic magnetometers measure weak

magnetic fields with picotesla resolution, which is widely used in biomedical applications, geophysical research, and fundamental physics experiments [40]. Rubidium element also play an important role in the development of atomic clocks which have been developed with techniques such as coherent population trapping (CPT) and saturation absorption spectroscopy and are frequently used in critical technologies such as communication systems, GPS and other global navigation satellite systems (GNSS) that require precise timing and frequency reference [41], [42]. The rubidium saturation absorption spectroscopy (SAS) method, which is examined in detail within the scope of this thesis, can make significant contributions to the improvement of rubidium element in terms of frequency stability and sensitivity in these atomic sensor applications.

2. LASER SPECTROSCOPY

Laser spectroscopy is a highly precise technique to study the interaction between laser light and atomic systems. Unlike traditional spectroscopy methods that rely on broadband light sources, laser spectroscopy utilizes monochromatic and coherent laser beams to investigate energy level transitions with very high spectral resolution. This technique enables the investigation of fine and hyperfine structures and Doppler-free transitions [2], [16].

The fundamental principle of laser spectroscopy is based on laser-atom interactions such as absorption, emission, or scattering of laser photons by atoms, allowing for precise measurements of transition frequencies, linewidths, and atomic interactions. Various advanced methods, such as saturation absorption spectroscopy, and Doppler-free spectroscopy have been developed to eliminate broadening effects and enhance spectral resolution. These techniques are widely applied in atomic clocks, high-precision metrology, atomic sensors, and fundamental physics experiments [2], [16].

In this study, laser spectroscopy will be employed to investigate the rubidium D_1 transition, using saturation absorption spectroscopy to resolve hyperfine structures and analyze the influence of experimental parameters such as laser power adjustments, polarization effect, and temperature of atomic vapor cell on rubidium atomic transitions. This study aims to contribute to the precision measurement and stabilization of laser frequencies, which are essential for high precision metrology and quantum technologies.

2.1. Rubidium Element

Rubidium (Rb) is an alkali metal with an atomic number of 37 and was discovered by Robert Bunsen and Gustav Kirchoff in 1861. It belongs to group IA of the periodic table and is characterized by its single valence electron in the outermost shell. The ground state electron configuration of rubidium element is given as $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^1$ [2]. This electron configuration makes the rubidium element highly reactive and suitable for laser spectroscopy studies [43]. Physical properties of rubidium element are given in **Table 2.1**.

Table 2.1: Physical properties of Rubidium element.

Group	1	Melting point	39.30 °C, 102.74 °F, 312.45 K
Period	5	Boiling point	688 °C, 1270 °F, 961 K
Block	s	Density (g cm⁻³)	1.53
Atomic number	37	Relative atomic mass	85.468
State at 20°C	Solid	Key isotopes	⁸⁵ Rb, ⁸⁷ Rb

There are two naturally occurring isotopes of rubidium: ⁸⁵Rb with 72.2% abundance and ⁸⁷Rb with 27.8% abundance [44]. ⁸⁷Rb is particularly interested in precision metrology, atomic clocks, and quantum optics due to its well-defined hyperfine structure and narrow spectral transitions. Properties of Rb isotopes are given in **Table 2.2**:

Table 2.2: Isotopes of Rubidium [45].

Isotope	Atomic mass	Natural abundance (%)	Half Life	Mode of decay
⁸⁵ Rb	84.912	72.17	-	-
⁸⁷ Rb	86.909	27.83	4.88 x 10 ¹⁰ year	β-

One of the key reasons the rubidium element is extensively studied in atomic physics is its low first ionization energy (4.18 eV), which allows efficient excitation using diode lasers operating near the near-infrared (NIR) region [46]. Furthermore, Rb atomic vapor cells are widely used in spectroscopy experiments due to their low melting point (39.30 °C). Therefore, enough atomic vapor can be created even at temperatures close to room temperature. This feature allows rubidium vapor cells to operate without complex heating systems[47].

In order to create a sufficient amount of atomic gas density, the glass cell needs to be heated. As the temperature increases, the vapor pressure also increases. Equation (2.1) is used to calculate the vapor pressure in the atomic gas cell [48].

$$\log(P(atm)) = A + BT^{-1} + C \log T + DT^{-3} \quad (2.1)$$

In equation (2.1); A , B , C , D are the constants for solid and liquid state of matter of elements and T is temperature. The values of these constants calculated for the Rb element are given in **Table 2.3**:

Table 2.3: A, B Constants for calculation Rb vapor pressure.

State of matter of Rb	A	B	C	D
Solid	4.857	-4215	-	-
Liquid	4.312	-4040	-	-

In this study, the solid rubidium element, which is available in 1-gram ampoules, is used. Therefore, the values given for the solid state of rubidium in **Table 2.3** will be used.

Equation (2.2) is used to calculate the number of atoms that change depending on a certain temperature:

$$N = \frac{P}{k_B T} = \frac{10^{(A+BT^{-1})}}{k_B T} \quad (2.2)$$

Here, N is the number of atoms, P is the pressure, k_B is the Boltzmann constant ($1.380649 \times 10^{-23} \text{ J} \cdot \text{K}^{-1}$), and T is the temperature. Based on this, alkali metal densities at different temperatures are calculated using equation (1.2), and the results are given in **Figure 2.1**, in which rubidium atomic density is given in solid red line.

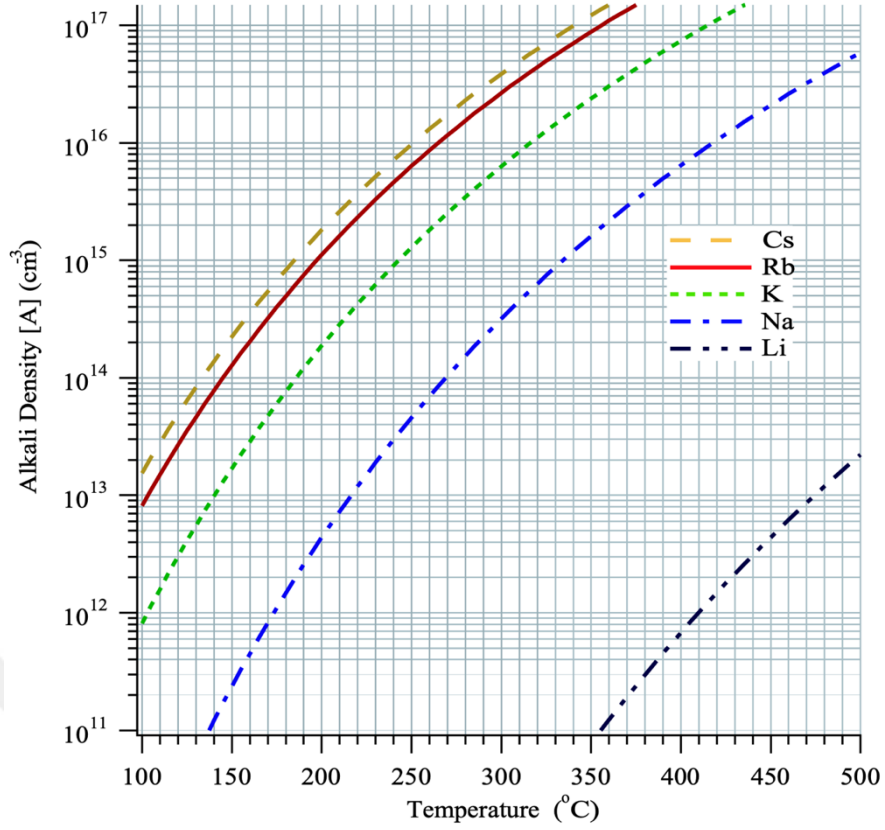


Figure 2.1: Alkali Metal Density – Temperature [49].

The rubidium atom exhibits a fine structure in its excited states due to spin-orbit coupling and a hyperfine structure arising from the interaction between the nuclear spin and the electronic angular momentum [50], [51]. The hyperfine structure is particularly significant for atomic frequency standards and laser frequency stabilization applications [52].

2.2. Rubidium D₁ Line

In alkali metals, the term D line refers to a pair of prominent optical transitions corresponding to the excitation of the outermost electron from the ground state (ns) to the first excited (np) state. These transitions are split into two distinct components due to spin-orbit interaction, resulting in what is known as the D₁ and D₂ lines [50], [51]. For rubidium, the atomic transitions are given in **Table 2.4**.

Table 2.4: Rb D Line.

D Line	Transition	Wavelength
D ₁	$5S_{1/2} \rightarrow 5P_{1/2}$	794.8 nm
D ₂	$5S_{1/2} \rightarrow 5P_{3/2}$	780.0 nm

These lines are of particular interest due to their well-resolved hyperfine structure in both naturally occurring isotopes, ^{85}Rb and ^{87}Rb . The D₁ line is especially significant in saturation absorption spectroscopy, where it enables Doppler-free resolution by probing the nonlinear interaction of pump and probe beams within a vapor cell [53]. This technique allows for precise laser frequency stabilization by locking the laser to specific atomic transitions, which is critical in fields such as atomic clocks and quantum optics. Therefore, a rubidium laser with 795 nm wavelength (D₁ line) was used in this study.

Since the rubidium electron configuration is $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^1$, the fourth electron shell is complete, and since there is a single valance electron in the fifth electron shell, it can be used in spectroscopy studies. The transitions made on the energy levels of the rubidium atom involve multi-level structures. The basis of this multi-level structure is the fine and hyperfine structure interactions [2].

The fine structure interaction occurs due to the interaction between the electron's spin angular momentum (S) and the orbital angular momentum (L). The hyperfine structure is a result of the magnetic interactions between the electron's spin and the nuclear spin (I). These interactions cause hyperfine separations in the energy levels, which can be observed in the transition lines of rubidium isotopes [50], [51].

2.2.1. Fine Structure

The spin motion of an electron in the spectrum is denoted by S , while L represents its orbital (angular) motion. The possible values of the total angular momentum J range between $J = L + S$ and $J = |L - S|$. This interaction splits energy levels that would otherwise have the same energy (degenerate). The spin-orbit interaction leads to the splitting of spectral lines. It is represented using the term notation $2s + 1L_J$,

which indicates the coupling of spin and orbital angular momentum. Here, L is orbital angular momentum ($L = 0 \rightarrow s, L = 1 \rightarrow p, L = 2 \rightarrow d$), j is the quantum number.

2.2.2. Hyperfine Structure

The hyperfine structure in rubidium arises from the interaction between the atom's nuclear spin (I) and its total angular momentum (J), leading to small splittings of atomic energy levels. Rubidium naturally occurs in two primary isotopes: ^{85}Rb ($I = 5/2$) and ^{87}Rb ($I = 3/2$), each exhibiting unique hyperfine energy-level splitting patterns due to their differing nuclear spin values. The ground state $5S_{1/2}$ and excited states $5P_{1/2}$ (D_1 line at 794.8 nm) and $5P_{3/2}$ (D_2 line at 780.0 nm) undergo hyperfine splitting into sublevels characterized by the total angular momentum quantum number F , defined by $F = I + J$ [50], [51].

The spectroscopic notation is expressed as $n(2S + 1)L_j$, where the term $(2S + 1)$ denotes the multiplicity arising from the electron spin state. In this notation, the principal quantum number is represented by n . The quantum number J in the L_j expression corresponds to the total angular momentum of the electron state.

For the sub-energy level $5S$ of the rubidium atom, the orbital angular momentum number of the ground energy level is $L = 0$, and the spin angular momentum number is $S = 1/2$. Since the spin angular momentum number S is greater than the orbital angular momentum number L , the multiplicity value is $2L + 1 = 1$, and this implies a single total angular momentum J value, namely $J = L + S = 1/2$. Since the nuclear spin values of rubidium isotopes are ^{85}Rb ($I = 5/2$) and ^{87}Rb ($I = 3/2$), when the interaction of electrons with the atomic nucleus is considered, the total angular momentum number of the atom is found as $F = I + J$ and $F = |I - J|$. Thus, the total angular momentum number F can be calculated.

For ^{85}Rb ($I = 5/2$):

$$F = I + J = \frac{5}{2} + \frac{1}{2} = 3 \rightarrow F = 3 (5S_{1/2}) \quad (2.3)$$

$$F = |I - J| = \left| \frac{5}{2} - \frac{1}{2} \right| = 2 \rightarrow F = 2 (5S_{1/2}) \quad (2.4)$$

For ^{87}Rb ($I = 3/2$):

$$F = I + J = \frac{3}{2} + \frac{1}{2} = 2 \rightarrow F = 2 (5S_{1/2}) \quad (2.5)$$

$$F = |I - J| = \left| \frac{3}{2} - \frac{1}{2} \right| = 1 \rightarrow F = 1 (5S_{1/2}) \quad (2.6)$$

In this case, two hyperfine structure energy levels are formed, $F = 3$ and $F = 2$ for ^{85}Rb ; $F = 2$ and $F = 1$ for ^{87}Rb .

For the excited energy level 5P of the rubidium atom, the orbital angular momentum number $L=1$, and the spin angular momentum number $S=1/2$. Since the spin angular momentum number S is smaller than the angular momentum number L , the degree of multiplicity is $2S+1=2$. Therefore, two hyperfine structures will be formed as $J=|L-S|=1/2$ and $J = L+S=3/2$. Since the nuclear spin numbers of rubidium isotopes are ^{85}Rb ($I=5/2$) and ^{87}Rb ($I=3/2$), the total angular momentum number includes values between $F=|I-J|$ and $F=I+J$ with a step of +1.

For ^{85}Rb ($I = 5/2$) and $J=1/2$:

$$F = |I - J| = \left| \frac{5}{2} - \frac{1}{2} \right| = 2 \quad F = I + J = \frac{5}{2} + \frac{1}{2} = 3 \quad (2.7)$$

According to equation (2.7), for $5P_{1/2} \rightarrow$ There are two hyperfine states as $F=2$ and $F=3$.

For ^{85}Rb ($I = 5/2$) and $J=3/2$:

$$F = |I - J| = \left| \frac{5}{2} - \frac{3}{2} \right| = 1 \quad F = I + J = \frac{5}{2} + \frac{3}{2} = 4 \quad (2.8)$$

According to equation (2.8), for $5P_{3/2} \rightarrow$ There are four hyperfine states as $F=1$, $F=2$, $F=3$ and $F=4$.

For ^{87}Rb ($I = 3/2$) and $J=1/2$:

$$F = |I - J| = \left| \frac{3}{2} - \frac{1}{2} \right| = 1 \quad F = I + J = \frac{3}{2} + \frac{1}{2} = 2 \quad (2.9)$$

According to equation (2.9), for $5P_{1/2} \rightarrow$ There are two hyperfine states as $F=1$ and $F=2$.

For ^{87}Rb ($I = 3/2$) and $J=3/2$:

$$F = |I - J| = \left| \frac{3}{2} - \frac{3}{2} \right| = 0 \quad F = I + J = \frac{3}{2} + \frac{3}{2} = 3 \quad (2.10)$$

According to equation (2.10), for $5P_{3/2} \rightarrow$ There are four hyperfine states as $F=0$, $F=1$, $F=2$ and $F=3$.

Hyperfine states of rubidium isotopes are given in **Table 2.5**:

Table 2.5: Hyperfine States.

Isotope	State	J	F
^{85}Rb	$5S_{1/2}$ (<i>Ground</i>)	$\frac{1}{2}$	2,3
^{85}Rb	$5P_{1/2}$ (D_1)	$\frac{1}{2}$	2,3
^{85}Rb	$5P_{3/2}$ (D_2)	$\frac{3}{2}$	1,2,3,4
^{87}Rb	$5S_{1/2}$ (<i>Ground</i>)	$\frac{1}{2}$	1,2
^{87}Rb	$5P_{1/2}$ (D_1)	$\frac{1}{2}$	1,2
^{87}Rb	$5P_{3/2}$ (D_2)	$\frac{3}{2}$	0,1,2,3

Hyperfine structure of ^{85}Rb is given in **Figure 2.2**.

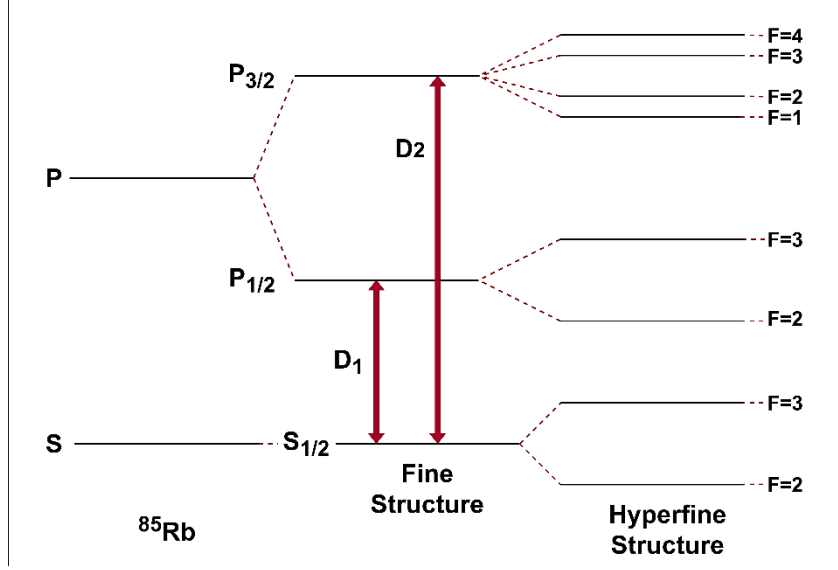


Figure 2.2: ^{85}Rb hyperfine structure [51].

Hyperfine structure of ^{87}Rb is given in **Figure 2.3**.

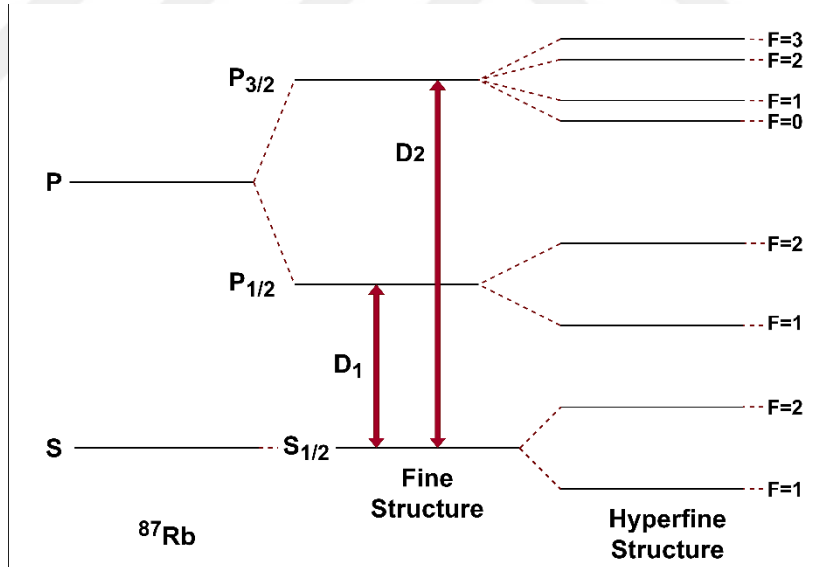


Figure 2.3: ^{87}Rb hyperfine structure [50].

Within the scope of the thesis, it was studied on the $5S_{1/2}$ and $5P_{1/2}$ atomic transitions located on the D_1 line of the rubidium atom. For ^{85}Rb , from the $5S_{1/2}$ (F=2) energy level, atoms can be raised to the $5P_{1/2}$ (F'=2,3) levels, and for the $5S_{1/2}$ (F=3) energy level, atoms can be raised to the $5P_{1/2}$ (F'=2,3) levels; For ^{87}Rb , from the $5S_{1/2}$ (F=1)

energy level, atoms can be raised to the $5P_{1/2}$ ($F'=1,2$) levels, and for the $5S_{1/2}$ ($F=2$) energy level, atoms can be raised to the $5P_{1/2}$ ($F'=1,2$) levels. **Figure 2.4** and **Figure 2.5** show the D_1 energy transition of the ^{85}Rb and ^{87}Rb isotopes respectively.

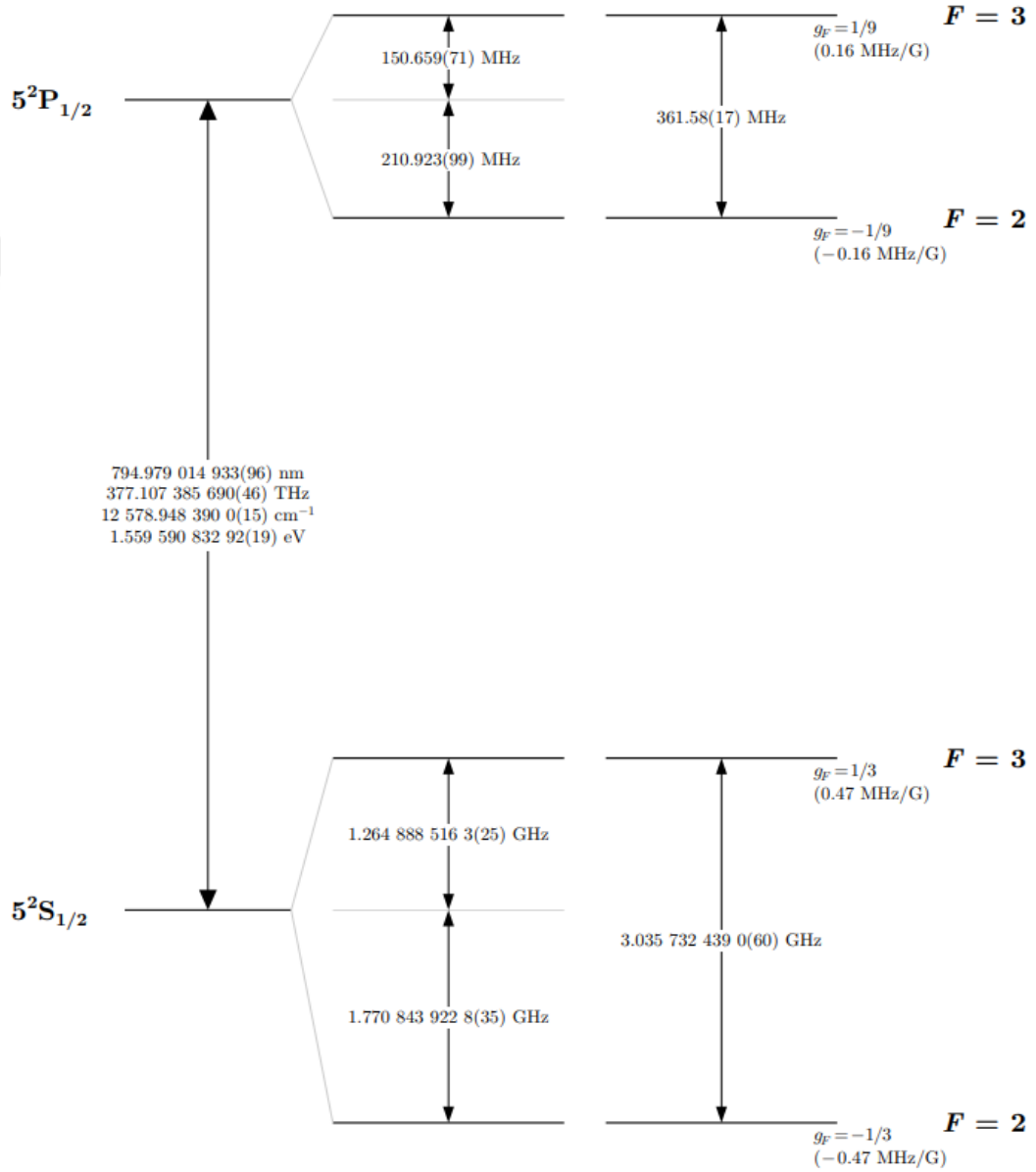


Figure 2.4: D_1 line of ^{85}Rb [51].

