Multi-V-type and Λ-type electromagnetically induced transparency experiments in rubidium atoms with low-power low-cost free running single mode diode lasers

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Abstract. In this work we present the experimental realization of electromagnetically induced transparency (EIT) in Λ-type and multi-V-type configurations in a sample of rubidium atoms inside a vapor cell at room temperature. Typical EIT windows are clearly visible in the Doppler-broadened absorption signal of the weak probe beam. The coherent optical pump and probe fields are produced by two tunable low-cost, low-power, continuous-wave (cw), free-running and single mode operated diode laser systems, temperature stabilized and current controlled, tuned to the D2 line of rubidium atoms at 780.2 nm wavelength. The continuum wave and single mode operation of our laser systems are confirmed by direct and saturated absorption spectroscopy techniques. Among other applications, these simple experiments can be used as a low-cost undergraduate laboratory in atomic physics, laser physics, coherent light-atom interaction, and high resolution atomic spectroscopy.

1. Introduction

Today, high-precision optical techniques allow bi-directional control of light and atoms; atoms can be manipulated with light, and light can be controlled by atoms [1]; in a quantum network a quantum bit must be stored in a quantum memory, which in turn re-emit a photon that must be transmitted between two distant quantum memories [2]; the experimental realization of super-radiance and of slow-light effects, which also can be used as quantum memories [3]; and the theoretical study of atomic ensembles in Λ-configuration, also good candidates for quantum memories [4], have been object of recent study. Although in most cases the proposed scheme are based in ultra-cold atomic samples, quantum memories schemes at the level of one-photon at room temperature, have also been studied [5], and in the last years long-live quantum optics memories have been also proposed [6]. In those applications, at some stage in its experimental realization, the requirement of an optical pump source, emitting light tuned with the atomic
transitions, i.e., for the production of photons where the information is encoded, or for the cooling and trapping of the atoms where the information must be stored, becomes an unavoidable task.

Our experimental group, at the Department of Physics of the University of Concepción (Chile), started its experimental activities in 2012 with the aim to conduct experimental research studies in coherent light-atom interaction such as that stated in the previous paragraph, in particular, on the interaction of laser light beams tuned to atomics transitions of rubidium atoms. Due to small budget for operation we have built our own coherent light sources based on semiconductor laser chips (diode lasers). The central wavelength and the range of tunability, as well as, the operation temperature range and the driven current of diode lasers are given by the manufacturer. Once the diode laser is chose for the specific atomic specimen, it can be tuned to the specific atomic transition changing its temperature, its current [9], or by means of an external cavity setup, in which a diffraction grating in a Littrow or LittmanMetcalf configuration, act as a wavelength selective element. The tunable properties of diode lasers have been used largely in atomic physics experiments [7]. Diode lasers systems with optical feedback, known as external cavity diode lasers (ECDL), have been used in saturated absorption spectroscopy of cesium and rubidium atoms [8] and in laser cooling and trapping experiments for undergraduate laboratories [10].

In the present paper we present our simple laser diode system built to produce a beam of laser light tuned to specifics transitions of rubidium atoms, in particular, to the D2 line at 780.2 nm wavelength. The beam of these sources are used to show experimental signal of electromagnetically induced transparency (EIT) in $\Lambda$-type and multi-$V$-type configurations.

The present paper is structured as follow: After the introduction §1, in section §2 we describe our tunable freerunning, low-cost, low power light source: Continuous wave and single mode operation of the light source are presented through direct and saturated absorption spectroscopy setups, respectively (see subsection §2.1). In section §3 we present the use of our source of light in electromagnetically induced transparency experiments. This section is divided in two subsections: In subsection §3.1 we present the main results for $\Lambda$-type configuration EIT, while section §3.2 is devoted to multi-$V$-type configuration. Finally, we present our conclusions in section §4.