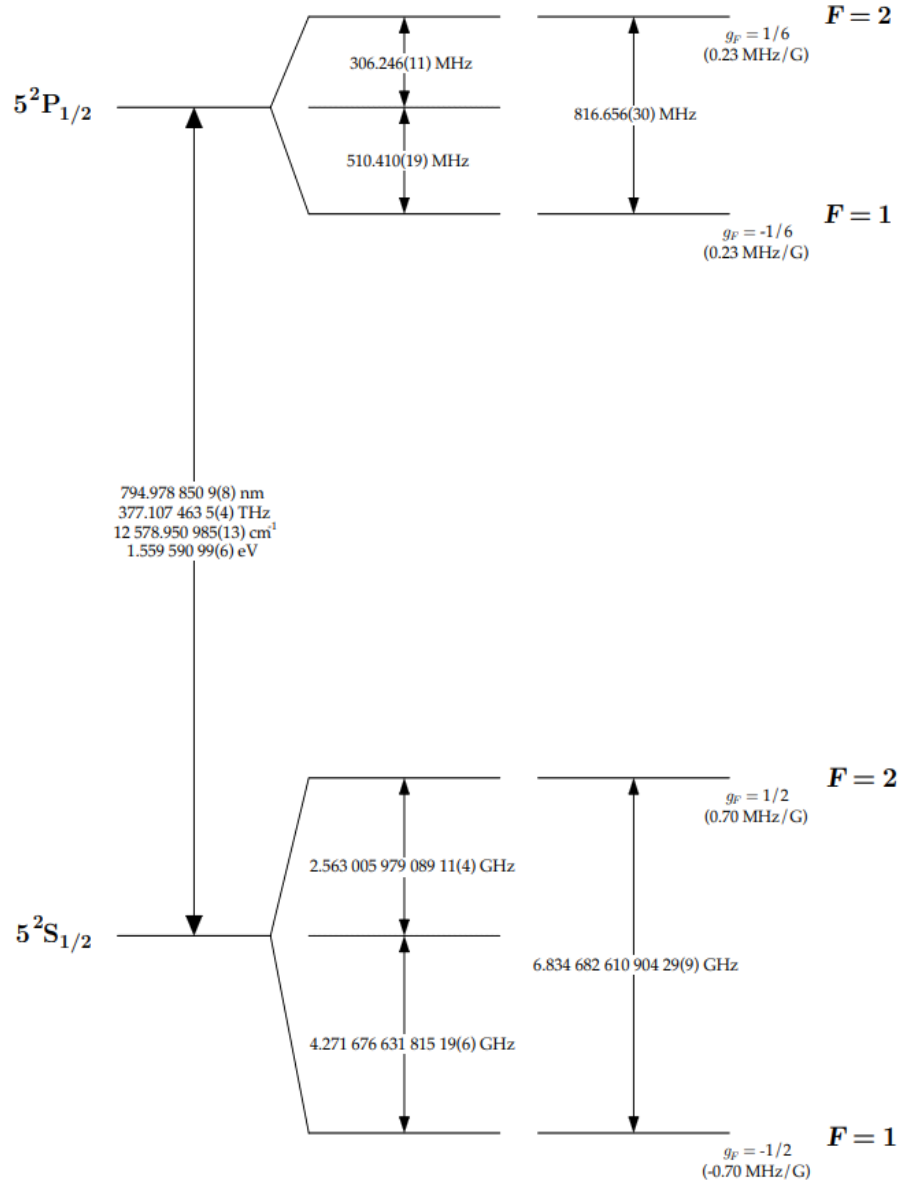


Figure 2.5: D₁ line of ⁸⁷Rb [50].

3. LASER ATOM INTERACTION

The interaction between laser light and atoms is a phenomenon that forms the basis of atomic physics and quantum optics. In these interactions, laser photons enable transitions between atoms' fundamental and excited energy levels. The atom absorbs the photon from the laser and rises to the excited energy level and then it descends back to the ground energy level, and it emits a photon. In order to transition to happen, energy of the laser photon must be equal to the atomic transition energy difference [54].

$$E_{excited} - E_{ground} = h\nu_{photon} \quad (3.1)$$

In equation (3.1), h represents the Planck constant ($h = 6.63 \times 10^{-34} \text{ J.s}$) and ν is the frequency of laser photon.

This process includes three basic mechanisms:

Absorption: The atom in the ground energy level absorbs the photon emitted from the laser and excites to an excited energy level when the photon energy exactly matches the energy difference of ground and excited states because atoms have discrete energy levels due to the Schrödinger equation [55]. The absorption mechanism is given in **Figure 3.1**.

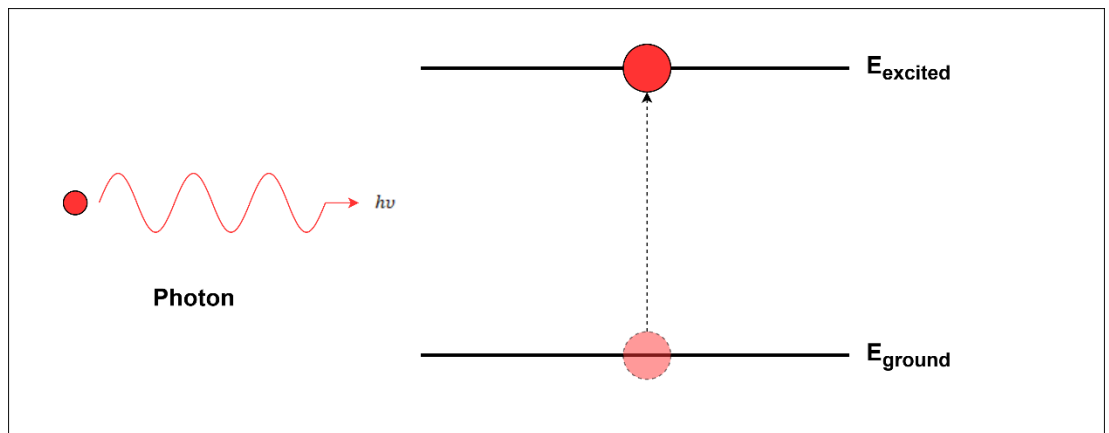


Figure 3.1: Photon absorption.

Spontaneous Emission: A photon with an energy equal to the difference between two states is released when an excited atom spontaneously decays to a lower energy state. This process, which is caused by quantum fluctuations in the electromagnetic field, occurs without interference of any outside influences. The photon's polarization, phase, and direction are all random [55]. The spontaneous emission mechanism is given in **Figure 3.2**.

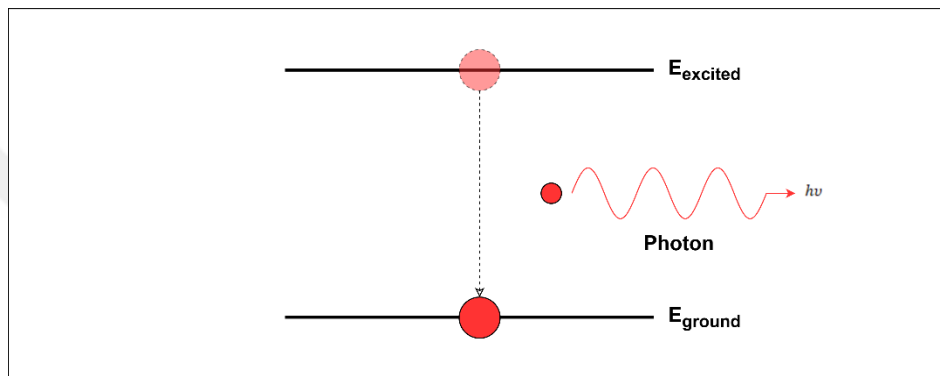


Figure 3.2: Spontaneous emission.

Stimulated Emission: Stimulated emission occurs when an atom, already in an excited state, encounters an incoming photon and responds by emitting a second photon that matches the first photon in energy, frequency, and phase. In this process, the photon prompts the atom to transition from a higher to a lower energy level, releasing a photon that carries away the exact energy difference. Because the two photons are identical in every aspect, the resulting light is coherent and amplified which is the principle of laser operation. The stimulated emission mechanism is given in **Figure 3.3**.

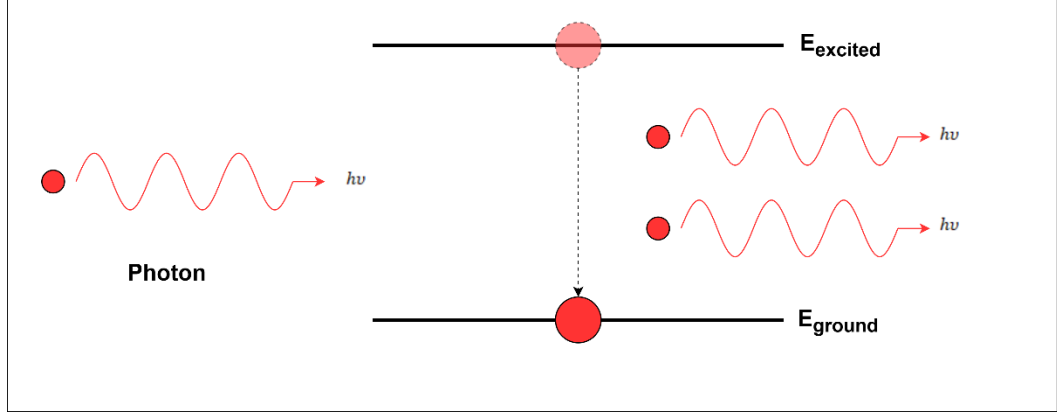


Figure 3.3: Stimulated emission.

Precise measurement of laser-atom interaction is crucial to evaluate atom energy levels and analyze details of atomic transitions. Saturation absorption spectroscopy is one of the effective techniques employed to measure transitions between atomic energy levels with precise accuracy. The technique enables high-resolution analysis of atom transitions in the absence of Doppler broadening [56].

The natural linewidth γ of the energy transition of the atoms in the upper level is determined by the natural lifetime of the atoms in the excited state. This lifetime is approximately 27.70 ns and 27.75 ns for the $5P_{1/2}$ level of ^{85}Rb and ^{87}Rb atoms respectively [50], [51]. The natural linewidths of Rb isotopes are calculated with equation (3.2).

$$\gamma = \frac{1}{2\pi\tau} \quad (3.2)$$

For ^{85}Rb :

$$\gamma = \frac{1}{2\pi\tau} = \frac{1}{2\pi(27.70 \text{ ns})} \cong 5.75 \text{ MHz} \quad (3.3)$$

For ^{87}Rb :

$$\gamma = \frac{1}{2\pi\tau} = \frac{1}{2\pi(27.75 \text{ ns})} \cong 5.74 \text{ MHz} \quad (3.4)$$

The natural linewidths of these two isotopes are almost the same because they both undergo the same atomic transition.

3.1. Velocity Distribution of Atoms

In this section, the absorption resonances that occur because of the interaction of the laser beam with the atomic gas will be discussed.

Velocity distribution of Rb atoms in the atomic vapor cell along the z direction is given with Maxwell-Boltzmann in equation (3.5) due to Rb atoms are in gas phase and in this case the velocity distribution of the atoms is described by the Maxwell-Boltzmann distribution according to the classical kinetic theory [57].

$$N = N_0 \frac{1}{V_0 \sqrt{\pi}} \exp \left[- \left(\frac{V_z}{V_0} \right)^2 \right] \quad (3.5)$$

Here, N_0 is atoms in the average velocity, V_0 is average velocity and V_z is the velocity of atoms in the z direction.

According to Maxwell-Boltzmann, atoms have such a velocity distribution that the velocity distribution can be shown by a Lorentzian model as in **Figure 3.4**.

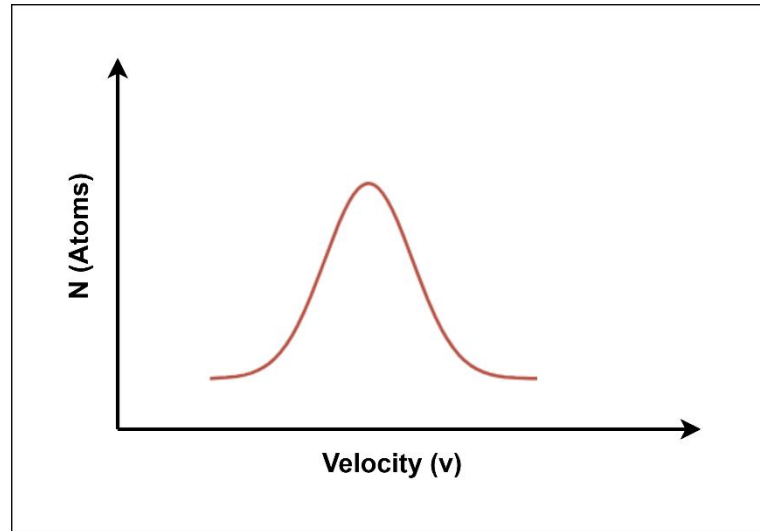


Figure 3.4: Maxwell-Boltzmann velocity distribution.

Atoms at rest, with a laser beam sent in the z-direction, will undergo an atomic transition only if the frequency of the laser beam is equal to the frequency difference between the two energy transitions. Equation (3.1) can be rewritten as equation (3.6).

$$E_{excited} - E_{ground} = \hbar\omega_{photon} \quad (3.6)$$

Here, $\hbar$ is the reduced Planck constant ($\hbar = h/2\pi$) and ω is the frequency of the laser beam ($\omega = 2\pi\nu$). The atoms inside the atomic vapor cell are under specific temperature and pressure values. Under these conditions, the non-stationary atoms have specific velocities. Therefore, a Doppler shift will occur due to their speeds. For the atoms to interact with the laser beam sent to the atomic vapor cell, the condition given in Equation 3.7 must be met.

$$\omega_L - \omega_0 = k \cdot v_z \quad (3.7)$$

Here ω_L is the frequency of the laser beam, ω_0 is the resonance frequency and k are the wave number of the laser beam. If the laser frequency of the beam and resonance frequency is the same ($\omega_L = \omega_0$), the condition is met where atoms with zero velocity. However, when it is considered atoms with non-zero velocities, the condition in equation (3.7) is satisfied only when $\theta = 90$.

$$k \cdot v_z = kv_z \cos \theta = kv_z \cos 90 = 0 \quad (3.8)$$

According to equation (3.7) and equation (3.8), in order to occur laser-atom interaction, the atoms must move perpendicularly to the direction of propagation of the laser beam. Since the laser beam interacts with the atoms as it passes through the atomic vapor cell, atoms absorb the laser photons when condition in the equation (3.7) is met, and transmitted light decreases which is sensed by photodetector. **Figure 3.5** shows the absorption resonance.

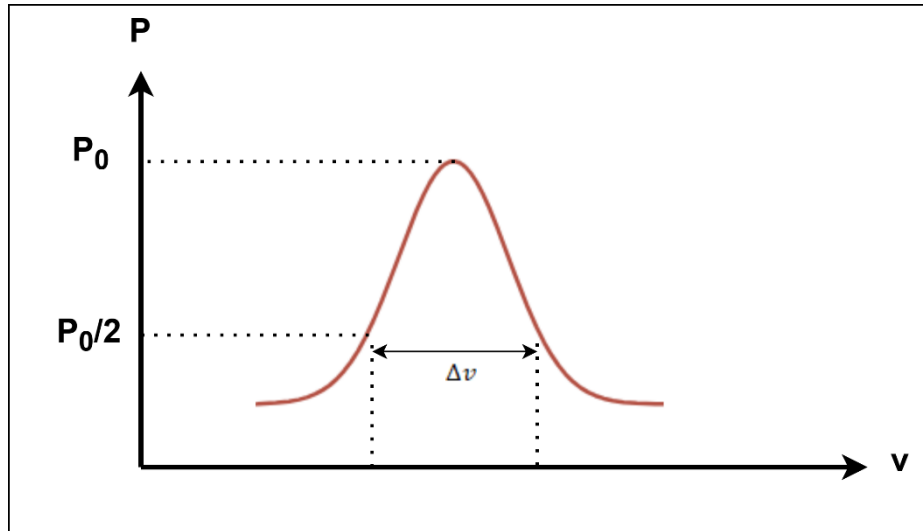


Figure 3.5: Frequency dependency of laser-atom interaction.

In **Figure 3.5**, absorption lines broaden around the resonance frequency, and it is not narrow shaped. There are two main reasons [2], [6]:

- **Natural linewidth broadening:** Lifetime of electrons to stay in the excited energy level.
- **Doppler broadening:** Velocity distribution of the atoms in the atomic vapor cell.

3.2. Natural Linewidth Broadening

Although the atoms making a transition between ground and excited states emit a photon with a well-defined frequency, spectral lines are not infinitely narrow [58]. Instead, emitted photons create a spectral line with a broadening from the resonance frequency shown in **Figure 3.6**.

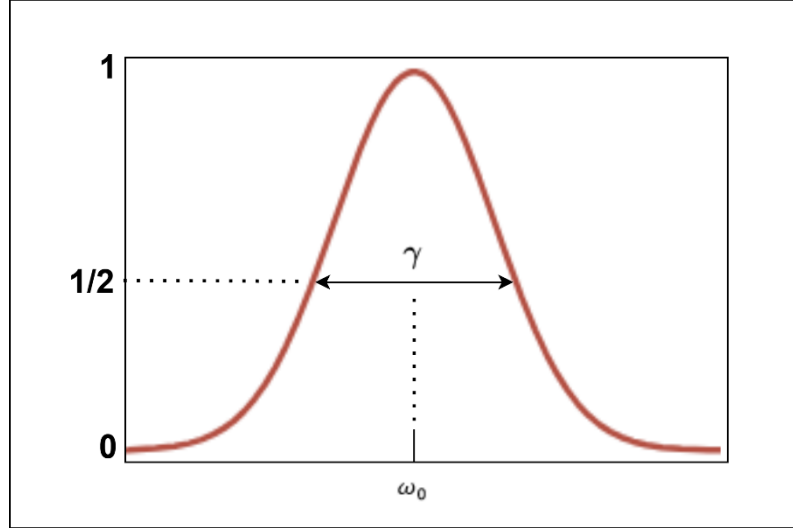


Figure 3.6: Natural linewidth broadening.

Due to Heisenberg's uncertainty principle, atoms stay in an excited state with their corresponding lifetime and eventually decay to the ground state by spontaneous emission shown in **Figure 3.2**.

Considering Heisenberg's uncertainty principle, uncertain energy of a level given in equation (3.9).

$$\Delta E \approx \frac{\hbar}{\Delta t} \quad (3.9)$$

By considering equations (3.6) and equation (3.9) becomes:

$$\Delta \omega \approx \frac{1}{\Delta t} \quad (3.10)$$

Due to this effect, spectral lines broaden around the resonance frequency with a Lorentzian shape since the excited state decays exponentially in time and this broadening is called natural linewidth broadening which depends only on the spectroscopic property of atoms [2], [6]. The spectral linewidth is determined by the time interval Δt and is typically expressed as the full width at half maximum (FWHM) of the corresponding spectral line.

3.3. Doppler Broadening

When atoms in the atomic vapor cell have a temperature above absolute zero, these atoms have a velocity distribution, and all move randomly inside the cell as a function of vapor temperature. The radiation absorbed or emitted by atoms due to their velocities under thermal equilibrium affects the interaction frequency and causes a broadening in the spectrum [3]. The thermal motion of these atoms is shown in **Figure 3.7**.

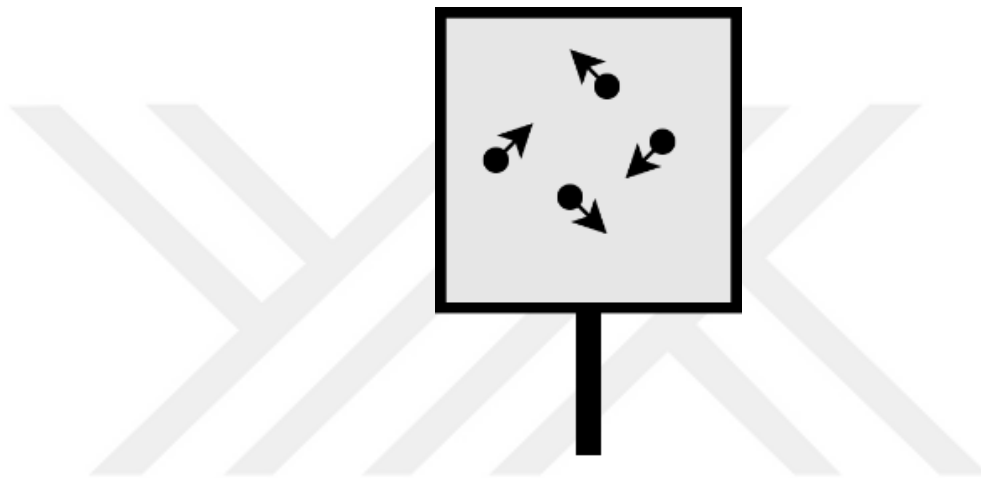


Figure 3.7: Thermal motion of atoms inside the atomic vapor cell.

The random motion of these atoms causes a Doppler shift in the resonance frequency. The atoms move towards the laser source encounter a frequency different from the laser frequency. This circumstance broadens the resonance frequency shown in **Figure 3.8**, and this phenomenon is called “Doppler Broadening” [59]. Therefore, broadened spectral lines are not able to fully give information about atomic structure [6].

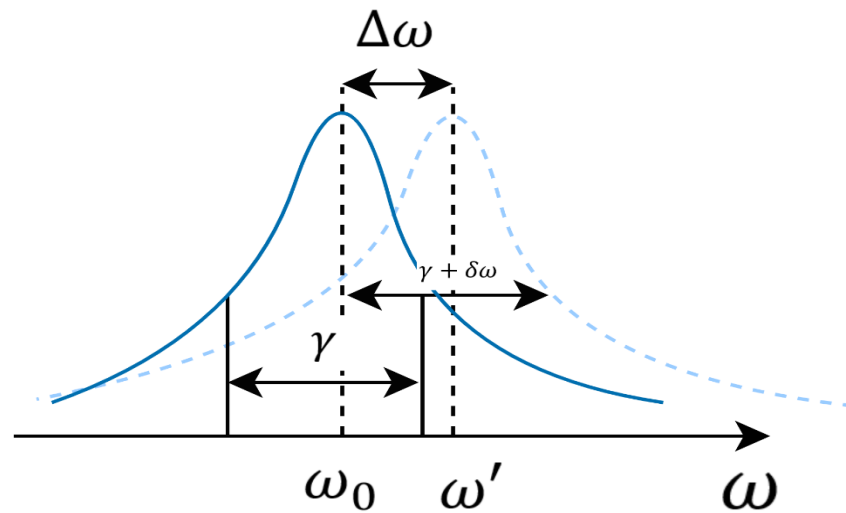


Figure 3.8: Doppler broadening of resonance frequency.

In order to investigate the Doppler broadening that causes broadening of spectral lines, first it must be considered the Doppler effect. If an atom moves relatively towards or in the opposite direction of laser light, the atom encounters different frequencies than laser (blue or red shifted) [59].

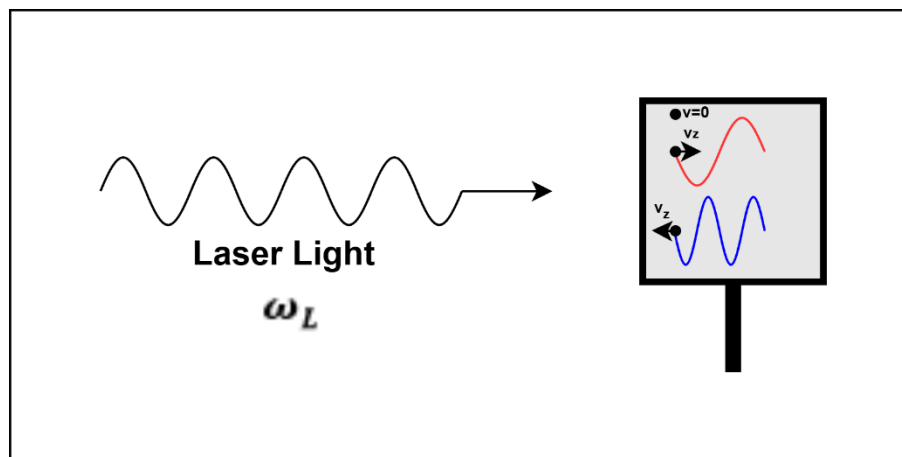


Figure 3.9: Blue and red shift by Doppler effect.

As seen in **Figure 3.9**, if atoms move towards the laser light, the laser frequency increases and (blue-shift); if atoms move away from the laser light, the laser frequency increases (red-shift).

If an atom inside the vapor cell moves relatively to the laser source in the z -direction, the Doppler shift frequency of the laser can be calculated as:

$$\omega_L = \omega_0 \left(1 - \frac{v_z}{c}\right) \quad (3.11)$$

Here, ω_L is the observed laser frequency, ω_0 is the resonance frequency when the atom is at rest, v_z is the velocity of the atom in the vapor cell in the z -direction and c is the speed of light.

If the atom moves towards the laser source ($v_z < 0$), then the observed laser frequency is bigger than the resonance frequency ($\omega_L > \omega_0$) and the atom observes a blue-shifted radiation. However, if the atom moves away from the laser source ($v_z > 0$), then the observed laser frequency is smaller than the resonance frequency ($\omega_L < \omega_0$) and the atom observes red-shifted radiation. Therefore, atoms that have a velocity distribution inside the vapor cell observe a wide range of frequencies and form a spectral line according to it.

In the thermal equilibrium of the vapor cell, the Maxwell-Boltzmann velocity distribution while the temperature of the atoms is T and their velocities between v_z and $(v_z + dv_z)$ can be written as in equation (3.12).

$$\rho_v(v_z)dv_z = \sqrt{\frac{m}{2\pi k_B T}} \exp\left(-\frac{mv_z^2}{2k_B T}\right) dv_z \quad (3.12)$$

Here, m is the mass of atoms inside the vapor cell and k_B is the Boltzmann constant. If v_z and dv_z in the equation (3.11) are rewritten as in equation (3.13).

$$v_z = c \left(\frac{\omega}{\omega_0} - 1\right), dv_z = \frac{c}{\omega_0} d\omega \quad (3.13)$$

And those are substituted into equation (3.12), the Maxwell-Boltzmann velocity distribution becomes:

$$\rho_\omega(\omega)d\omega = \frac{2}{\delta\sqrt{\pi}} \exp\left(-\frac{4(\omega - \omega_0)^2}{\delta^2}\right) d\omega \quad (3.14)$$

where $\delta = 2 \left(\frac{\omega_0}{c} \right) \sqrt{\frac{2k_B T}{m}}$ and the resulting linewidth is given in equation (3.15).

$$\Delta\omega_D = \delta\sqrt{\ln 2} = \frac{\omega_0}{c} \sqrt{\frac{8k_B T \ln 2}{m}} \quad (3.15)$$

As seen in the equation (3.15), the resulting linewidth $\Delta\omega_D$ have a Gaussian profile and is much larger than natural linewidth γ [3].

The natural line broadening is usually in the order of MHz and is quite narrow, while the Doppler broadening is in the order of several hundred MHz for atomic gases at room temperature [15]. For example, in the case of D₁ line of Rb atoms at room temperature the Doppler broadening $\Delta\omega_D \cong 500 \text{ MHz}$ and as mass m increases, the $\Delta\omega_D$ decreases; as temperature T increases, the $\Delta\omega_D$ increases [15].

In real conditions, natural linewidth broadening and Doppler broadening occur simultaneously. Thus, the total spectral line formed is specified by the Voigt profile, which is a combination of the Lorentz and Gaussian profiles [6], [59].

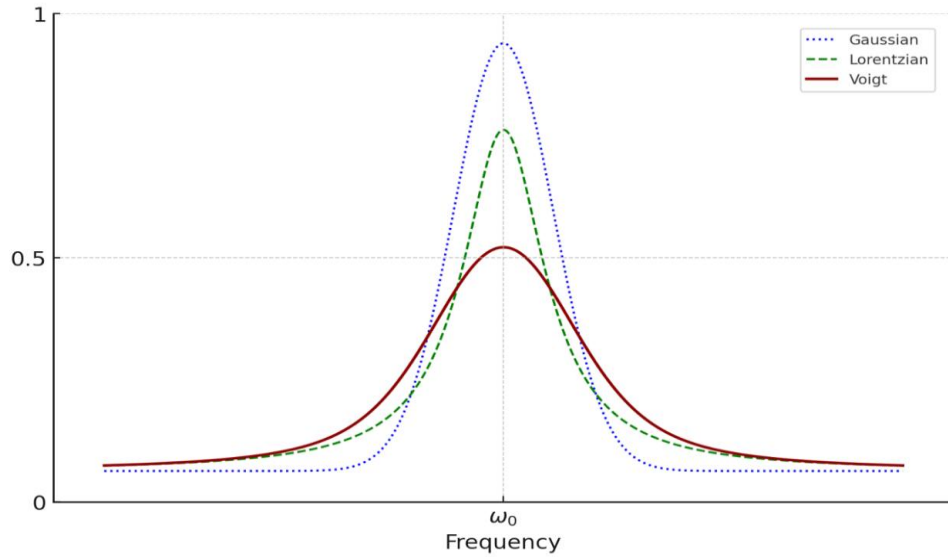


Figure 3.10: Voigt profile of broadening.

The Doppler broadening examined in this section makes it difficult to precisely determine the true resonance frequencies of atomic transitions due to frequency shifts

and broadening resulting from the thermal motions of the atoms [59]. The Doppler broadening $\Delta\omega_D$ at room temperature for Rb atoms has been calculated to be approximately 500 MHz and this value constitutes a significant resolution barrier in the study of atomic hyperfine transitions [15].

In order to overcome these limitations encountered in spectroscopic measurements, Doppler-free methods that operate independently of the Doppler effect are needed. The saturation absorption spectroscopy technique selectively excites only atoms in certain velocity groups with laser beams propagating in opposite directions and enables sharp absorption structures (Lamb dips) by eliminating Doppler broadening. As a result, the Doppler-free saturation absorption spectroscopy method is of critical importance in high-resolution measurements of narrow atomic transitions such as hyperfine structures [16]. Thanks to this method, high accuracy and precision are achieved in sensitive metrological applications such as atomic spectroscopy, laser frequency stabilization and atomic clocks.

4. DOPPLER-FREE SATURATION ABSORPTION SPECTROSCOPY

In the spectroscopic measurements, Doppler broadening occurs due to velocity distribution resulting from thermal motions of atoms and makes it difficult to observe clearly hyperfine transitions in the MHz range [15]. The most important of the Doppler-free techniques developed to overcome this problem is the saturation absorption spectroscopy (SAS) technique [56].

In the simple linear absorption spectroscopy, laser beam directly passes through the atomic vapor cell and is captured by a photodetector shown in **Figure 4.1**.

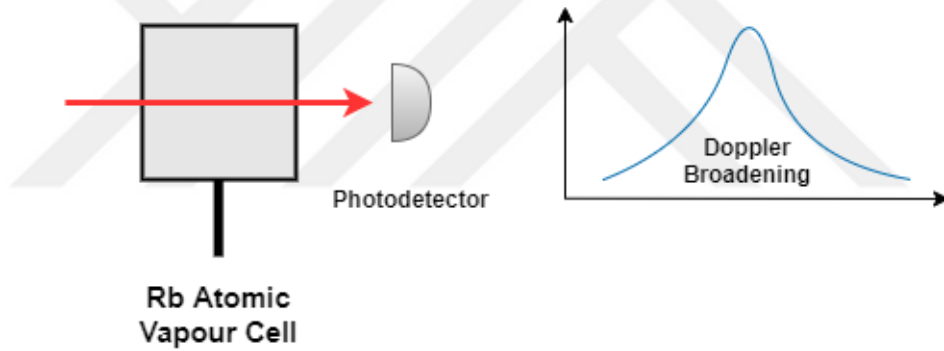


Figure 4.1: Linear absorption spectroscopy technique.

In this case, due to thermal motions of Rb atoms inside the vapor cell, Doppler broadening causes the broadening of spectral line. Thus, the spectral line is typically broadened and limited by Doppler effect.

To overcome this phenomenon, a specific velocity group selective technique is applied, which is called saturation absorption spectroscopy. In this technique, two counter-propagating laser beams with the same frequency from the same laser source are sent through the Rb atomic vapor cell in opposite directions [60]. The strong powered laser beam is called pump beam, and the weak powered laser beam is called probe beam. While the pump beam saturates Rb atoms of a specific velocity group,

the probe beam moving in the opposite direction interacts with this same atom group. As a result of this interaction, a narrow dip (Lamb dip) in the absorption of the probe beam is observed shown in **Figure 4.2** [56]. Thus, a high-resolution signal, free from the Doppler effect, shows the true atomic resonance frequency.

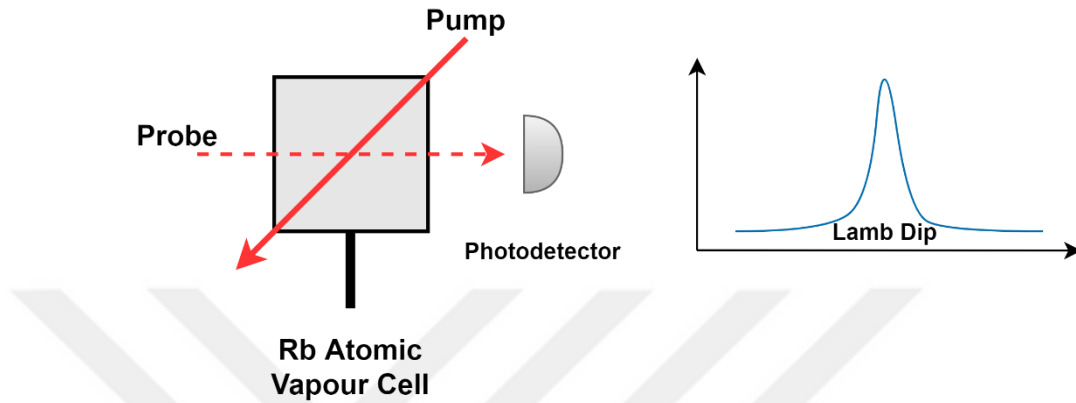


Figure 4.2: Saturation absorption spectroscopy technique.

The comparison of these two techniques is given in **Table 4.1**:

Table 4.1: Linear absorption spectroscopy and saturation absorption spectroscopy [2], [6], [56].

Feature	Linear Absorption Spectroscopy	Saturation Absorption Spectroscopy
Number of Beams	One	Two, Pump & Probe
Direction	One direction	Two opposite directions
Doppler Effect	Yes	No, Doppler-Free
Spectral Line Profile	Broad, Gaussian	Narrow, Lorentzian Lamb Dip
Area of Use	Simple spectroscopic measurements	Laser frequency locking, precision metrology

In the SAS technique, the strong pump beam saturates the Rb atoms and make them transparent and the weak probe beam overlaps with the pump beam in the Rb atomic vapor cell and captured by the photodetector to obtain absorption resonance signal. The strong pump beam is for exciting the Rb atoms to the higher energy level and

controlling the atom population in the excited state while the probe beam is for interacting with the same atoms the pump beam affected. If the pump beam is blocked from passing through the atomic vapor cell, only the Doppler broadening absorption spectrum is observed in the absorption signal shown in **Figure 4.3**.

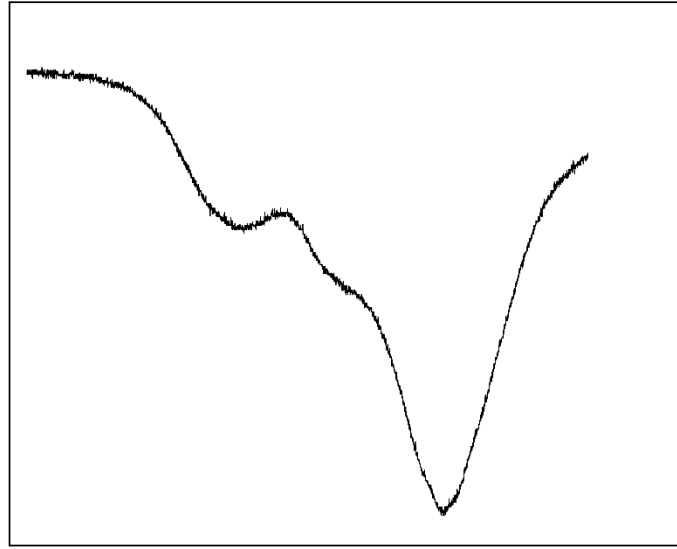


Figure 4.3: Blocked pump of $^{85}\text{Rb } 5S_{1/2}(F = 2) - 5P_{1/2}(F' = 2,3)$ and $^{87}\text{Rb } 5S_{1/2}(F = 1) - 5P_{1/2}(F' = 1,2)$ atomic transitions of D₁ line of the rubidium atom.

If the pump beam is not blocked and sent through the atomic vapor cell, counter-propagating pump and probe beams are overlapped inside the cell and sub-Doppler resonances appear in the absorption signal shown in **Figure 4.4**. Therefore, hyperfine atomic resonances can be obtained, and Doppler broadening is avoided. In **Figure 4.4**, $^{85}\text{Rb } 5S_{1/2}(F = 2) - 5P_{1/2}(F' = 2,3)$ atomic transitions and $^{87}\text{Rb } 5S_{1/2}(F = 1) - 5P_{1/2}(F' = 1,2)$ atomic transitions of D₁ line of the Rb atom is shown.

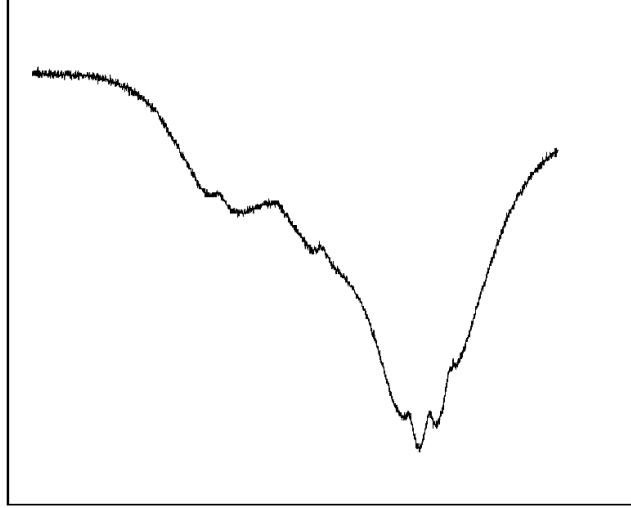


Figure 4.4: Unblocked pump of ^{85}Rb $5S_{1/2}(F = 2) - 5P_{1/2}(F' = 2,3)$ and ^{87}Rb $5S_{1/2}(F = 1) - 5P_{1/2}(F' = 1,2)$ atomic transitions of D_1 line of the rubidium atom.

In **Figure 4.4**, there are 6 sub-Doppler resonances that appeared in the absorption signal. ^{85}Rb atomic transitions from right to left:

- $5S_{1/2}(F = 2) - 5P_{1/2}(F' = 3)$
- $5S_{1/2}(F = 2) - 5P_{1/2}(F' = 2 \text{ co } 3)$
- $5S_{1/2}(F = 2) - 5P_{1/2}(F' = 2)$

^{87}Rb atomic transitions from right to left:

- $5S_{1/2}(F = 1) - 5P_{1/2}(F' = 2)$
- $5S_{1/2}(F = 1) - 5P_{1/2}(F' = 1 \text{ co } 2)$
- $5S_{1/2}(F = 1) - 5P_{1/2}(F' = 1)$

The atomic transitions ^{85}Rb of $5S_{1/2}(F = 2) - 5P_{1/2}(F' = 2 \text{ co } 3)$ and ^{87}Rb of $5S_{1/2}(F = 1) - 5P_{1/2}(F' = 1 \text{ co } 2)$ are crossover resonances that correspond to the average frequencies of these transitions.

4.1. Saturation Absorption Spectroscopy

Two counter-propagating pump and probe laser beams are sent through the Rb atomic vapor cell and overlapped in the middle. Due to the direction of these beams are different, they interact with different velocity group of Rb atoms. This interaction

creates different dips on the spectrum when the Maxwell-Boltzmann velocity distribution plot is equal to the resonance frequency, less than the resonance frequency, and greater than the resonance frequency [16].

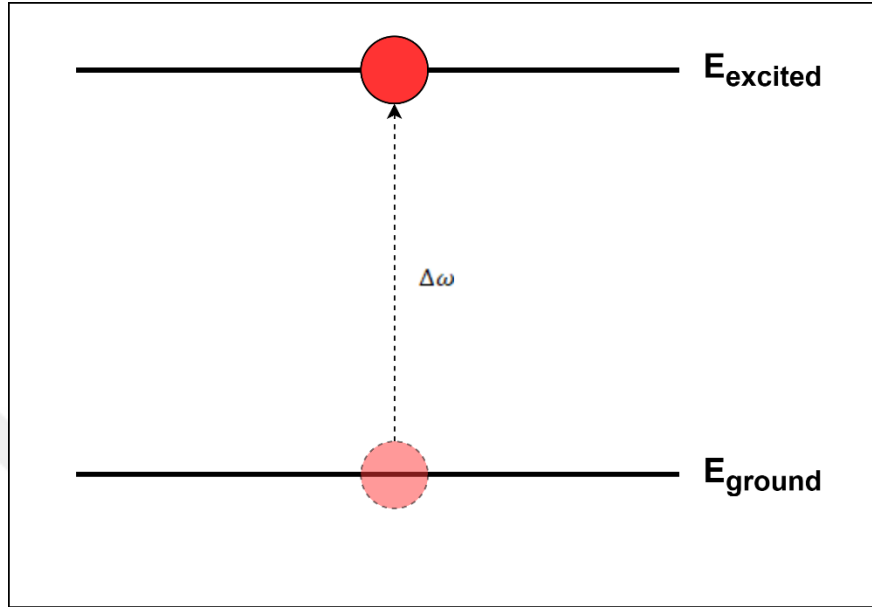


Figure 4.5: Atomic transition.

- If $(\omega_L > \omega_0)$, considering Doppler effect in the equation (3.11) the velocity of Rb atoms is opposite direction as the pump beam ($v_z < 0$) and blue-shifted. Due to pump and probe beams interacting with different velocity groups of atoms, they create dips in the different places in the Doppler-free saturation absorption spectrum. The dip created by the pump beam is much bigger than the dip created by the probe beam because the pump beam is stronger and excited more atoms in the ground energy level. The created Doppler-free saturation absorption spectrum is given in **Figure 4.5** [56].

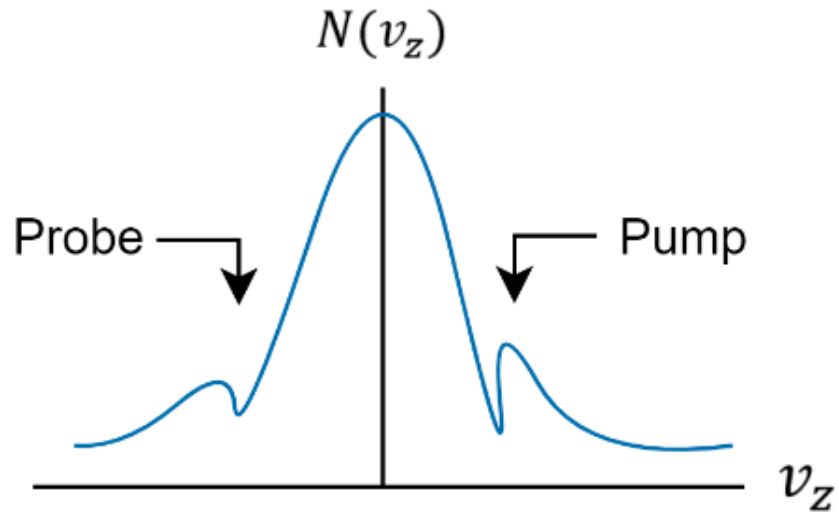


Figure 4.6: $\omega_L < \omega_0$ Doppler-free saturation absorption spectrum.

- If ($\omega_L < \omega_0$), considering Doppler effect in the equation (3.11) the velocity of Rb atoms is in the same direction as the pump beam ($v_z > 0$) and red-shifted. Due to pump and probe beams interacting with different velocity groups of atoms, they create dips in the different places in the Doppler-free saturation absorption spectrum. The dip created by the pump beam is much bigger than the dip created by the probe beam because the pump beam is stronger and excited more atoms in the ground energy level. The created Doppler-free saturation absorption spectrum is given in **Figure 4.6** [56].

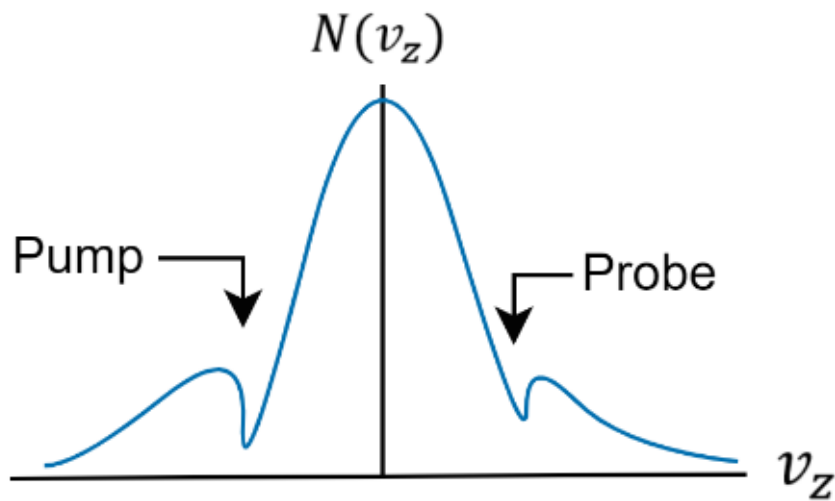


Figure 4.7: $\omega_L > \omega_0$ Doppler-free saturation absorption spectrum.

- If ($\omega_L = \omega_0$), the pump and probe beams interact with zero velocity atoms or velocities of atoms perpendicular to the pump and probe beams. In other words, the pump and probe beams interact with the same group of atoms. As a result, the collapse occurs at the resonance frequency called Lamb dip. The created Doppler-free saturation absorption spectrum is given in **Figure 4.7** [56].