2. Tunable laser light source

Our low-cost, low-power laser light system is a free running diode laser stabilized in temperature and controlled in current. A tunable infrared diode laser 780 nm, 80 mW laser diode with PD DL-7140-211N (SANYO) [11] is placed inside a diode laser collimation tube with optic LT220P-B (Thorlabs), which in turn is placed inside a home-made aluminum case for temperature stabilization. A piece of aluminum about three times in size compared to the home-made case is used as heat reservoir. The diode laser case and the reservoir are sandwiched with a thermoelectric cooler TEC3-6 (Thorlabs) in between for temperature stabilization and a thermistor TH10k (Thorlabs) is placed in a drilled hole in the case for temperature monitoring. Both the temperature stabilization and the driven current for the diode laser are taken from a commercial laser diode and temperature controller ITC102 (Thorlabs), current driven by an AC-DC linear regulated power supply (Acopian).

Because the typical wavelength of our tunable diode laser is 785 nm and due to the fact that we are not using it in an external cavity setup, we achieve single mode operation at the desired wavelength only by stabilizing the temperature and controlling the injected current to the system. So, for a work temperature $\sim 20^\circ$C and an injected current $\sim 120$ mA our system is able to emit $\approx 60$ mW of power in a single-mode continuum-wave (cw) at 780 nm wavelength, resonant with the D2 line of rubidium atoms. Two systems with similar characteristics are developed and their spectral emission are tested with simple pass and saturated absorption techniques in a rubidium vapor cell at room temperature. Another similar system, tuned to
the D1 line of rubidium atoms at 795 nm wavelength, is used in a simple experiment of second
harmonic generation at 397.5 nm wavelength inside a PPKTP, Type-I, nonlinear crystal [12].

2.1. Direct and saturated absorption spectroscopy

The single-mode continuum-wave operation of our laser light system is tested extracting a
small portion of the beam to a direct and saturated absorption spectroscopy, schematically
showed in Fig.1: The setup consists of two 25 mm diameter common glass plates, a 25 mm
diameter and 75 mm long cell filled with natural $^{85}$Rb and $^{87}$Rb isotopes composition of rubidium
atoms (Triad Technology) at room temperature, a pair of broad-band photo-detectors, and an
oscilloscope (not showed in the figure). The frequency of the diode laser is scanned around the
D2 resonance line for both $^{85}$Rb and $^{87}$Rb isotopes, injecting a small modulating voltage from a
commercial Tektronix AFG3021B function generator via the modulation injection port available
in the current driver controllers system. Direct and saturated absorption signals are registered
by photo-detectors PD1 and PD2, respectively, and their photo-currents are visualized in an
oscilloscope. Typical signals from this setup are shown in Fig.2.

The hyperfine atomic structure of the D2 resonance line of rubidium atoms at 780 nm
wavelength of both $^{85}$Rb and $^{87}$Rb isotopes are clearly visible in Figure 2. Figure 2.a) [2.b]
show the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transition between the fundamental $F = 2 \{ F = 3 \}$ and the excited
$F' = 1, 2, 3 \{ F' = 2, 3, 4 \}$ hyperfine levels of the $^{85}$Rb isotope. The separation in frequency
between the two fundamental hyperfine levels $F = 2$ and $F = 3$ for $^{85}$Rb is 3.035 GHz. Figure
2.c) [2.d)] show the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transition between the fundamental $F = 1 \{ F = 2 \}$ and
the excited $F' = 0, 1, 2 \{ F' = 1, 2, 3 \}$ hyperfine levels of the $^{87}$Rb isotope. The splitting in
frequency between the two fundamental hyperfine levels $F = 1$ and $F = 2$ for $^{87}$Rb is 6.834 GHz.
These curves are taken with a small amplitude modulation signal, a few millivolts peak-to-peak,
injected in the driven current of the diode laser. When the amplitude of the modulation signal
is increased, we are able to see these four curves in only one screen without mode-hope, that
means, we are able to scan the frequency of the diode laser system in more than 7 GHz. This
is a clear evidence of a single-mode free-running continuum-wave operation of our laser system.
Furthermore, the ability to resolve the hyperfine structures of both $^{85}$Rb and $^{87}$Rb isotopes
reveals us that the emission line-width of our system is, at least, less than the natural line-width of the transition, $\Gamma \sim 2\pi \times 6 \times 10^6$ Hz [13, 14] for the D2 line at 780 nm wavelength.