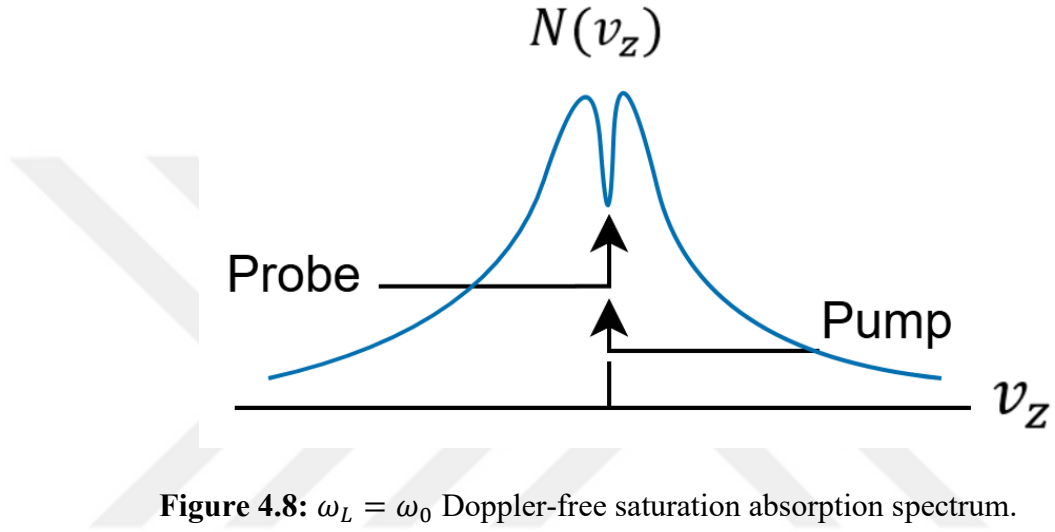


Figure 4.8: $\omega_L = \omega_0$ Doppler-free saturation absorption spectrum.

4.2. Crossover Resonances

As discussed in **Section 4.1**, if the pump and probe beams interact with the zero velocity atoms or velocities of atoms perpendicular to the pump and probe beams, the Lamb dips appear in the Doppler-free saturation absorption spectrum, thus these beams affect the same group of atoms. If the frequency of pump and probe beams is exactly half of the two atomic transitions and the atoms have some specific velocity group, the pump and probe beams can interact those atoms because of their specific velocity vectors. For example, when there are two atomic transitions (ω_1 and ω_2) the atoms may be in such a velocity group that the pump beam excites these atoms at ω_1 , while the same atoms absorb the probe beam at ω_2 or vice versa. Consequently, these atoms are saturated with the pump and probe beams simultaneously [61]. This leads to a fall in the Doppler-free saturation absorption spectrum and creates a Lamb dip shown in **Figure 4.8**.

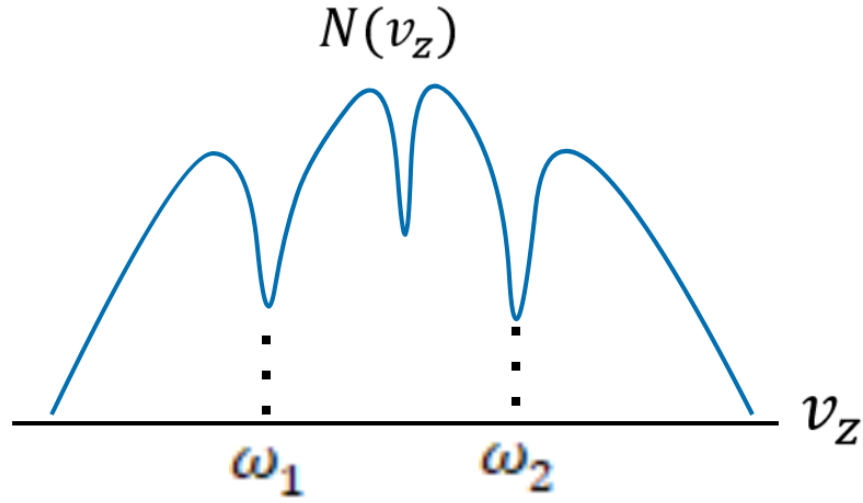


Figure 4.9: Crossover resonance.

In **Figure 4.9**, the velocity configuration that can be led to form direct and crossover resonances are given [61].

- In the first case, the pump and probe frequencies are ω_1 and the atom has zero velocity: This zero-velocity atom resonates only to the ω_1 transition $\rightarrow$ Direct resonance (Lamb dip) [61].
- In the second case, the pump and probe frequencies are ω_2 and the atom has zero velocity: This zero-velocity atom resonates only to the ω_2 transition $\rightarrow$ Direct resonance (Lamb dip) [61].
- In the third case, the observed frequencies of the pump and probe beams by the atom are shifted due to velocity vector of the atom. Thus, the atom resonates ω_2 transition with the pump beam and ω_1 transition with the probe beam $\rightarrow$ Crossover resonance [61].
- In the fourth case, the observed frequencies of the pump and probe beams by the atom are shifted due to velocity vector of the atom. Thus, the atom resonates ω_1 transition with the pump beam and ω_2 transition with the probe beam $\rightarrow$ Crossover resonance [60].

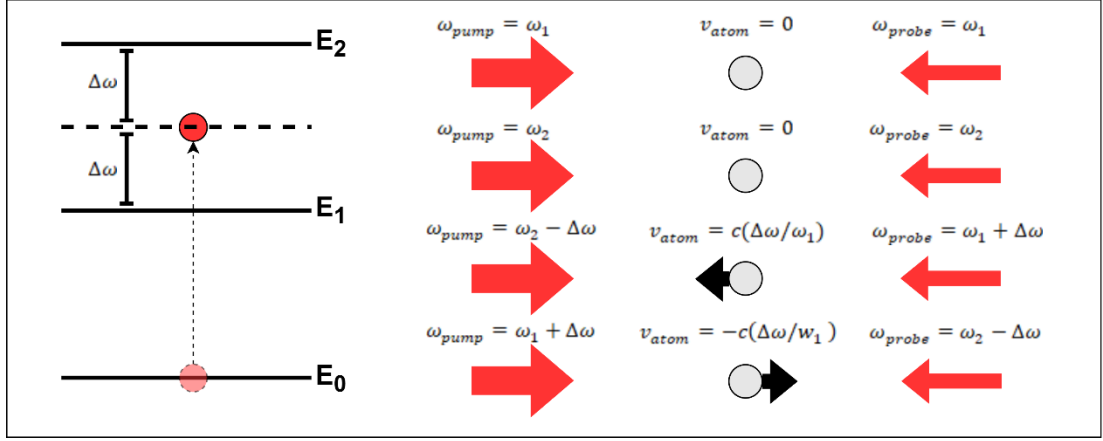


Figure 4.10: Formation for direct and crossover resonances [60].

These crossover peaks can be relatively intense—sometimes even exceeding the strength of the direct resonances [62]. Crossover resonances are used as frequency references in spectroscopic measurements. These resonances contribute significantly to the precise determination of fundamental transitions and frequency calibration. Crossover resonances, especially observed by the SAS method in spectroscopic measurements of alkali atoms such as rubidium and caesium, play a critical role in the precise frequency determination of hyperfine transitions [63].

5. EXPERIMENT

The experimental setup in which the observation of Doppler-free saturation absorption resonances is given in **Figure 5.1**. In order to adjust the polarization states and beam powers of the pump and probe, the optical setup was set up in the laboratory as shown in the figure.

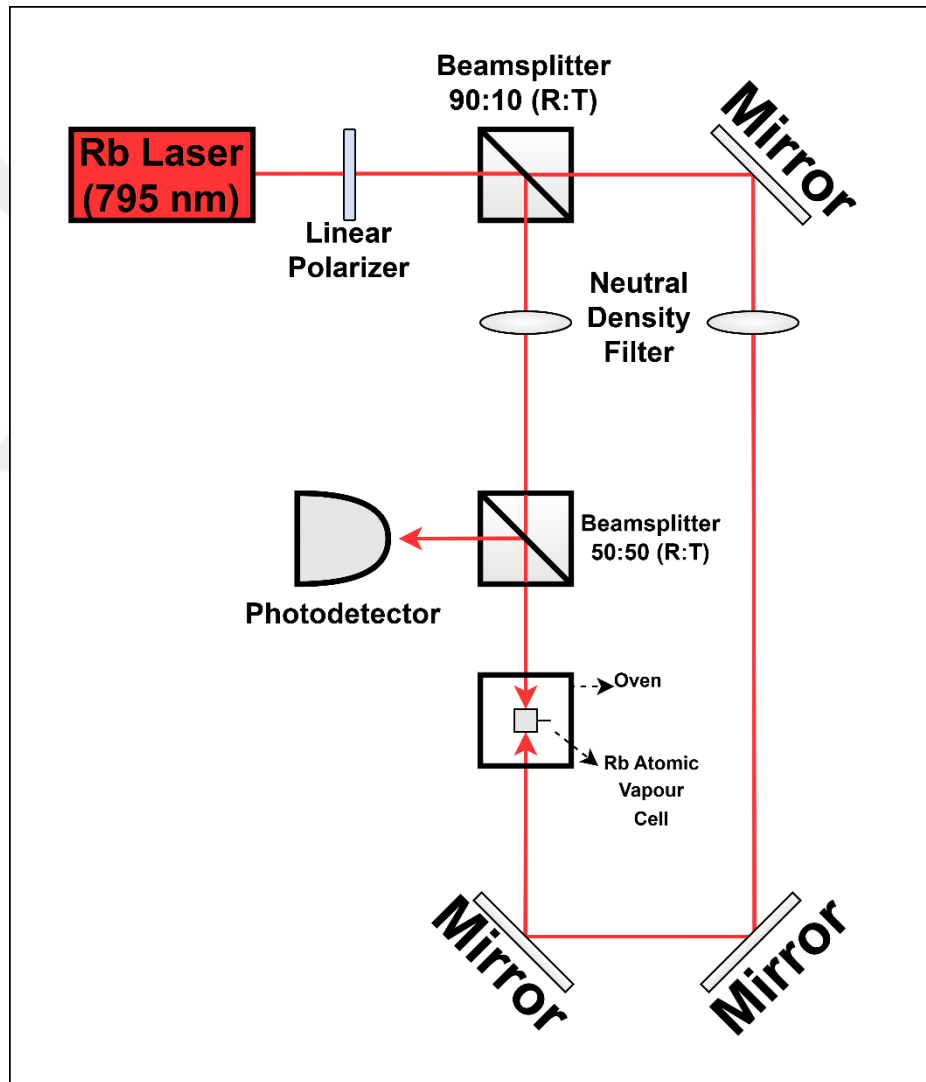


Figure 5.1: Experimental setup.

In the saturation absorption spectroscopy setup, a 795 nm laser beam first passes through the linear polarizer to create a linearly polarized laser beam, and the beam

splits into two beams by a beamsplitter- pump and probe. Therefore, two beams have the same frequency but different power. The pump has a relatively stronger intensity than the probe beam. Neutral density filters are used to determine the pump and probe beam powers. In the middle of the Rb atomic vapor cell, the pump and probe beams are overlapped, and the probe beam passed through the atomic vapor cell is captured by a photodetector. Finally, Doppler-free saturation absorption resonances are observed by an oscilloscope.

The experimental setup that is built in the laboratory is given in **Figure 5.2**.

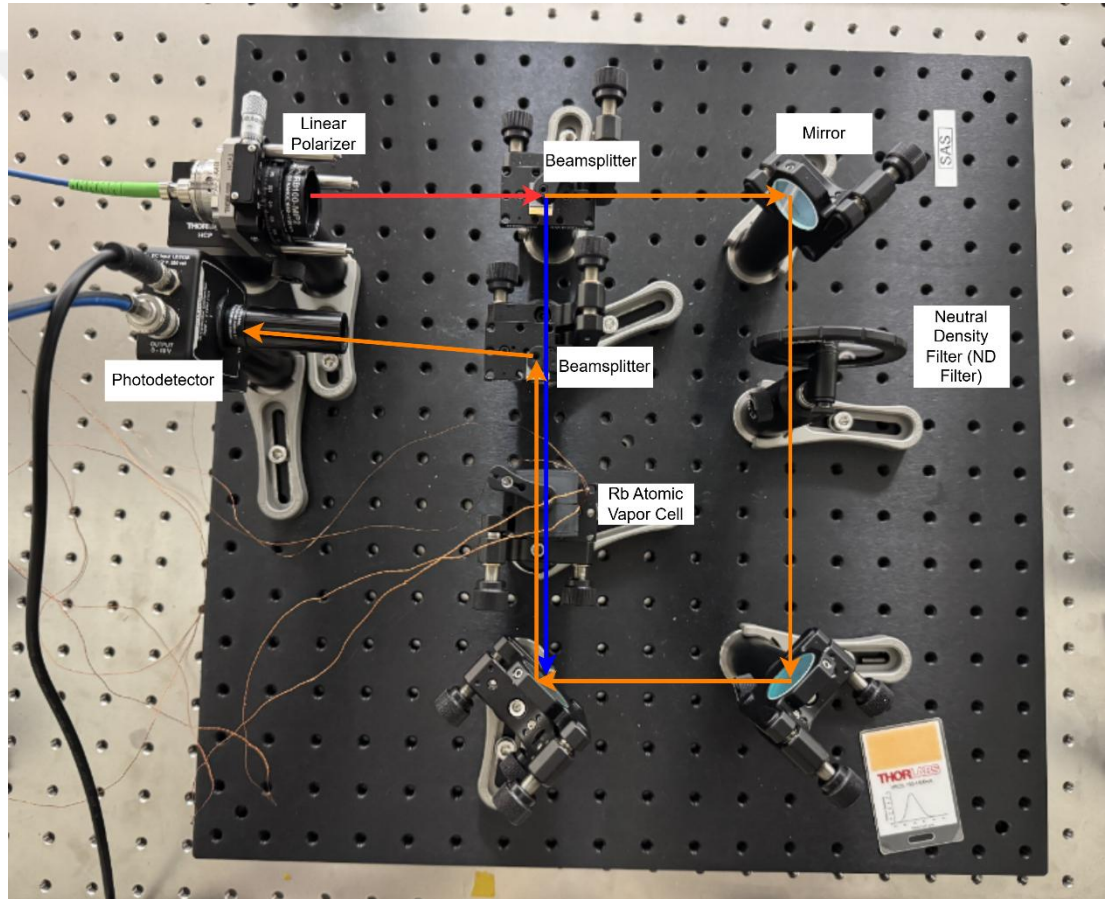


Figure 5.2: Experimental setup in the laboratory.

In the experiment, polarization states of the pump and probe beams need to be adjusted. Since light is an electromagnetic wave, it has an electric field $\vec{E}$ and a magnetic field $\vec{B}$ oscillating perpendicularly to the propagation vector. Polarization defines how the direction of oscillation of the electric field vector $\vec{E}$ of an electromagnetic wave

changes in space [6]. Polarization types are examined in three groups: linear, circular and elliptical and given in **Figure 5.3a**.

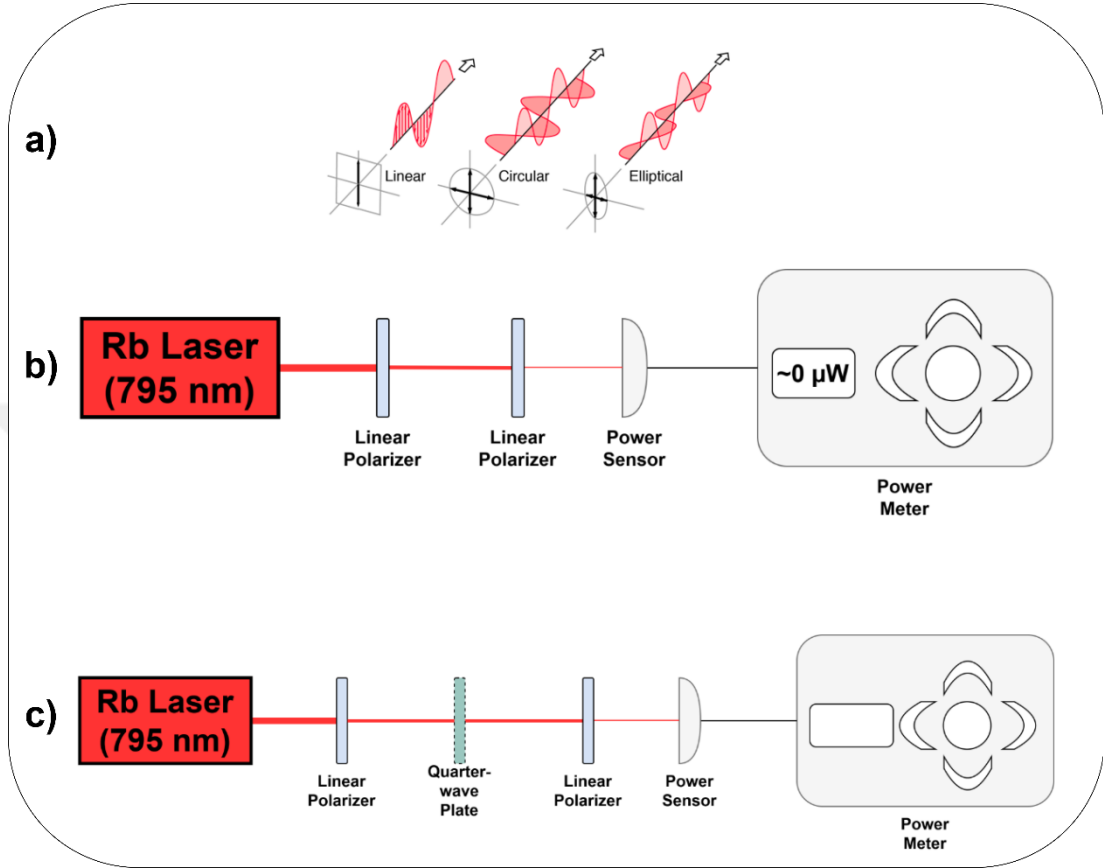


Figure 5.3: a) Polarization types [64]. b) Linear polarization setup. c) Circular polarization setup.

In the experiment, the pump and probe beams are polarized linearly and circularly. In order to create a linearly or circularly polarized beams, linear polarizer and quarter-wave plate are used.

In order to create a linearly polarized light, a linear polarizer is used. The linear polarizer is put in front of the incident beam, thus only the electric field component aligned with the axis of linear polarizer is transmitted. Therefore, the incident beam is linearly polarized. The setup for creating a linear polarized beam is given in **Figure 5.3b**.

In **Figure 5.3b**, the optic power meter measures near zero watt (W). This means, those two linear polarizers are adjusted perpendicularly, and no light is measured by

the optic power meter. As a result, if only one of the linear polarizers is used in front of the laser beam, the laser beam becomes linearly polarized.

In order to create a circularly polarized light, a linear polarizer and a quarter-wave plate are used. The linear polarizer is put in front of the incident beam, thus only the electric field component aligned with the axis of linear polarizer is transmitted. Therefore, the incident beam is linearly polarized. In addition, if the axis of a quarter-wave plate is placed 45° with respect to linear polarizer axis, it creates an optical path difference of $\lambda/4$ between the two perpendicular components of the light. Thus, the phase difference between the two perpendicular components of the linearly polarized light is $\pi/2$, resulting in circularly polarized light beam [6]. The setup for creating a linear polarized beam is given in **Figure 5.3c**.

If the electric field vector $\vec{E}$ of circularly polarized beam rotates clockwise with respect to its propagation direction, the beam is right-handed circularly polarized σ^+ . However, if the electric field vector $\vec{E}$ of circularly polarized beam rotates counterclockwise with respect to its propagation direction, the beam is left-handed circularly polarized σ^- [6].

To create a circularly polarized beam, two linear polarizers whose polarization axes are perpendicular to each other are used. Thus, no light passes through the linear polarizers. After a quarter-wave plate is placed between the linear polarizers and it is rotated until zero watt is measured by the optic power meter. If the quarter-wave plate is rotated 45° clockwise, the beam is right-handed circularly polarized σ^+ , but it is rotated 45° counterclockwise, the beam is left-handed circularly polarized σ^- .

5.1. Properties of Laser, Rubidium Atomic Vapor Cell and Shapal

5.1.1. Laser Module

The laser used in this experiment is a 795 nm Vescent D2-100 DBR (Distributed Bragg Reflector) Laser Module. It is chosen due to its high power (~ 100 mW) and a low linewidth feature. It has a 35 dB optical isolator for preventing back reflection of unwanted lights reaching the laser cavity and causing mode hop. An example of Vescent D2-100 DBR laser module is given in **Figure 5.4**.



Figure 5.4: Vescent D2-100 DBR laser module.

The technical properties of DBR Laser Module are given in **Table 5.1**.

Table 5.1: Technical properties of Vescent D2-100 DBR laser module.

Laser Type	DBR (Distributed Bragg Reflector)
Wavelength	795 nm
Operation Mode	Continuous wave (CW)
Linewidth	~ 1 MHz
Output Power	~ 100 mW
Isolation	> 35 dB
Beam Diameter	1.1 mm

5.1.2. Laser Controller Module

The temperature and current controls of the laser module are made by Vescent D2-105-500 Laser Controller Module. It provides precise current and temperature control

of the laser diode and ensures stability and wavelength control of the laser output. An example of Vescent D2-105-500 Laser Controller Module is given in **Figure 5.5**.



Figure 5.5: Vescent D2-105-500 laser controller module.

The technical properties of Vescent D2-105-500 Laser Controller Module are given in **Table 5.2**.

Table 5.2: Technical properties of Vescent D2-105-500 laser controller module.

Current Control Range	0-500 mA
Current Noise Density	$< 200 \text{ pA}/\sqrt{\text{Hz}}$
Temperature Stability	$< 0.002 \text{ }^{\circ}\text{C}$
Temperature Coefficient	$< 5 \text{ } \mu\text{A}/^{\circ}\text{C}$
Temperature Setpoint Range	1-50 $^{\circ}\text{C}$
Long Term Stability (T2)	$\sim 1 \text{ mK/day}$

5.1.3. Laser Servo Module

Vescent D2-125-PL Laser Servo Module generates PID control signals for laser frequency stabilization. It is especially used for frequency locking to atomic resonances. An example of Vescent D2-125-PL Laser Servo Module is given in Figure 5.6.



Figure 5.6: Vescent D2-125-PL laser servo module.

The technical properties of Vescent D2-125-PL Laser Servo Module are given in Table 5.3.

Table 5.3: Technical properties of Vescent D2-105-500 laser controller module.

Input and Output Impedance	50 Ω
Bandwidth	> 10 MHz
Proportional Gain (ref to DC Error)	-66 to +6 dB
Ramp Amplitude	± 5 V
Ramp Frequency	500 Hz

The complete laser system is given in **Figure 5.7**.



Figure 5.7: The complete laser system.

5.1.4. Rubidium Atomic Vapor Cell

The Rubidium atomic vapor cell is produced in the TÜBİTAK National Metrology Institute Atomic Sensors Laboratory. The rubidium metal is filled inside the glass cell. Due to the project confidentiality procedures, the atomic vapor cell production phase cannot be mentioned. The cubic shaped rubidium atomic vapor cell with a dimension of 4x4x4 mm and borosilicate glass type used in the experiment is given in **Figure 5.8**.

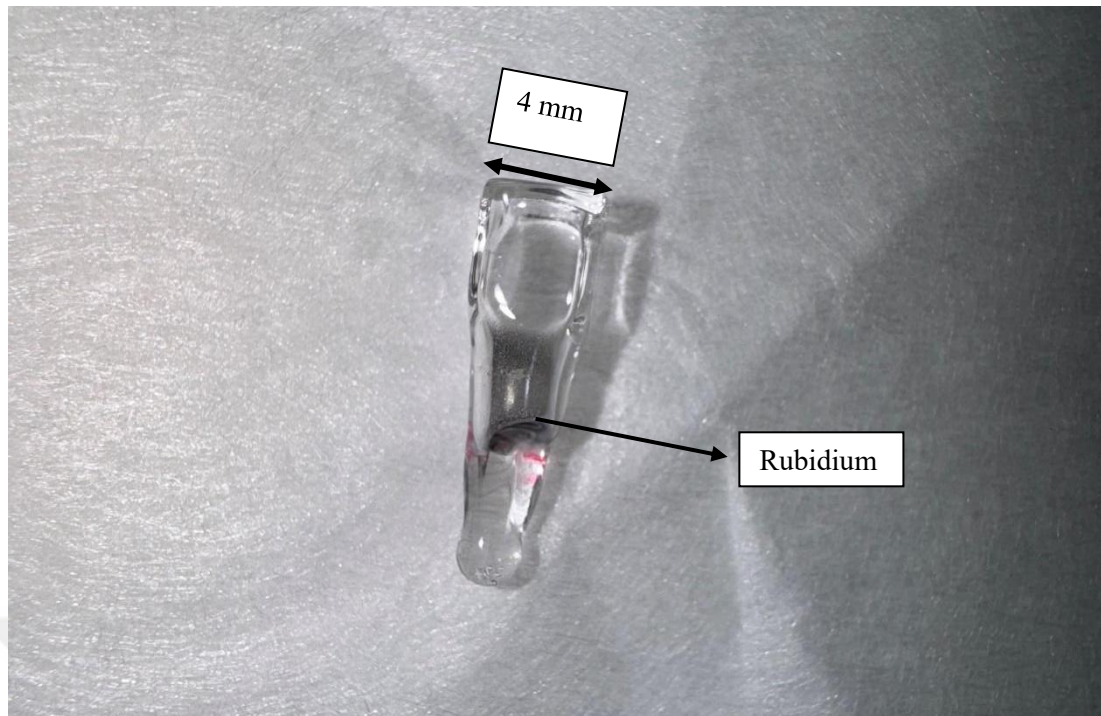


Figure 5.8: Rubidium atomic vapor cell.

5.1.5. Shapal

The atomic vapor cell is placed into a shapal material which is used as an oven around the cell. It can withstand high temperatures, has good heat conduction and distribute the temperature homogeneously. Therefore, Rb atomic vapor is heated homogeneously. The material was supplied by Precision Ceramic USA and shaped according to the produced atomic vapor cell. The shapal used in the experiment is given in **Figure 5.9**.

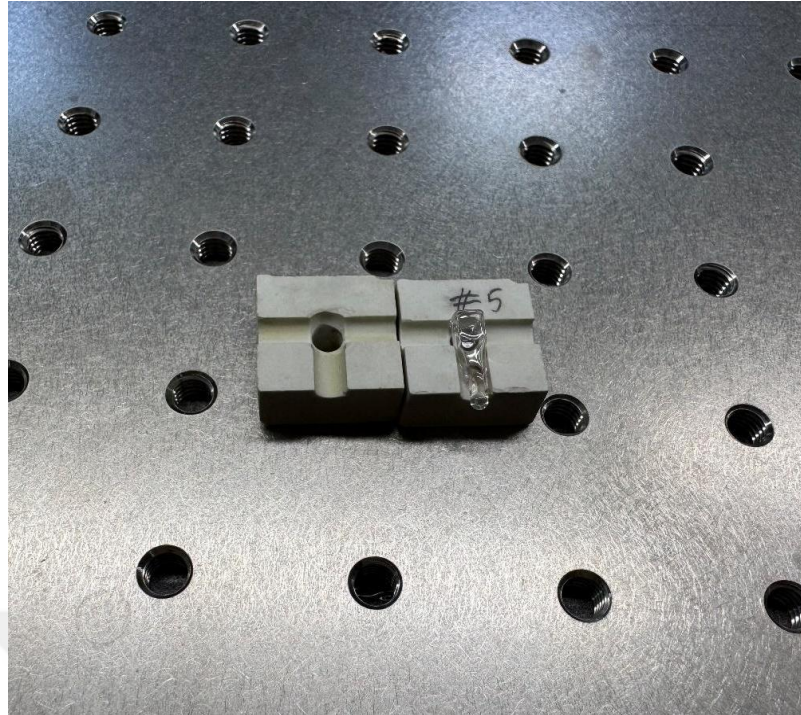


Figure 5.9: Shapal material.

The heater and PT1000 temperature sensor are placed onto the shapal given in **Figure 5.10**.

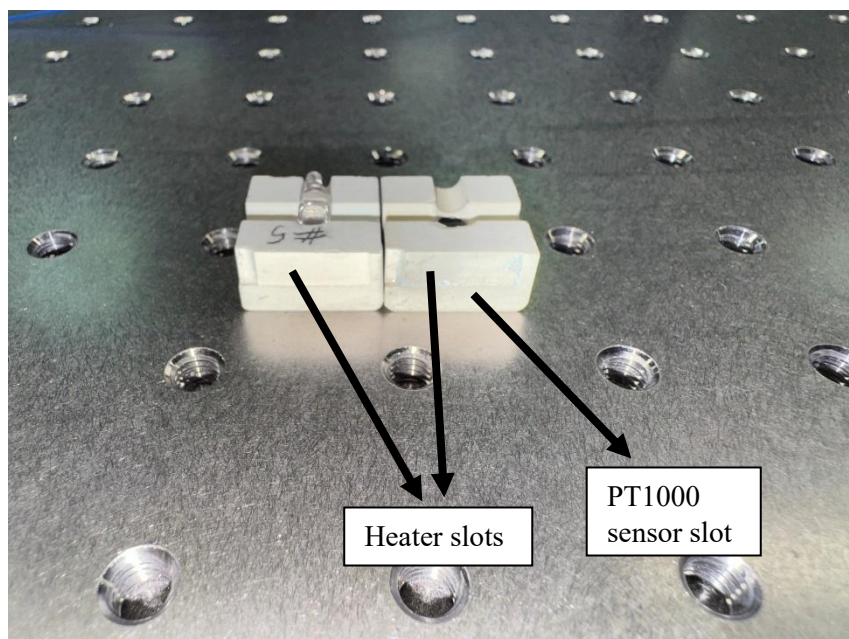


Figure 5.10: Heater and PT1000 sensor.

It was operated at the desired temperature values with the heater placed on the shapal. The necessary temperature control cards and software were designed and arranged in the Atomic Sensors Laboratory. The card block used is given in **Figure 5.11**.

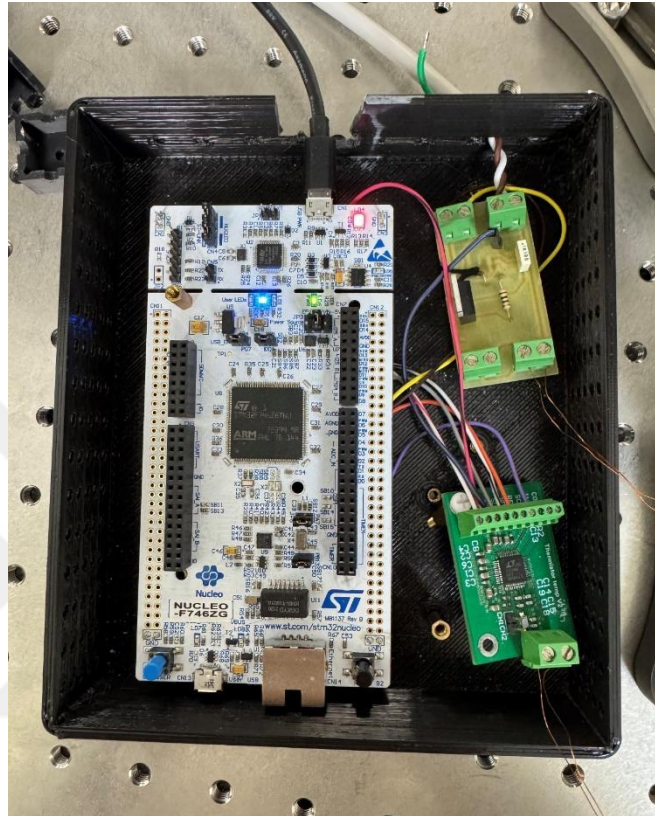


Figure 5.11: Temperature control card.

The shapal material is enclosed by a heat isolation material. It is used for preventing temperature instability around the atomic vapor cell. The complete atomic head module is given in **Figure 5.12**.

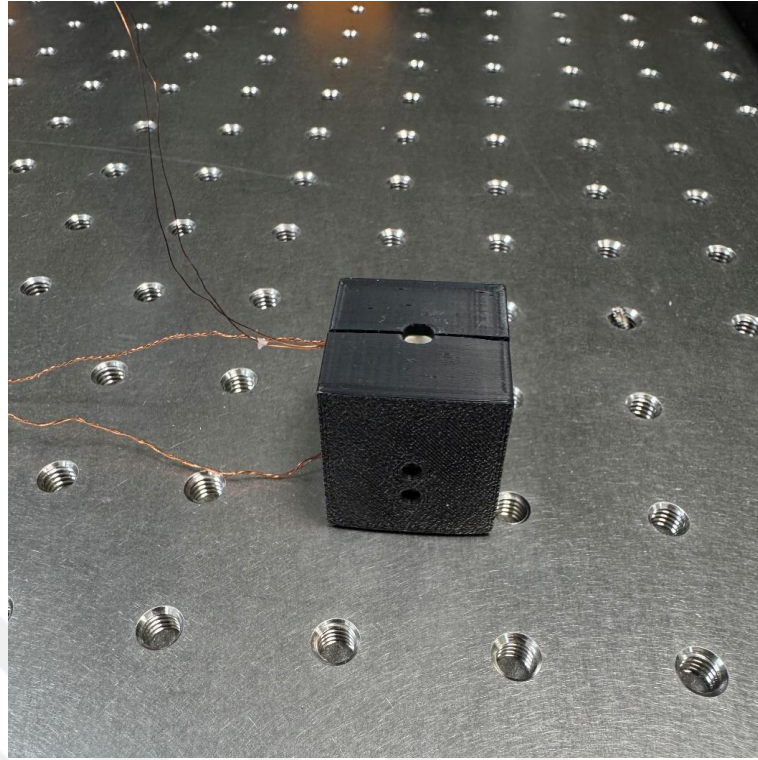


Figure 5.12: The atomic head module.

The temperature control of the atomic vapor cell is carried out with a feedback mechanism and in this process, the PT1000 sensor is used for temperature measurement and the PWM (Pulse Width Modulation) method is used for heating control. PT1000 is a sensor whose resistance value changes depending on the temperature and the instantaneous temperature of the cell is read by the microcontroller via this sensor. This temperature value is compared with the predetermined set temperature and the difference is evaluated with a PID (Proportional-Integral-Derivative) control algorithm. The PID algorithm controls the power applied to the heater by adjusting the duty cycle of the PWM signal to minimize this difference. The heater is operated with on-off pulses at certain rates instead of a fixed voltage by the PWM and thus the heating is performed more precisely and stably. As a result, the temperature value of the atomic vapor cell is shown simultaneously by a computer.

6. RESULTS

In the experiment, the results of experimental measurements on the 795 nm D₁ transition line of rubidium atoms are presented. How atomic transitions change are investigated by changing three basic parameters:

- (i) the temperature of the atomic vapor cell
- (ii) the polarization states of the pump and probe laser beams
- (iii) the powers of the pump and probe laser beams

The linewidths of the atomic transitions determine how well the hyperfine structure is formed. Lower linewidth values of atomic resonances mean it is closer to the natural linewidth γ . This offers sensitive measurements in terms of atomic sensors technologies.

The D₁ line atomic transitions of rubidium is given in **Figure 6.1**. As seen in the figure, there are four Doppler resonances: From right to left, $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2}$, $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2}$, $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2}$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2}$ atomic transitions are shown. ^{85}Rb atomic transitions are in the middle of the spectrum and ^{87}Rb atomic transitions are on the edges of the spectrum.

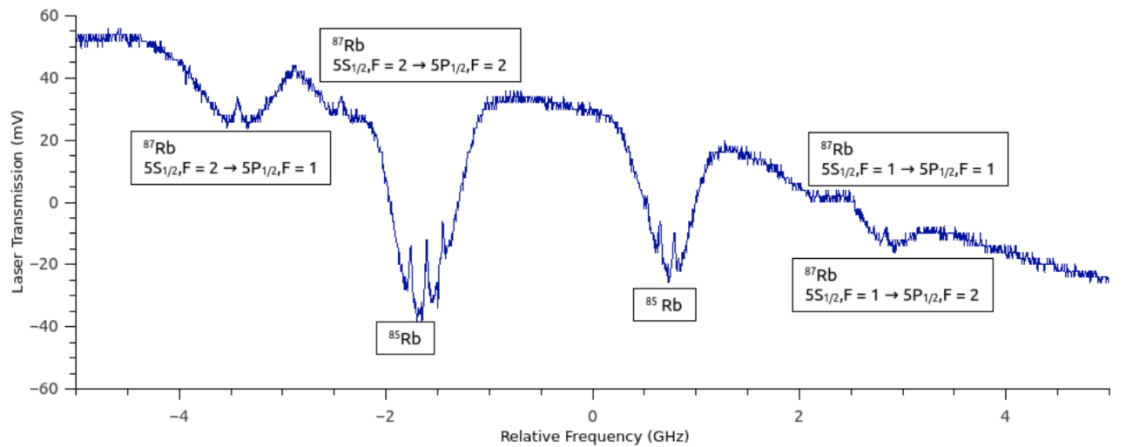


Figure 6.1: D₁ Line atomic transitions of rubidium [65].

In the experiment, the 795 nm laser is swept into the range of D_1 transitions of the rubidium atom and coupled into a fiber. The fiber is connected to a fiber port to provide laser beam to the experimental setup. The optical setup as shown in **Figure 5.2** is installed. The pump and probe laser beams are overlapped inside the rubidium atomic vapor cell and the probe beam passed through the cell is captured by the photodetector and atomic transitions are observed by an oscilloscope. The results are saved to a computer to analyze them after.

Since the x-axis of the oscilloscope is time, in order to convert the time axis to relative frequency, the frequency difference between the atomic transitions of ^{87}Rb $5S_{1/2} (F = 2) - 5P_{1/2} (F = 2)$ & $5S_{1/2} (F = 2) - 5P_{1/2} (F = 1) = 814.5 \text{ MHz}$ is used [66]. The time axis is recalculated accordingly. In addition, the y-axis of the oscilloscope is amplitude (V), but it is rearranged as absorption %.

Considering this, the following three situations were examined in this study:

- (i) The temperature of the atomic vapor cell is changed by specific amounts by the temperature control card, and changes in the atomic resonances are observed.
- (ii) The polarization states of the pump and probe beam is changed by the polarizers and quarter-wave plates, and changes in the atomic resonances are observed.
- (iii) The laser powers of the pump and probe beams are changed by the neutral density filters, and changes in the atomic resonances are observed.

6.1. Effect of Temperature of Atomic Vapor Cell

When the temperature of atomic vapor cell is changed, the atom density inside the cell changes accordingly. Therefore, the atom population that interacts with the pump laser changes. The number of atoms that interact with the pump laser affects the atomic resonances and alters them. Since this phenomenon directly affects the absorption of laser radiation in the vapor cell, the effect of the cell temperature on the resonance absorption profiles is studied.

Rubidium metal accumulates at the tail of the atomic vapor cell when the cell is at room temperature, as shown in **Figure 5.7**. To diffuse the rubidium metal at the tail to the center of the cell where the pump and probe beams overlap and the absorptions

occur, the cell is heated. As the cell is heated, due to the low vapor pressure of rubidium metal, the rubidium atoms gradually evaporate and create a sufficient atom density for conducting a saturation absorption spectroscopy experiment. When the temperature reaches a certain level, the laser is completely absorbed by the atoms and there will be no atomic resonances observed since there is no probe beam captured by the photodetector. In the experiment, the temperature of the atomic vapor cell is changed between 40-130 °C and atomic resonances are recorded. The pump power is set as 1 mW and the probe is set as 40 μ W.

Doppler-free saturation absorption spectrum of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions are observed in **Figure 6.2**. In **Figure 6.3**, the simplified version of the graphic is given.

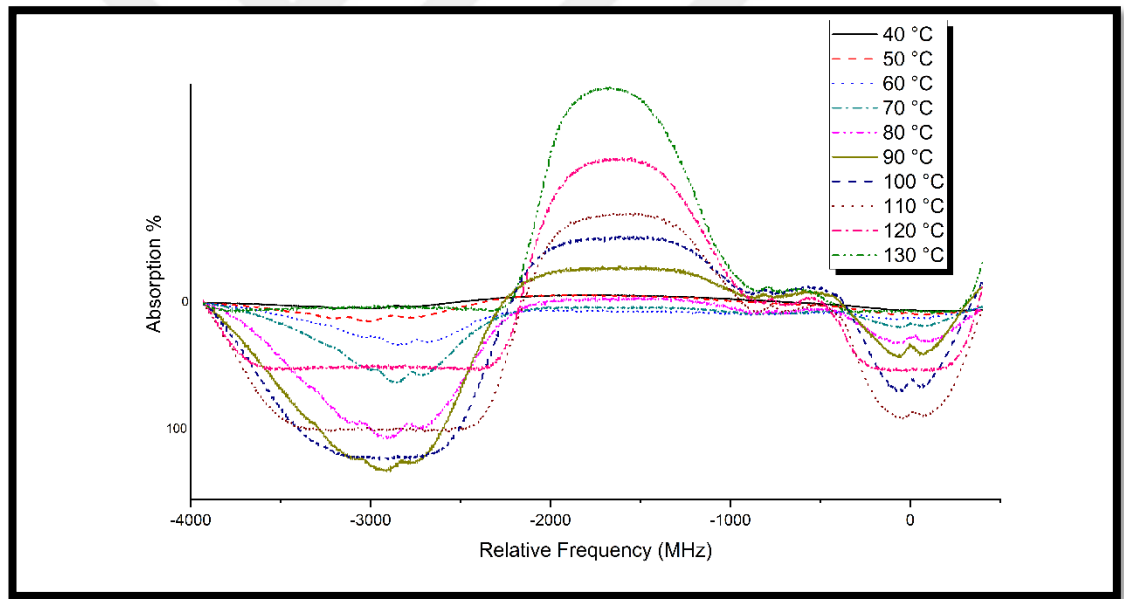


Figure 6.2: $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions with different cell temperatures.

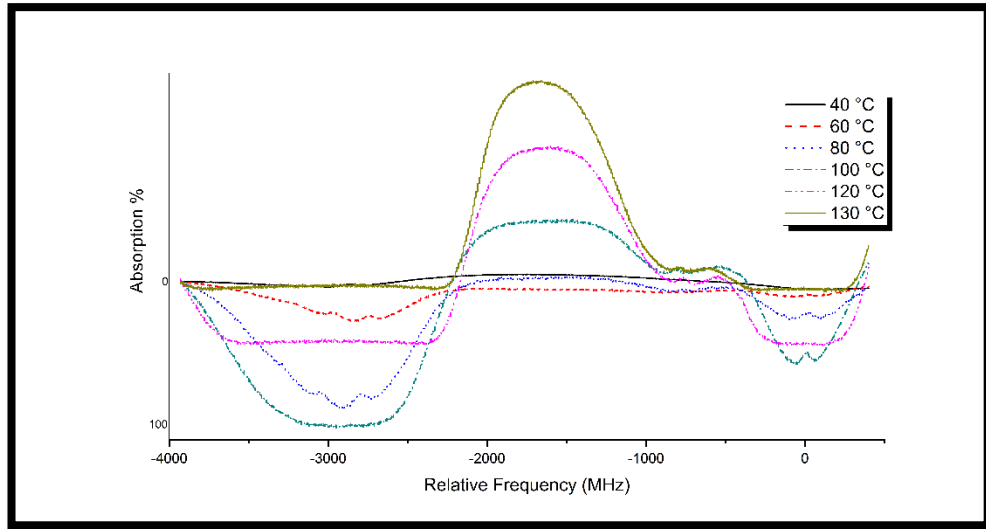


Figure 6.3: The simplified of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions with different cell temperatures.

Doppler-free saturation absorption spectrum of $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions are observed in **Figure 6.4**. In **Figure 6.5**, the simplified version of the graphic is given.

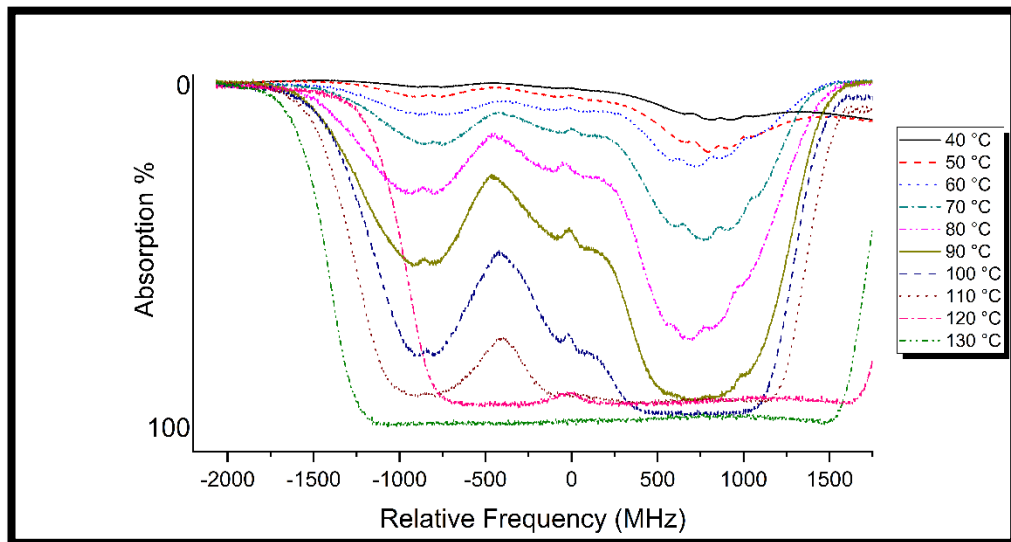


Figure 6.4: $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions with different cell temperatures.