3. Electromagnetically induced transparency

The term EIT, acronym of Electromagnetically Induced Transparency, was introduced by Harris et al [15] in 1990 to show that a three-state atomic system exhibit a significant reduction in the absorption of a beam from a weak probe laser field in the presence of a strong laser field which couples an atomic transition that shares a common state with the transition coupled for the probe beam. The first experimental evidence of EIT was presented in 1991 [16] using high-power pulsed laser to produce the coupling and probe fields resonant with atomic transitions of strontium vapor. From that experiment, EIT has gained great attention in both theoretical and experimental aspects [17]. Although $\Lambda$-type EIT is the most common configuration used, multi-V-type [18] and ladder-type EIT [19] have been also reported.

Electromagnetically induced transparency involve three electronics transitions, commonly labeled $|1\rangle$, $|2\rangle$ and $|3\rangle$, and two laser beams: The strong pumping, driving or coupling beam of angular frequency $\omega_c$ is resonant with the $|2\rangle \rightarrow |3\rangle$ transition; and the weak probe beam (non absorbed by the medium) of angular frequency $\omega_p$ being scanned around the $|1\rangle \rightarrow |2\rangle$ transition. In the present paper we focus our attention in the experimental realization of $\Lambda$-type and multi-V-type EIT configurations using rubidium atom as the atomic medium and the diode laser system, described in the previous section, as the sources for the coupling and probe beams. The three energy states for these configurations are sketched in Fig.3 where the state $|2\rangle$ is used as the common state shared for the two EIT types.

The experimental setup, used for both multi-V and $\Lambda$-type EIT, is shown in Fig.4. Two diode laser systems equipped with their respective saturated absorption setups (for reference in
Figure 3. Three energy-levels diagrams for \( \Lambda \)-type (Left) and \( V \)-type (Right) EIT. In the two diagrams \((\omega_p, \Delta_1)\) and \((\omega_c, \Delta_2)\) denotes the angular frequency and the de-tuning from the probe and coupling laser beams, respectively.

frequency) produces the driving or coupling (Drive Laser) and the probe (Probe Laser) beams. Half-wave plates (HWP) and a polarizing-beam splitter cube PBS1 are used to control the polarization and the power of the beams interacting inside the vapor cell (Rb cell) filled with \(^{85}\text{Rb}\) and \(^{87}\text{Rb}\) isotopes at room temperature. At the polarizing-beam splitter cube PBS1 the two beams are recombined and sent to the rubidium cell: The probe laser beam is transmitted through the cube with horizontal polarization, while the driving laser beam is reflected with vertical polarization in the same cube. After their interaction with the atoms in the cell both the probe and the driving beam are separated using another polarizing-beam splitter cube PBS2: The transmitted probe beam is detected using a photo-detector and the photo-current signal is sent to an oscilloscope; the reflected driving beam is blocked. Two apertures, one at the input face and the other at the output face of the rubidium cell (not shown in the figure) are used to control the cross-sectional area of the beams and their co-propagation into the atomic medium.

Figure 4. Experimental setup for \( \Lambda \)-type and multi-\( V \)-type electromagnetically induced transparency. HWP: half-wave plate; PBS: polarizing beam-splitter cube.