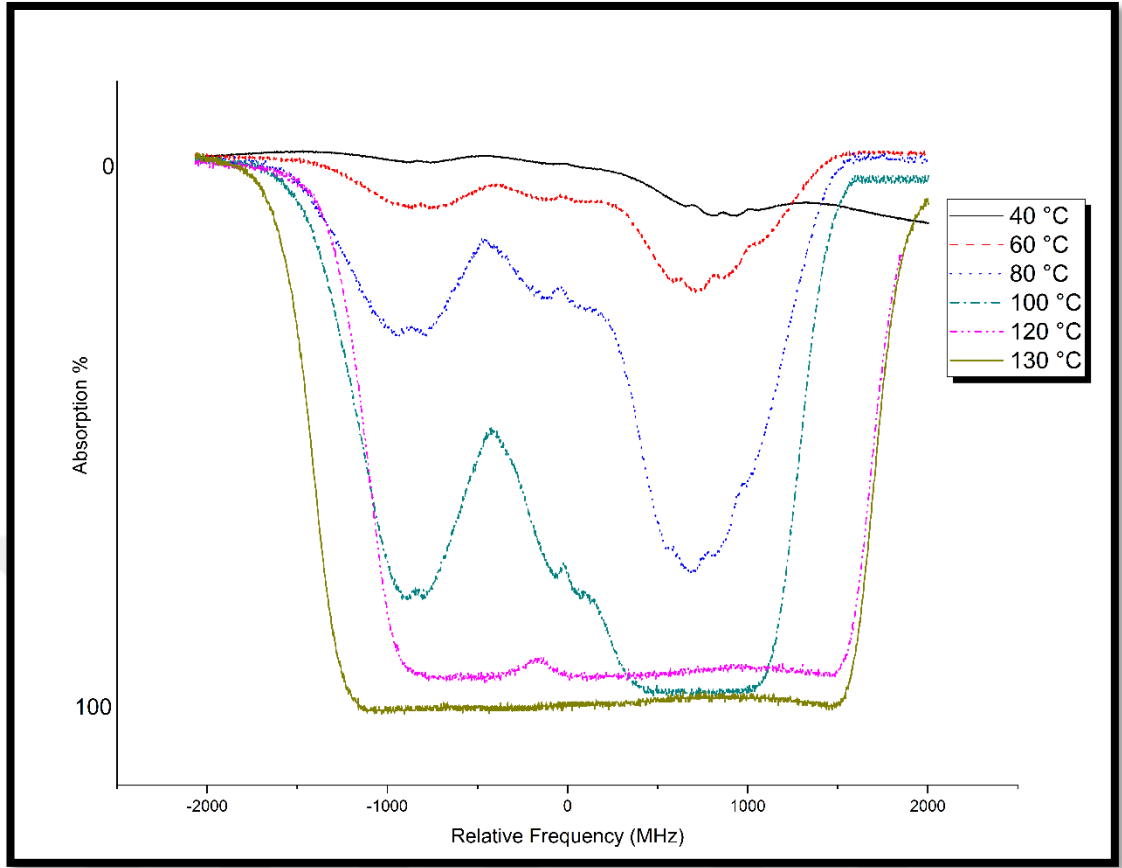


Figure 6.5: The simplified of $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions with different cell temperatures.

In **Figure 6.3**, the atomic transitions of 40, 60 and 80 °C are clearly visible but broaden as the temperature increases. When temperature of 100 °C is examined, only the $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ transition is visible. Other transitions are not visible due to absorption. When the atomic transitions at 120 and 130 °C are examined, the atomic transitions are completely disappeared due to complete absorption of the probe beam.

In **Figure 6.5**, the atomic transitions of 40, 60 and 80 are clearly visible but broaden as the temperature increases. When the temperature of 100 °C is examined, only the ^{87}Rb transitions are visible, and the ^{85}Rb transitions are completely saturated. When the atomic transitions at 120 and 130 °C are examined, the atomic transitions are completely disappeared due to complete absorption of the probe beam.

In addition, as the temperature of the atomic vapor cell increases, the collisions between atoms increase and this leads to resonance broadening and shifting in the spectrum because the collisions between atoms lower the lifetime of excitation of the atoms.

In conclusion, as the temperature of the atomic vapor cell increases, Doppler saturation absorption spectrum broadens, and the amplitude of sub-Doppler resonances decreases. Since the entire probe laser beam is absorbed by the atoms in the cell at a certain temperature value, the transmission of probe beam through the atomic vapor cell becomes zero.

6.2. Effect of Polarization of Pump and Probe

The direction of the electric field vector of an electromagnetic wave determines the polarization state and it is the primary factor affecting which energy levels atoms can transition.

The polarization states of the pump and probe beams directly affect the selection rules of atomic transitions, which determine which sublevel transitions are excited and consequently how the spectral structure appears. When the polarized laser beam interacts with the atoms in the fundamental Zeeman level, it excites them to the selected Zeeman levels according to the laser polarization state. In the fundamental level, the atoms are in Zeeman levels with the values $m_F = -F \leftrightarrow F = -F, -F + 1, \dots, 0, F + 1, \dots, F$. Linear polarization state π transitions and circular polarization state σ^+ and σ^- transitions excite atoms at different Zeeman levels.

- For linear polarization state π transition: Only excites $m_F = 0$ transitions. This implies that only the sublevels having the same magnetic quantum number can be excited among the magnetic sublevels of atom. This form of polarization forms a simple and more symmetric transition spectrum.
- For right-handed circular polarization state σ^+ and circular left-handed polarization state σ^- transition: Only excite $m_F = +1$ and $m_F = -1$ transitions respectively. This implies more transitions between magnetic sublevels and asymmetry and polarization-related separations in spectral lines.

Possible Zeeman transitions for the $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 3)$ are given in **Figure 6.6**. In the left part of the figure, the D₁ line of the ^{85}Rb transitions are given

and in the right part of the figure possible Zeeman transitions are given. Sublevels of energy levels are given for $5S_{1/2}$ ($F = 2$) and $5P_{1/2}$ ($F = 3$). Linear polarization π transitions are given in black colour while right-handed circular polarizations σ^+ and left-handed circular polarization σ^- transitions are given in red and blue colour respectively.

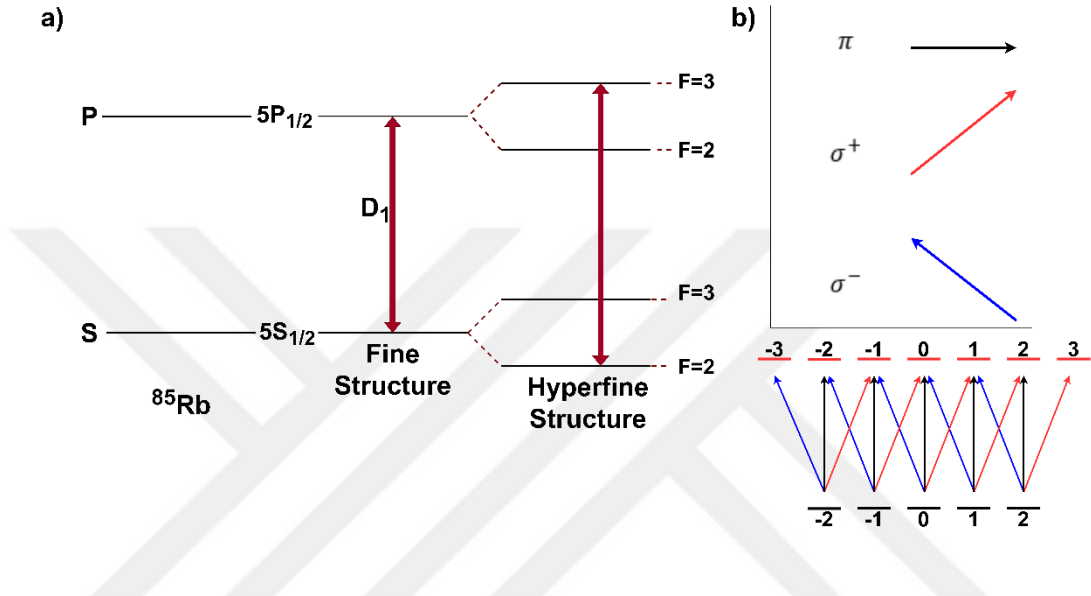


Figure 6.6: a) ^{85}Rb transition of $5S_{1/2}$ ($F = 2$) – $5P_{1/2}$ ($F = 3$) [67]. b) Possible Zeeman transitions.

Possible Zeeman transitions for the ^{87}Rb $5S_{1/2}$ ($F = 1$) – $5P_{1/2}$ ($F = 2$) are given in **Figure 6.7**. In the left part of the figure, the D_1 line of the ^{87}Rb transitions are given and in the right part of the figure possible Zeeman transitions are given. Sublevels of energy levels are given for $5S_{1/2}$ ($F = 1$) and $5P_{1/2}$ ($F = 2$). Linear polarization π transitions are given in black colour while right-handed circular polarizations σ^+ and left-handed circular polarization σ^- transitions are given in red and blue colour respectively.

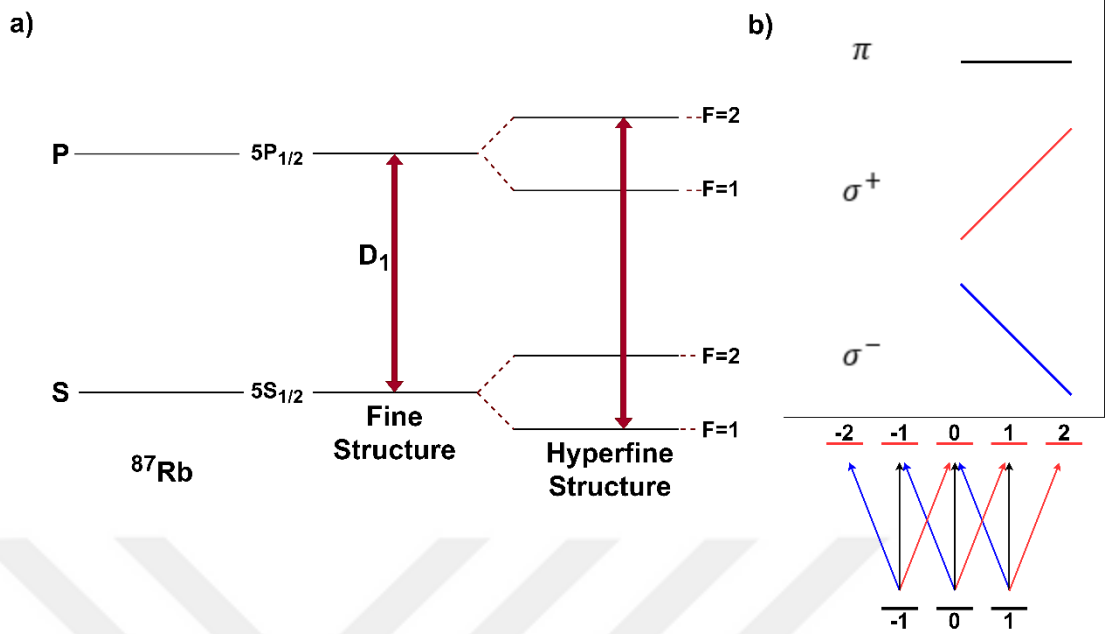


Figure 6.7: a) ^{87}Rb transition of $5S_{1/2}$ ($F = 1$) – $5P_{1/2}$ ($F = 2$) [67]. b) Possible Zeeman transitions.

In the polarization effect experiment, the pump and probe lasers are set as 1mW and 10 μ W respectively and the cell temperature is set at 60 $^{\circ}\text{C}$ to create sufficient atomic vapor density. To change polarizations Quarter-wave plates are placed as in **Figure 6.8**.

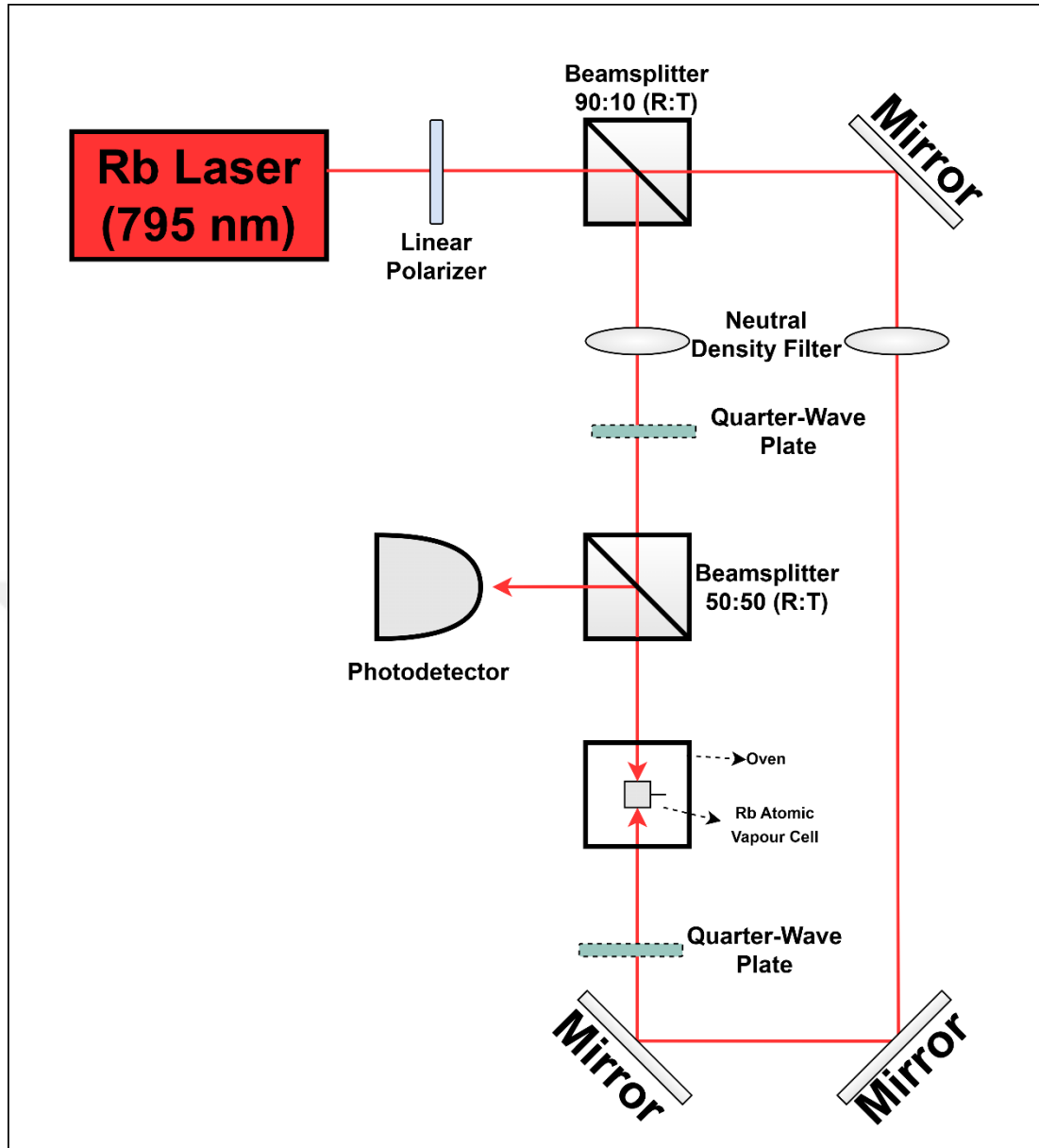


Figure 6.8: Polarizers in the experimental setup.

Doppler-free saturation absorption spectrum of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions are observed in **Figure 6.9**. In **Figure 6.10** and **Figure 6.11**, the linearly and circularly polarized separated versions of the graphics are given respectively.

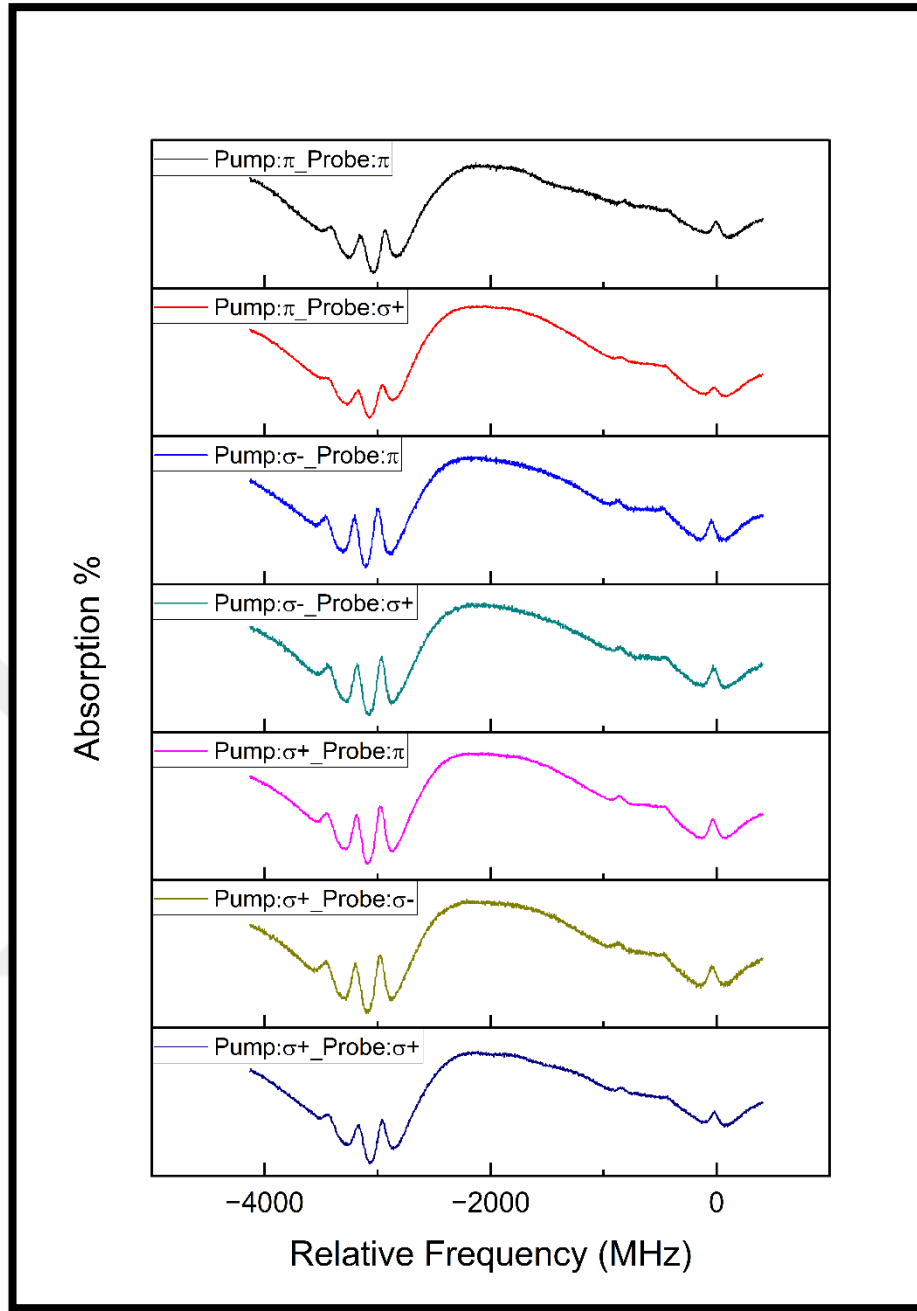


Figure 6.9: $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions with different polarization configurations.

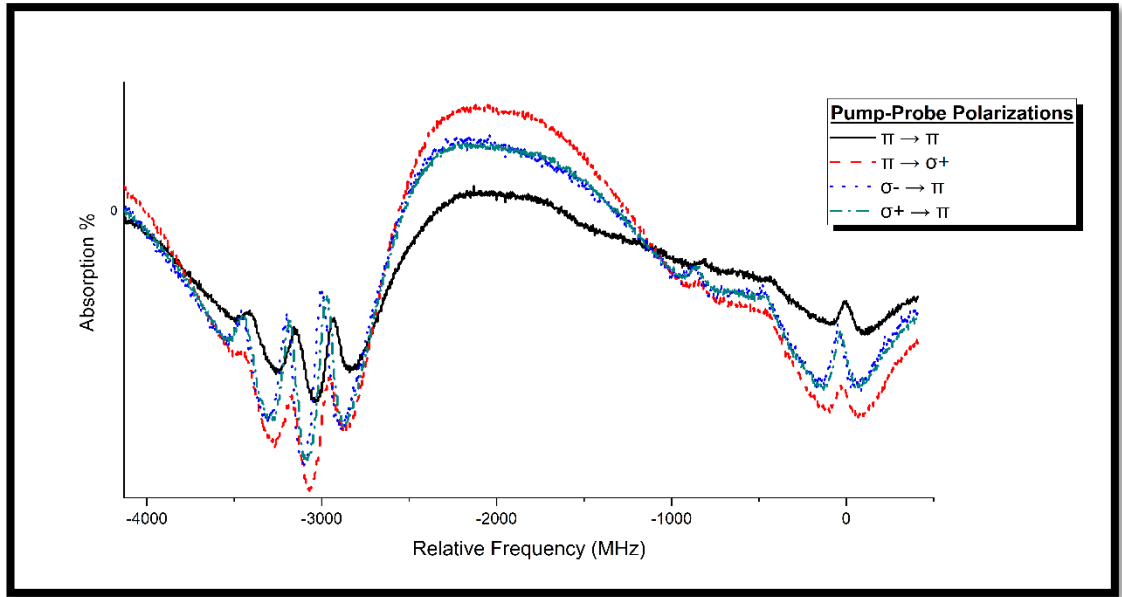


Figure 6.10: Separated linearly polarization of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions with different polarization configurations.

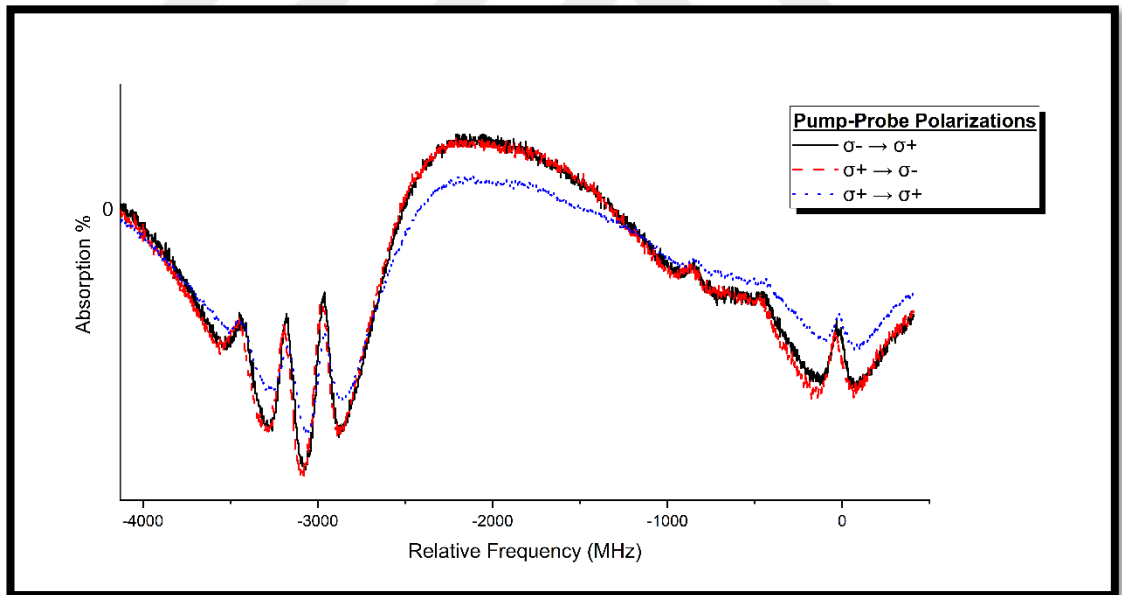


Figure 6.11: Separated circularly polarization of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions with different polarization configurations.

Doppler-free saturation absorption spectrum of $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions are

observed in **Figure 6.12**. In **Figure 6.13** and **Figure 6.14**, the linearly and circularly polarized separated versions of the graphics are given.