Armed with this experimental setup we proceed to record the typical EIT and saturated absorption signals for the probe laser beam. The results are presented in the following two subsections.
3.1. Λ-type EIT

A general scheme for Λ-type EIT is presented in Fig.3 (Left): The driving laser beam of frequency \( \omega_c \) is tuned to the \(|3 \rightarrow 2|\) transition, while the probe laser beam is scanned around the \(|1 \rightarrow 2|\) transition. As mentioned above, in this EIT configuration the two field couples transitions from different ground levels to a common one high-energy level. In Fig.5 (Left) we show a typical probe laser beam absorption signal from the PD3 photo-detector (see Fig.4) with a clear EIT peak (red curves) together with the saturated absorption signal of the same beam, from which the hyperfine splitting of the \(5^2P_{3/2}\) state is clearly visible (blue curves); Fig.5 (Right) show the corresponding energy-level diagram for this EIT configuration. In this particular case the driving laser beam is resonant \( (\Delta_2 \approx 0) \) with the \(5^2S_{1/2} (F = 3) \equiv |3| \rightarrow 5^2S_{1/2} (F' = 3) \equiv |2| \) transition, with the probe laser beam being scanned around the \(5^2S_{1/2} (F = 2) \equiv |1| \rightarrow 5^2S_{1/2} (F' = 1, 2, 3) \equiv |2| \) transitions for \(^{85}\text{Rb}\). From those curves we see a non-absorption peak in the Doppler-broadened absorption spectra of the probe beam through the rubidium atoms cell “Rb cell” (see Fig.4) exactly at the \(5^2P_{3/2} (F' = 3) \) hyperfine level of \(^{85}\text{Rb}\), the same level coupled by the driving field resonant with the \(5^2S_{1/2} (F = 3) \equiv |3| \rightarrow 5^2S_{1/2} (F' = 3) \equiv |2| \). The power of the probe and coupling fields at the input face of the rubidium cell are 93 \(\mu\)m and 1.37 mW, respectively.

![Energy-level diagram for \(^{85}\text{Rb}\) with bold vertical lines showing the corresponding transitions coupled for the fields.]

**Figure 5.** Probe laser beam absorption versus probe frequency. Left: Doppler-broadened probe absorption signal with EIT peak (red curves) and saturated probe absorption signal (blue curves). Right: Energy-levels diagram for \(^{85}\text{Rb}\) with bold vertical lines showing the corresponding transitions coupled for the fields.

3.2. Multiple-V-type EIT

Electromagnetically induced transparency in V-configuration or V-type EIT has been observed experimentally and theoretically modeled in sodium atomic beam [20] showing a decreasing fluorescence and absorption related to the detuning of the probe and coupling fields. After that,
EIT in an open V-type Na$_2$ molecular system, in both co- and counter-propagating arrangements for the direction of propagation of the driving and probe fields, was also experimentally observed and simulated [21]. Cesium atoms have been used in experimental observation of absorption and dispersion in V-type configuration [18] and in multi-V-type EIT and hyperfine structure of atomic levels measurement [22]. Using rubidium atoms as the atomic medium, V-type mismatched EIT of a probe laser field tuned to the $^5\!S_{1/2} \rightarrow ^6\!P_{3/2}$ transition at 420 nm wavelength, using a low power near infrared driving field at 780 nm wavelength, has also been experimentally observed and theoretically modeled [23], and a detailed experimental investigation and theoretical analysis of a V-type EIT using $^{85}\!$Rb isotope, showing seven transparency windows- with a double-peak-structure included- have been also reported [24].

![Schematic diagram of energy levels](image)

**Figure 6.** Schematic energy-levels structure of a multi-V-type EIT configuration. $\omega_c$ and $\omega_p$ denotes the frequency of the coupling and probe beams, respectively. $\Delta p_i$ and $\Delta c_j$ (with $i, j = 2, 3, 4$) denotes detuning of the probe and coupling fields from the $|i\rangle$,$|j\rangle$ levels.

A schematic diagram of the energy levels involved in a multi-V-type EIT configuration, adapted from Ref.[24], is shown in Fig.6. In Fig.6.a) the coupling laser beam of frequency $\omega_c$ is seen blue shifted by an amount $\Delta c_2$ from the transition $|1\rangle \rightarrow |2\rangle$ and the probe laser beam, being swept in frequency around the $|1\rangle \rightarrow |2\rangle$, $|3\rangle$, $|4\rangle$ transitions, can be seen blue shifted by the amounts $\Delta p_2$, $\Delta p_3$ and $\Delta p_4$ from the $|1\rangle \rightarrow |2\rangle$, $|1\rangle \rightarrow |3\rangle$ and $|1\rangle \rightarrow |4\rangle$ transitions, respectively. Figures 6.b) and 6.c) represent similar situations where the coupling field is seen red shifted by the amounts $\Delta c_3$ and $\Delta c_4$ from the $|1\rangle \rightarrow |3\rangle$ and $|1\rangle \rightarrow |4\rangle$ transitions, respectively. The EIT structure will appear when the two-photon resonance condition $\Delta p_i = \Delta c_j$ (with $i, j = 2, 3, 4$) be satisfied by the sweep in frequency of the probe field. As pointed in the reference, this is the origin of the multi-EIT-windows for this configuration.

In this paper we do not make any theoretical analysis nor a detailed experimental investigation of the multi-V-type EIT, but we show that our low cost low power diode laser system also can be used for this type of research. In Fig.7 we show a Doppler-broadened probe laser beam absorption signal (red curves) for a multi-V-type EIT experiment at the D2 line of $^{85}\!$Rb atoms at 780 nm wavelength. Also in the same figure we show a typical saturated absorption signal for the same probe beam (blue curves). In this particular case we set the frequency of the coupling laser beam resonant with the frequency of the $^5\!S_{1/2} (F = 3) \rightarrow ^5\!P_{3/2} (F' = 2)$ transition, being the
Figure 7. Probe laser beam absorption versus probe detuning. Doppler-broadened probe laser beam absorption signal with EIT peaks (red curves) and saturated probe absorption signal (blue curves) of $^{85}$Rb for the transition $5^2 S_{1/2} (F = 3) \rightarrow 5^2 P_{3/2} (F' = 2, 3, 4)$ of the D2 line at 780 nm wavelength.

probe laser beam scanned around the $5^2 S_{1/2} (F = 3) \rightarrow 5^2 P_{3/2} (F' = 2, 3, 4)$ transitions. The Doppler-broadened curve shows a non-absorption peak for the probe laser beam exactly at the $5^2 S_{1/2} (F = 3) \rightarrow 5^2 P_{3/2} (F' = 2)$ transition, the same transition coupled for the driving laser field (typical signature of the EIT phenomenon), together with a very weak peak followed by a double-peak-structure. Our experimental result agree partially with those reported in Ref.[24] and we attribute this to different experimental conditions, such as, coupling and probe field powers, line-width of our diode laser systems and the temperature of the rubidium sample.

4. Conclusions

In conclusion, we have reported the experimental implementation of electromagnetically induced transparency in $\Lambda$-type and multi-$V$-type configurations in a cell of rubidium atoms at room temperature. For the former, our results are in agreement with the ones previously reported in the literature, showing the clear EIT window for a weak probe laser beam interacting with an atomic sample pumped by another coherent laser field. For the latter, our results are in partial agreement with result recently reported in the literature and we attribute this to different experimental conditions, such as, coupling and probe laser beam powers, line-width of our diode laser systems and the temperature of the rubidium sample. For the realization of these experiments we developed low-cost, low-power diode laser systems in a continuum wave (cw) and single mode operation, stabilized in temperature and current controlled, tuned to the D2 line of rubidium atoms at 780.2 nm, whose spectral characteristics were also showed by standard direct and saturated absorption spectroscopy techniques. Among others applications, these simple
experiments can be used as a low-cost and suitable ones in undergraduate laboratory in atomic physics, laser physics, coherent light-atom interaction, and high resolution atomic spectroscopy.

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