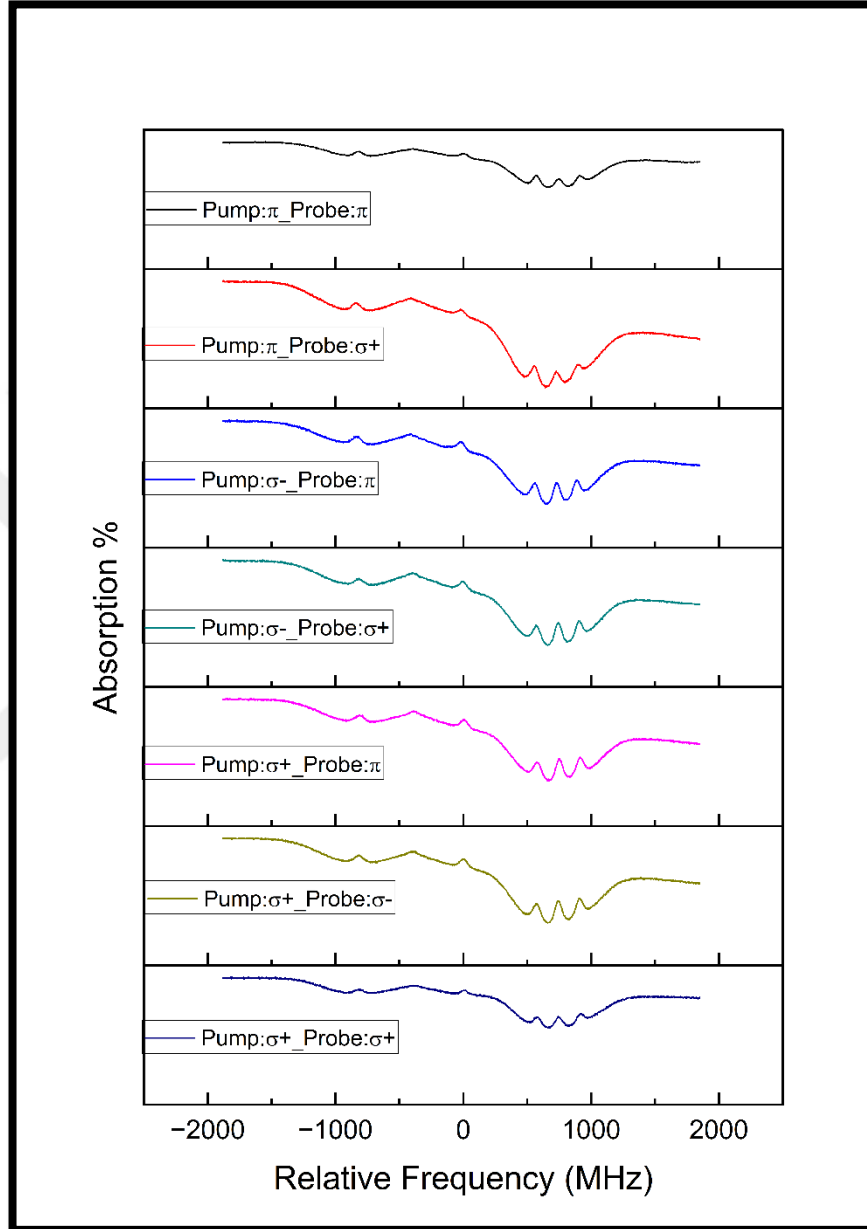


Figure 6.12: $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions with different polarization configurations.

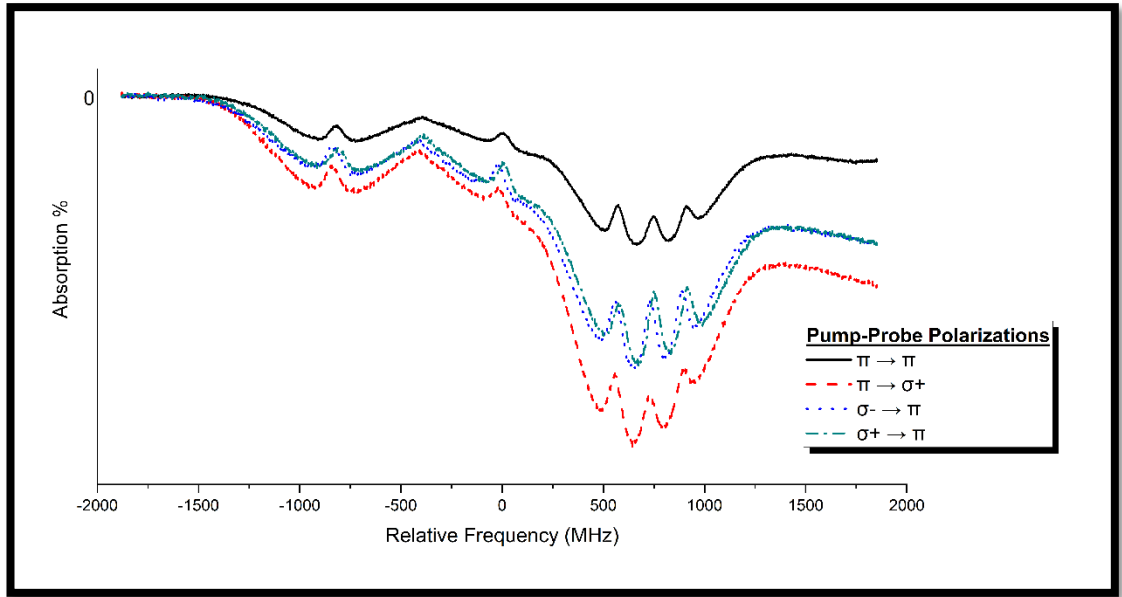


Figure 6.13: Separated linearly polarization of $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions with different polarization configurations.

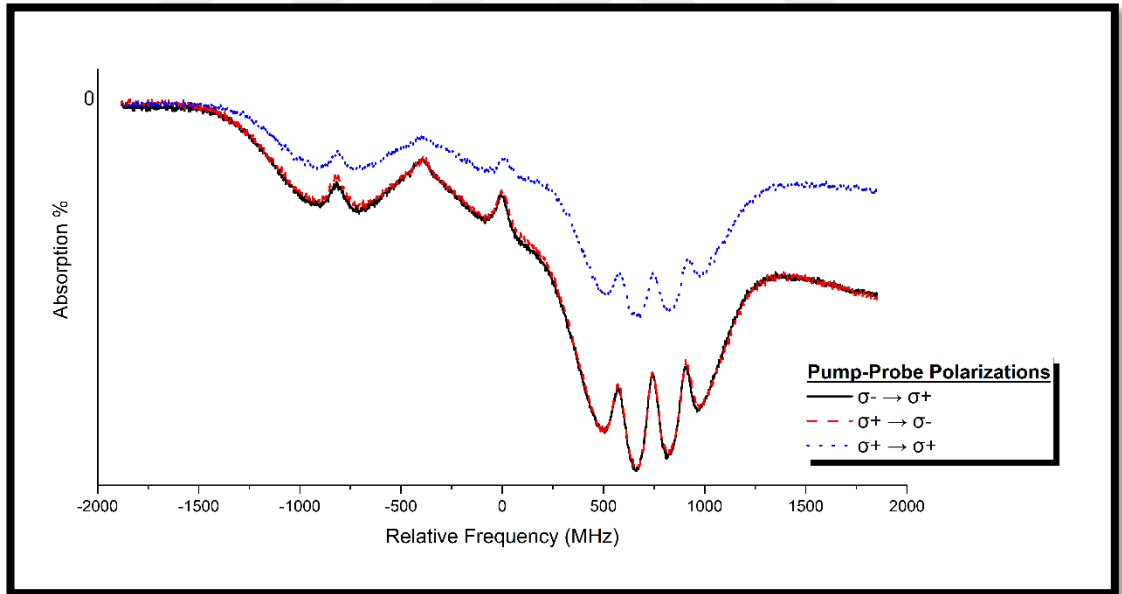


Figure 6.14: Separated circularly polarization of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions with different polarization configurations.

As the figures show, the linearly polarized pump and probe beams form simpler and symmetrical spectra than those formed by circular polarization states. **Figure 6.10**

shows that when one of the laser beams has a circular polarization state, there is more absorption and the amplitude of atomic transitions is larger than when the pump and probe beams are linear polarized, especially when the pump beam is σ^- and the probe beam π polarized. In **Figure 6.11**, when both the pump and probe laser beams have right-handed circular polarized σ^+ , the absorption level is lower than when one of the beams has a different circular polarization state. In addition, there is almost no difference in absorption spectrum of $\sigma^+ - \sigma^-$ and $\sigma^- - \sigma^+$ pump and probe beam polarization states.

In **Figure 6.12**, the results are similar those in **Figure 6.10** and **Figure 6.11**. However, there is difference in absorption amounts of different polarization configurations. When both pump and probe beams have same polarization states ($\pi - \pi$) or ($\sigma^+ - \sigma^+$), their absorption spectra are much lower than different polarized pump and probe beams' absorption spectra. As shown in **Figure 6.14**, similar to **Figure 6.11**, when both the pump and probe laser beams have right-handed circular polarized σ^+ , the absorption level is lower than when one of the beams have different circular polarization state and there is almost no difference in absorption spectrum of $\sigma^+ - \sigma^-$ and $\sigma^- - \sigma^+$ pump and probe beam polarization states.

6.3. Effect of Pump and Probe Laser Powers

The pump and probe powers are effective parameters for the shape and amplitude of atomic transitions while obtaining a Doppler-free saturation absorption spectrum since the Rb atoms directly absorb laser photons [56]. This determines the absorption and saturation levels and, thus, the linewidth of the atomic resonances.

Since the pump and probe laser beams must interact with the same atoms for Doppler-free saturation absorption to occur, the power of these lasers is effective in forming absorption lines and their linewidths. The pump laser power is the primary factor for transferring atoms from the ground state to the excited state. As the pump laser power increases, a significant portion of the atoms in the ground state transfer to the excited state and the number of atoms in the ground state decreases [56]. This lowers the absorption of the probe laser and deepens the resonance dips referred to as Lamb dips.

Increasing the pump laser power increases absorption and creates deeper Lamb dips until its maximum point (saturation level). It also increases the linewidths of the atomic

resonances when the saturation level is exceeded, which is called power broadening [56], [61]. However, if the intensity of the pump laser beam is close to the saturation level, the linewidths of the atomic resonances get closer to the natural linewidth γ . As a result, the linewidth of the atomic resonances is calculated as given in equation (6.1).

$$\gamma = \gamma_{nat} \sqrt{1 + \frac{I}{I_{sat}}} \quad (6.1)$$

Where I_{sat} is the saturation intensity for the D₁ line of rubidium and it is calculated as in equation (6.2) [56].

$$I_{sat} = \frac{2\pi^2 \hbar c \gamma}{3\lambda^3} = \frac{2\pi^2 (6.63 \times 10^{-34} \text{ J.s}) \left(3 \times 10^8 \frac{\text{m}}{\text{s}}\right) (5.75 \times 10^6 \text{ Hz})}{3 * (795 \times 10^{-9} \text{ m})^3} \quad (6.2)$$

$$I_{sat} \approx 1.5 \text{ mW/cm}^2 \quad (6.3)$$

Where λ is the wavelength of the laser. γ was calculated in equation (3.3) for the ^{85}Rb and equation (3.4) for the ^{87}Rb . Since the difference between them is so small, only one of them is included in the equation.

The probe laser beam is used to measure the change of absorption amount. Thus, it is usually kept smaller than the saturation intensity I_{sat} to avoid impairing the saturation effect. When it close to the saturation intensity, it excites the atoms partially and changes the real saturation amount and causes power broadening.

In this experiment, the cell temperature is set at 60 °C to create sufficient atomic vapor density and polarization of pump and probe beams are set as linearly polarized. The probe power is set as 10 μW and pump power are set as 10 μW , 50 μW , 100 μW , 200 μW , 500 μW and 1mW.

Doppler-free saturation absorption spectrum of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions are observed in **Figure 6.15**.

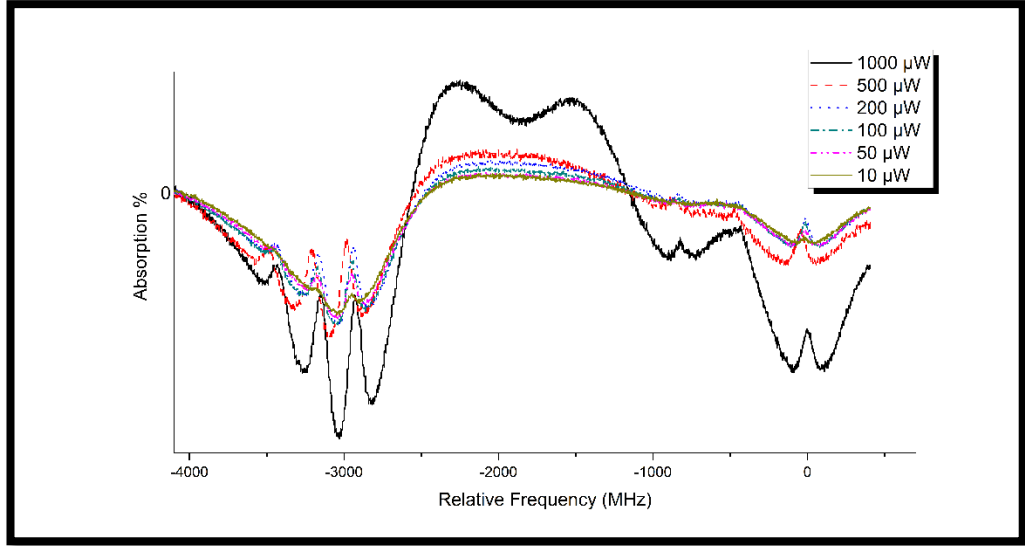


Figure 6.15: $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ atomic transitions with different pump powers.

Doppler-free saturation absorption spectrum of $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions are observed in **Figure 6.16**.

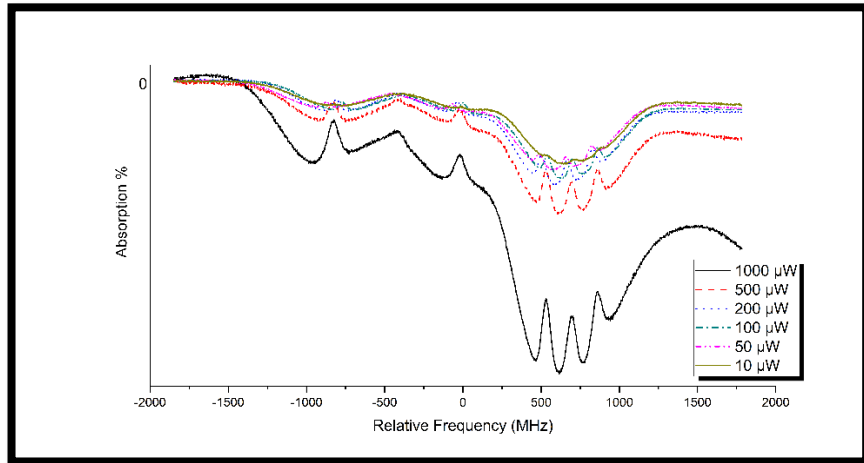


Figure 6.16: $^{85}\text{Rb } 5S_{1/2} (F = 3) - 5P_{1/2} (F = 2, 2 \text{ co } 3, 3)$ and $^{87}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 1, 1 \text{ co } 2, 2)$ atomic transitions with different pump powers.

As Figure 6.15 and Figure 6.16 show that when the probe power is kept at weaker value and the pump power is increased gradually, the absorption amount increases accordingly, and atomic resonances deepen.

The linewidths of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ and $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 3)$ are investigated in this study, as the pump power increases, how the linewidths of these atomic transitions change is analysed. The probe power is kept at $10 \mu\text{W}$, and pump powers of $10 \mu\text{W}$, $100 \mu\text{W}$ and 1 mW are considered. To calculate the linewidths of the atomic resonances Origin program is used and the linewidths are calculated by Lorentz fitting. Full width at half maximum (FWHM) of Lamb dips are considered as linewidths of Lamb dips.

In Figure 6.17, atomic transitions of only the three selected pump powers are given.

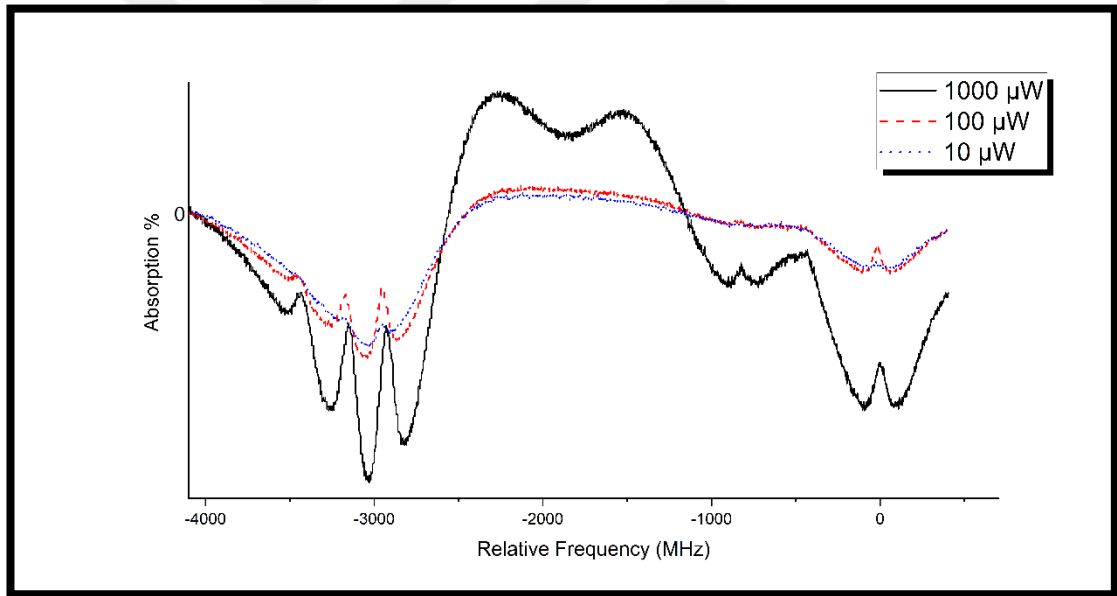


Figure 6.17: Three selected pump powers ($10 \mu\text{W}$, $100 \mu\text{W}$ and 1 mW).

6.3.1. The Linewidth of ^{87}Rb

In Figure 6.18, only the $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ transitions are given.

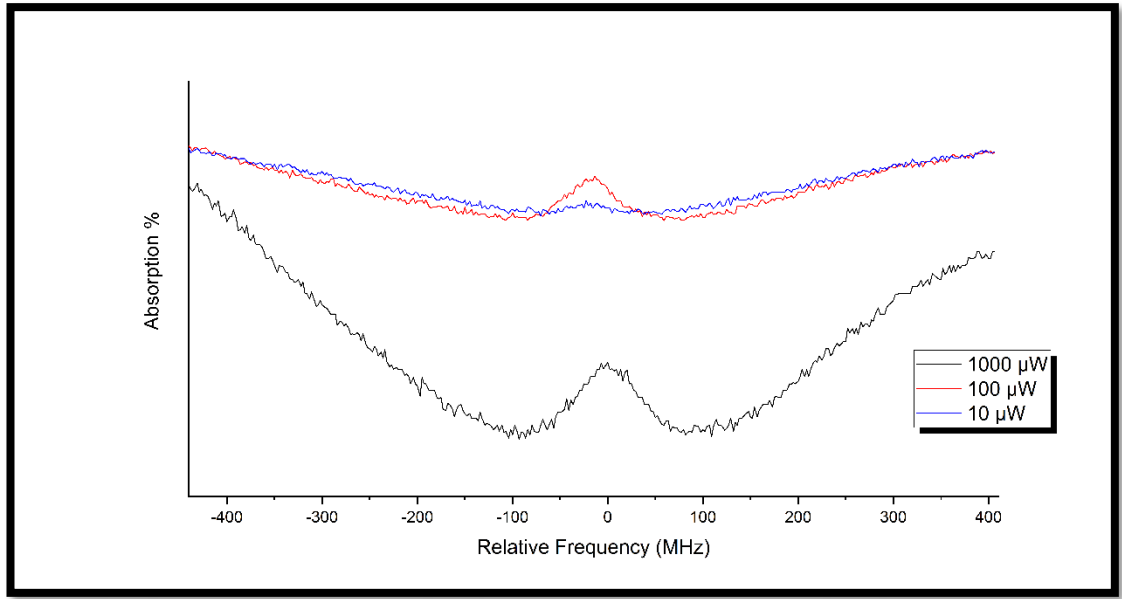


Figure 6.18: $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ atomic transitions of 1 mW, 100 μW and 10 μW pump powers.

Lorentz fit function is used to calculate the linewidths of atomic transitions, and the corresponding equation is given as:

$$y = y_0 + \frac{2A}{\pi} \frac{w}{4(x - x_c)^2 + w^2} \quad (6.4)$$

Where w value is the full width at half maximum (FWHM) of the curve and, it is considered as linewidth of the curve. When Lorentz fit is applied to the atomic transitions, w value and corresponding linewidths of the atomic transitions can be calculated. The linewidths of pump power 1 mW, 100 μW and 10 μW of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ transition is given in **Figure 6.19**, **Figure 6.20** and **Figure 6.21** respectively.

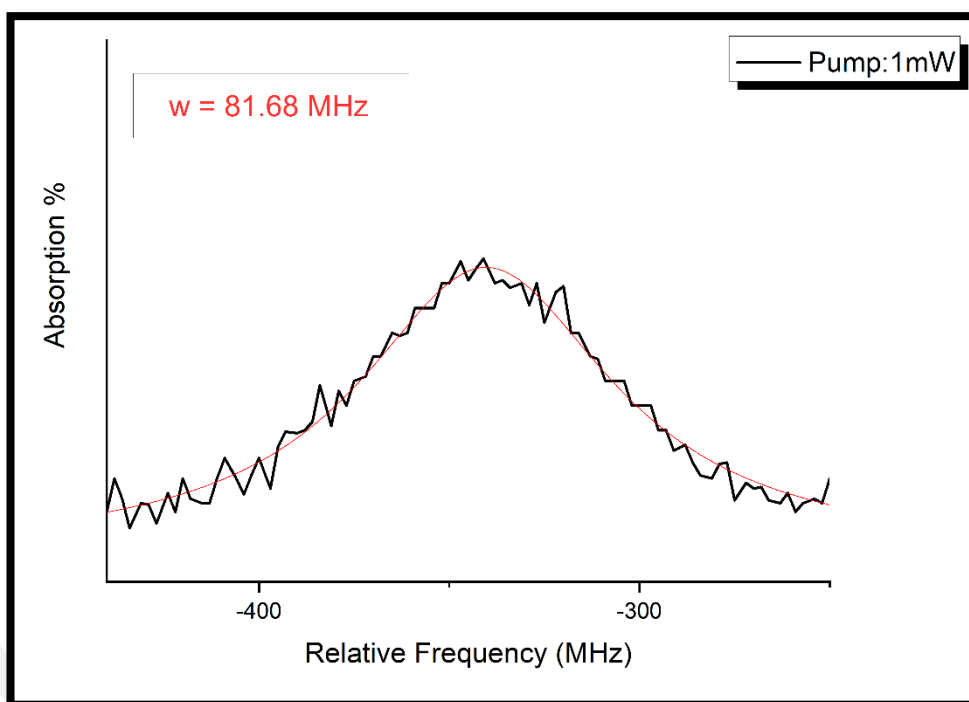


Figure 6.19: Linewidth of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ atomic transition while the pump power is 1 mW.

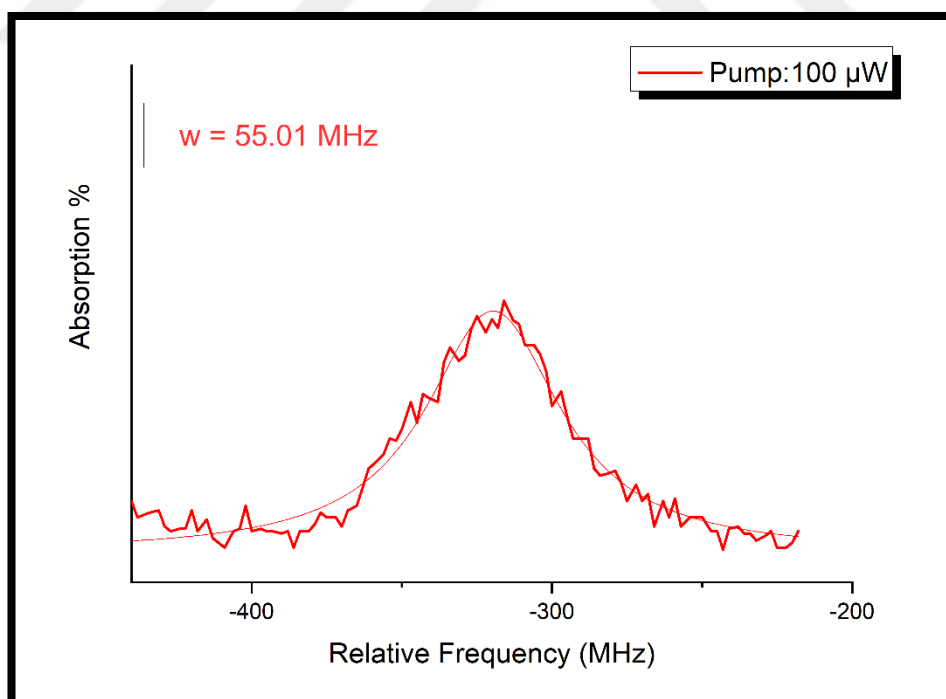


Figure 6.20: Linewidth of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ atomic transition while the pump power is 100 μW .

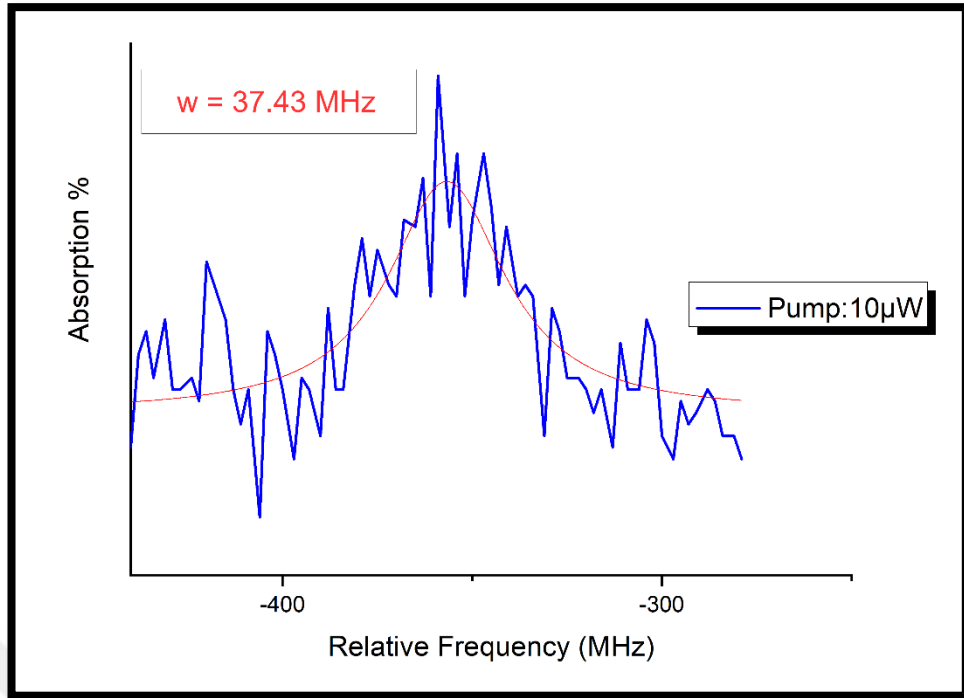


Figure 6.21: Linewidth of $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ atomic transition while the pump power is $10 \mu\text{W}$.

6.3.2. The Linewidth of ^{85}Rb

In **Figure 6.22**, only the $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 3)$ transitions are given.

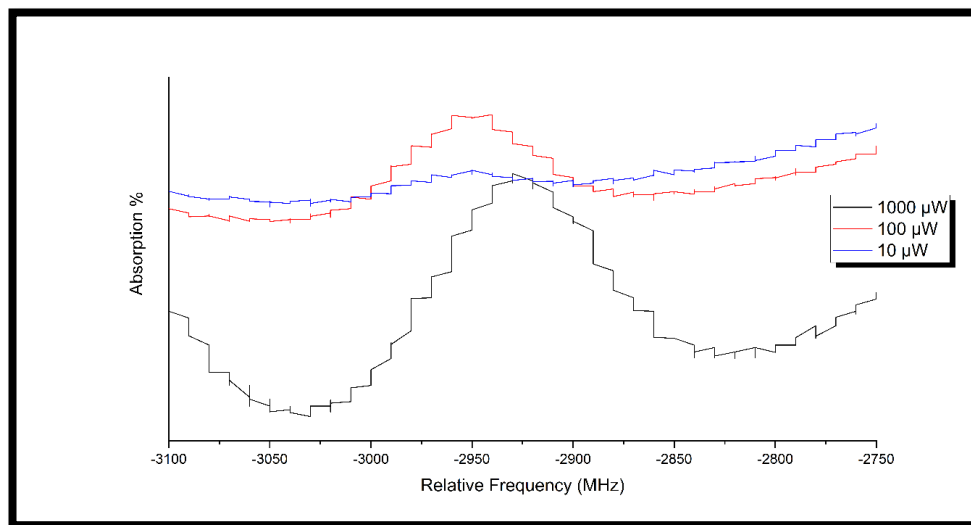


Figure 6.22: $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 3)$ atomic transitions of 1 mW , $100 \mu\text{W}$ and $10 \mu\text{W}$ pump powers.

Lorentz fit function is used to calculate the linewidths of atomic transitions. The linewidths of pump power 1 mW, 100 μ W and 10 μ W of ^{85}Rb $5S_{1/2}$ ($F = 2$) – $5P_{1/2}$ ($F = 3$) transition is given in **Figure 6.23**, **Figure 6.24** and **Figure 6.25** respectively.

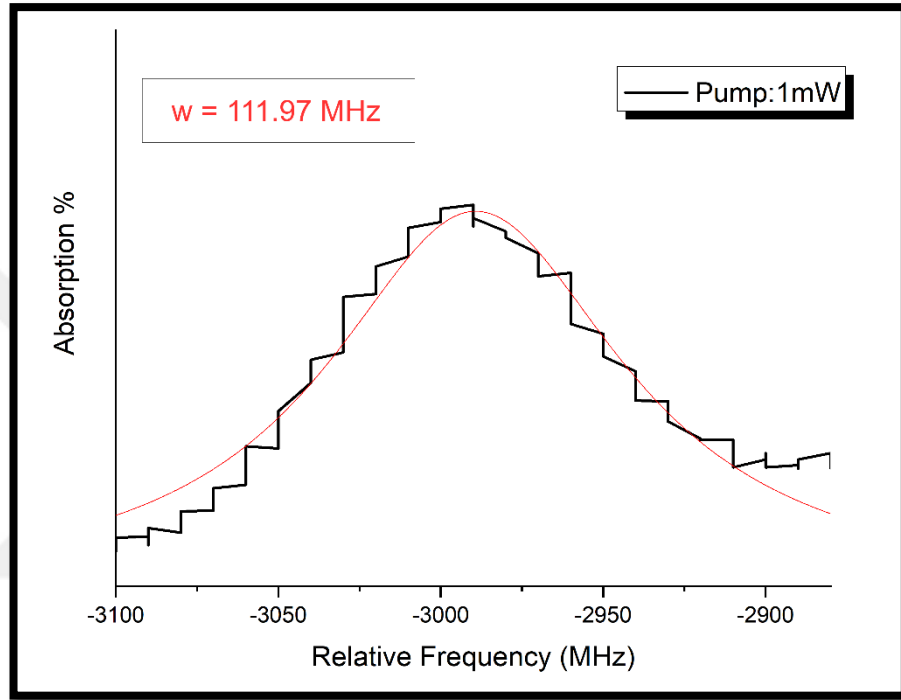


Figure 6.23: Linewidth of ^{85}Rb $5S_{1/2}$ ($F = 2$) – $5P_{1/2}$ ($F = 3$) atomic transition while the pump power is 1 mW.

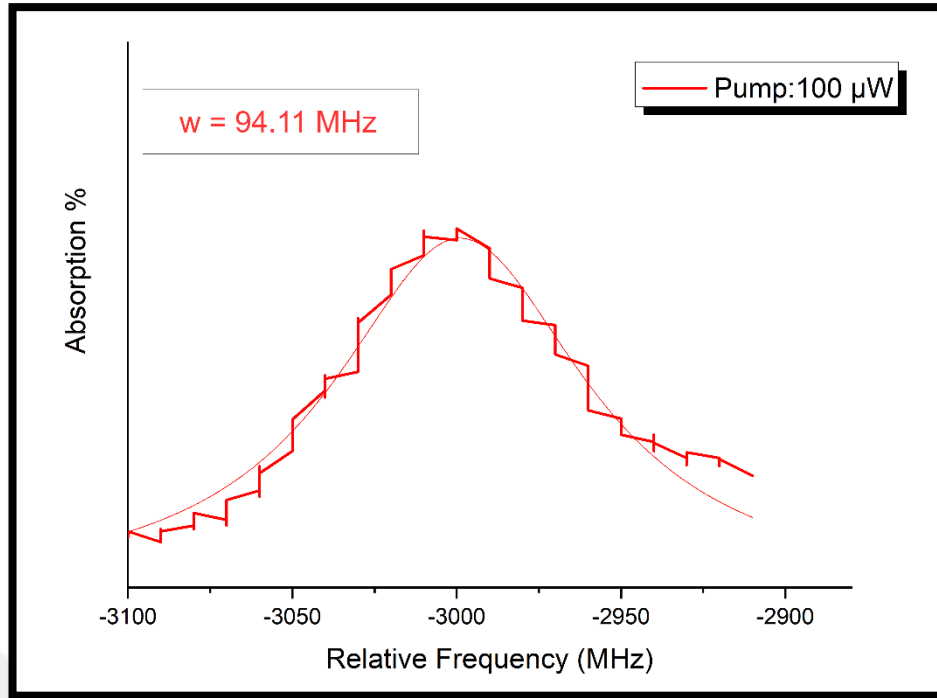


Figure 6.24: Linewidth of $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 3)$ atomic transition while the pump power is $100 \mu\text{W}$.

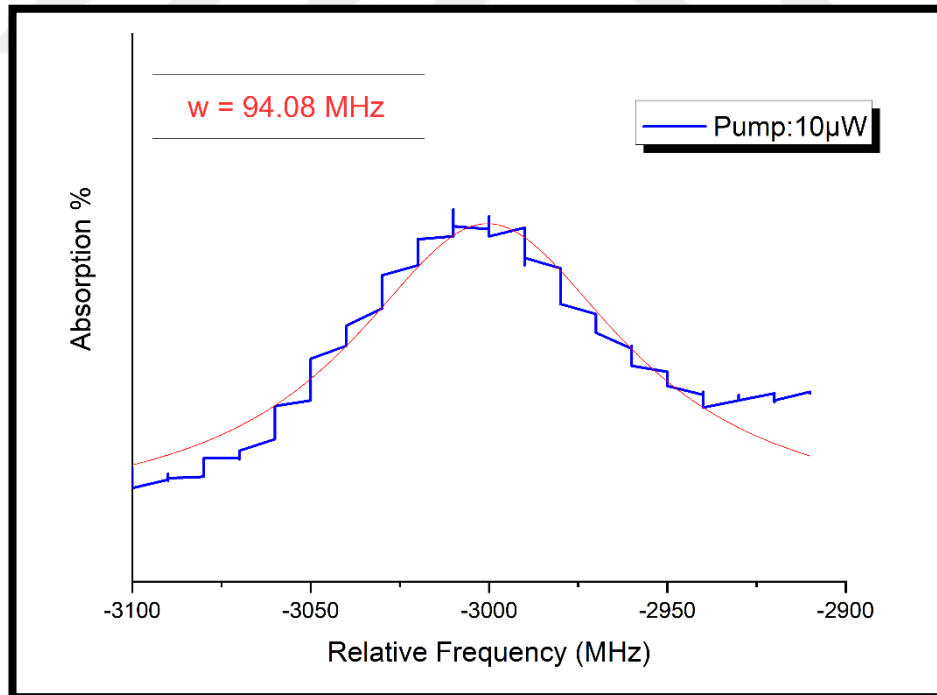


Figure 6.25: Linewidth of $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 3)$ atomic transition while the pump power is $10 \mu\text{W}$.

6.3.3. The Linewidth Analysis

When the linewidths of those atomic transitions are examined altogether, the correlation is given in **Figure 6.26**.

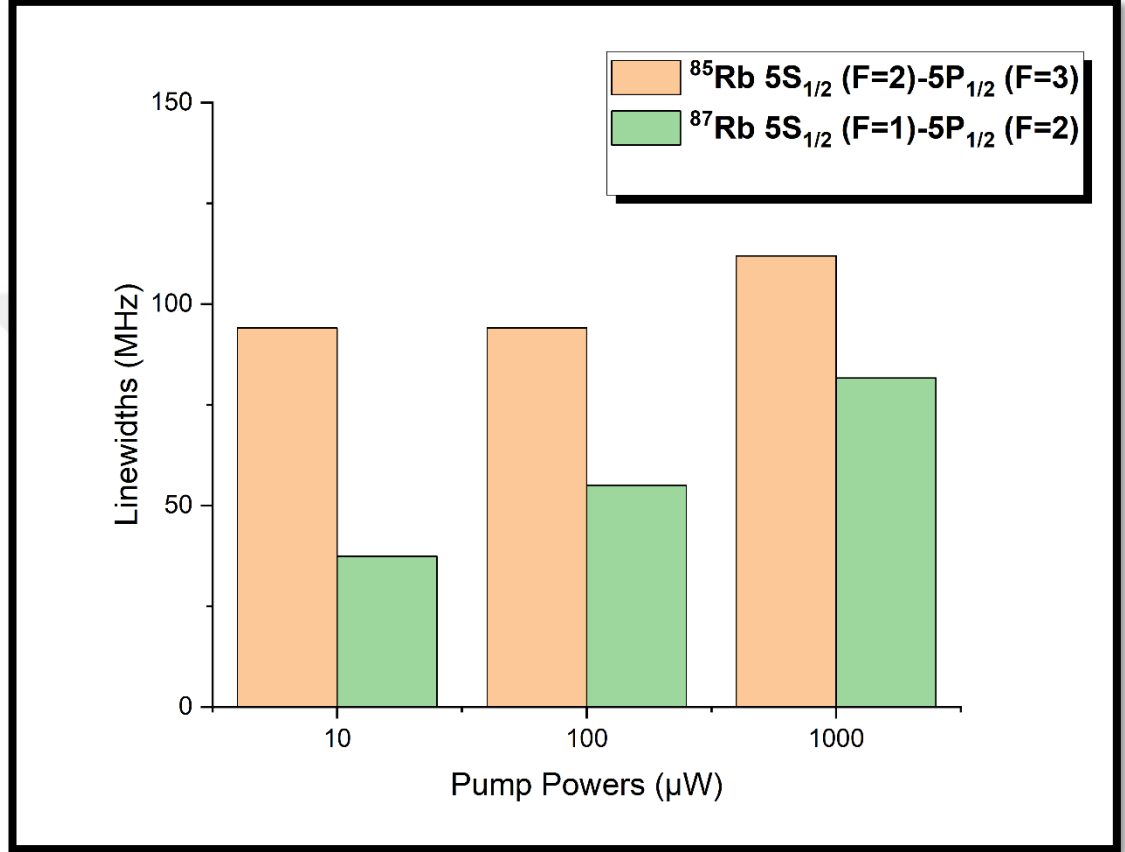


Figure 6.26: Linewidth analysis.

As seen in **Figure 6.26**, the linewidths of the selected atomic transitions increase as the pump power increases, as predicted.

Due to selected the ^{85}Rb transition having more Zeeman sublevel m_F , the pump beam interacts with more possible transitions, and this causes more power broadening and wide linewidths when compared to ^{87}Rb linewidth values. In addition, since the ^{85}Rb isotope is 72% and the ^{87}Rb isotope is 28% in the natural rubidium atom, the density of the ^{85}Rb atoms is higher at the same temperature and as the higher atomic density leads to deeper transitions and saturation amount [68].

However, the linewidth change rate of the $^{85}\text{Rb } 5S_{1/2} (F = 2) - 5P_{1/2} (F = 3)$ atomic transition is much less when compared to the linewidth change rate of the $^{87}\text{Rb } 5S_{1/2} (F = 1) - 5P_{1/2} (F = 2)$ atomic transition. Due to the higher atomic density of ^{85}Rb , saturation occurs earlier than with ^{87}Rb . Therefore, the linewidth change rate is less when compared to ^{87}Rb .



7. CONCLUSION

In this study, saturation absorption spectroscopy of the Rb D1 line is investigated. What laser spectroscopy is and how it is done is explained. Fine and hyperfine structures of the Rb atom are calculated. The situations that can occur as a result of laser-atom interaction are discussed and the absorption mechanism is explained. It is explained how atoms interact with lasers and how the lifetime of atoms at a higher energy level causes natural line broadening in absorption lines. It is stated that atoms have a velocity distribution due to their thermal motion, which causes the Doppler effect. This effect leads to Doppler broadening in the absorption lines. It is explained that since these broadenings negatively affect the laser spectroscopy results, techniques that can minimize these broadenings should be developed.

It was explained that to prevent this broadening, the Doppler-free saturation absorption spectroscopy technique should be used. It was stated that, with this technique, the pump and probe laser beams should simultaneously affect the atoms within a certain velocity group, and it was shown that Lamb dips would be formed as a result. It was understood that the formation of these Lamb dips meant that Doppler broadening was prevented.

The technique of Doppler-free saturation absorption spectroscopy was explained. Pump and probe laser beams with the same frequency were overlapped in the Rb atomic vapor cell. It was explained that the pump beam elevates the Rb atoms to a higher energy level, and the probe beam is used to monitor this interaction. It was stated that Lamb dips would occur when the pump and probe beams interact with atom groups with zero velocity or atom groups with a velocity perpendicular to these beams. It was stated that if the laser frequency coincides with half the frequency of two atomic transitions and the atoms are in a certain velocity group, the pump and probe beams will also interact with these atoms and create crossover resonances. It was stated that these resonances are deeper in the absorption spectrum compared to other atomic transition resonances and that these resonances are used in frequency reference systems.

The experimental setup and the features of the equipment used in the experiment were explained, and their use was demonstrated. The structure of the Rb atomic vapor cell and the installation of the temperature control system in the experimental setup were shown. How the experiment was performed was explained. In this study, it was investigated how atomic transitions were affected by various factors in the saturation absorption spectroscopy experiment. How the shape and linewidths of the Rb atomic transitions changed with the temperature of the atomic vapor cell, the polarization states and powers of the pump and probe beams were examined.

It was predicted that the atomic density in the cell would change with the change in temperature of the atomic vapor cell and thus the number of atoms that could interact with the laser would increase. It was observed that the amount of Rb that went into the vapor state increased due to the low melting temperature of the Rb metal as the atomic vapor cell was heated. It was stated that as the temperature increased, the amount of Rb atoms would increase and therefore the collisions between the atoms would cause the resonances to expand. Additionally, it was predicted that when the temperature reached a certain level, the atomic resonances would no longer be observed since the entire laser beam would be absorbed by the atoms. Based on the results obtained in the experiment, it was seen that the atomic transitions disappeared in the resonance spectrum when the atomic gas cell temperature reached 120 °C.

It was stated that laser beams will interact with atoms according to polarization state selection rules. It was explained which Zeeman sublevel transition will occur depending on the polarization state of the laser beam. It was stated that the laser beam with linear polarization will only affect $\Delta m_F = 0$ transitions and as a result, simple and symmetric atomic transitions will be seen. It was stated that the laser beam with circular polarization will affect $\Delta m_F = \pm 1$ transitions according to right-handed or left-handed circularity and these transitions will be more asymmetric. As a result of the experiment, it was seen that the resonance spectrum created by laser beams with linear polarization has more symmetric atomic transitions, while the atomic transitions created by laser beams with circular polarization have a more asymmetric shape. It was seen that there was almost no difference in atomic transitions between pump and probe laser beams being $\sigma^+ - \sigma^-$ and $\sigma^- - \sigma^+$.

Since the Rb atoms in the atomic vapor cell interact directly with the laser beams, it was predicted that the laser powers would have an effect on the atomic transitions. It

was stated that the shape of the atomic transitions would change with the change in laser powers, that is, the linewidths of the atomic transitions that occur would differ. It was explained that since the pump beam transfers the atoms to a higher energy level, it would have a direct interaction with the atoms and would directly affect the amount of atoms that transfer to a higher energy level. As the pump laser power increases, the amount of atoms that will be transferred to the upper level will increase and the amount of atoms at the ground energy level will decrease, so the absorption of the probe beam will decrease and it was predicted that it would create deeper atomic resonances in the spectrum. However, it was stated that after the pump beam passed the saturation level, the linewidths of the atomic transitions would increase due to the power broadening effect. When the experimental results were examined, it was seen that increasing the pump laser power increased the linewidths of the atomic transitions. Since the Rb element is found to be stable in nature, ^{85}Rb is found at 72% and ^{87}Rb is found at 28%, it was observed that the ^{85}Rb isotope density would be higher than ^{87}Rb at the same temperature and therefore, it would undergo more absorption.

As a result of the experiments, it was observed that atomic transitions changed with various factors. These results are intended to support future studies. Since the saturation absorption spectroscopy technique is of critical importance in laser stabilization studies, atomic transitions with narrower linewidths and higher signal-to-noise (SNR) ratios will directly affect the laser frequency stabilization sensitivity. Thus, by examining these parameters in more detail, it is aimed to reduce the linewidths of atomic transitions and consequently increase the laser frequency stabilization sensitivity.

The high-resolution, Doppler-free atomic transitions obtained in this study provide extremely precise and reliable reference points for laser frequency stabilization studies. The narrow and high SNR spectral lines observed especially around the D_1 transitions of rubidium allowing locking the frequency of a laser and developing a stabilized laser. In this way, laser systems that minimize frequency deviations on both short and long time scales can be designed. Such frequency references are critical not only for fundamental spectroscopy studies, but also for metrological applications, time-frequency standards and quantum optics experiments.

Furthermore, locking the laser frequency to a stable atomic transition opens the door to a new level of precision in atomic sensor technologies. For example, in systems such as magnetometers, atom interferometers or atomic clocks, the stability of the laser directly determines the measurement accuracy and the noise level of the system. The SAS-based spectroscopic infrastructure developed in this thesis can be used as the basis for compact, low-cost and high-sensitivity sensor systems based on rubidium atomic vapor cells in future studies. Thus, an important contribution is made to both basic research and applied sensor technologies.



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