Analysis of high-efficiency widely-tunable N-resonances in Cs vapor

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Abstract. The narrow-band coherent N-type resonance, promising for the development of advanced atomic clocks, can be considered as a type of three-photon resonance, where a two-photon Raman excitation is combined with a resonant optical pumping field. In this communication, we present an experimental study and a theoretical analysis related to three-photon, bi-chromatic excitation of Cs atomic vapor contained in an 8-mm long cell with 20 Torr of neon. If a coupling laser is fixed at a frequency that is lower by several GHz than the position of the absorption profile of the F\textsubscript{0} = 4 set of transitions, and a probe laser is tuned over the D\textsubscript{2} line (λ = 852 nm), a narrow high-contrast enhanced absorption N-resonance will be observed in the probe light profile, superimposed on the absorption profile of the F\textsubscript{0} = 4 set of transitions. We present theoretical modeling aimed to clarify the processes behind the efficiency of the N-resonance preparation for different frequency positions of the coupling laser within the D\textsubscript{2} line of Cs.

1. Introduction
Coherent laser spectroscopy of alkali vapor contained in thermal optical cells is widely used in various applications; among them wavelength references, atomic clocks, precise optical magnetometers, slow and stored light, photonic sensors based on coherent population trapping (CPT), electromagnetically-induced transparency (EIT) resonances, etc. For these applications, various research groups are still exploring suitable approaches aimed at a profitable combination of the advantages of CPT/EIT with other processes. Recently, optical systems based on Rb atoms, in which narrow-band N-type resonances appear, have been extensively studied [1-4]. The N-resonance has been considered as a type of three-photon resonance, where a two-photon Raman excitation is combined with a resonant optical pumping field. Experimental works related to the three-photon, bi-chromatic excitation of Cs atomic vapor contained in an 8-mm-long cell with 20 Torr of neon have been reported in ref. [5-7].

In this communication, we report on an experimental study complemented by theoretical modeling of the related processes and analyze the N-resonance preparation for different frequency positions of the coupling laser within the D\textsubscript{2} line of Cs. A coupling laser was fixed at a frequency lower than the

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position of the absorption profile of the \( F_g = 4 \) set of transitions, while the probe laser was tuned over the \( D_2 \) line (\( \lambda = 852 \) nm). A high-contrast narrow enhanced-absorption N-resonance was observed in the probe light profile, superimposed on the absorption profile of the \( F_g = 4 \) set of transitions. The theoretical model proposed, based on Bloch optical equations, is briefly described here in order to introduce the theoretical simulation concept. The theoretical model will be discussed in detail in a further communication. The simulation shows the formation of an enhanced absorption N-resonance superimposed on the \( F_g = 4 \) absorption profile at a frequency position depending on the coupling beam frequency position.

2. Experimental setup

Figure 1 shows a schematic diagram of the experimental setup, which is similar to that used in ref. [6, 7]. Two narrow-band distributed feedback (DFBs) lasers are used. The coupling laser has a fixed frequency \( \nu_c \), while the probe one with frequency \( \nu_p \) is tuned over the \( D_2 \) line. Both laser beams have a 3\( \times \)2-mm spot size and are carefully superimposed on a beam splitter BS and then directed at the 8-mm-long optical cell. The polarizations of the coupling and probe lasers are linear and mutually orthogonal. The optical cell is filled with atomic cesium with 20 Torr of neon gas added as a buffer. Part of the probe radiation is directed to an additional cell with a thickness \( L = 6\lambda \) used as a frequency reference.

In the experiments, the transmission signals of the probe and coupling beams were registered with the probe beam scanned in a frequency interval covering the entire \( D_2 \) line absorption. The probe beam was separated from the coupling one by a polarizing beam splitter. The broad transmission spectrum of the probe laser beam was measured with a two-photon resonance superimposed on it, for different frequency positions of the coupling beam.

![Figure 1](image)

**Figure 1.** Schematic diagram of the experiment: DFB – distributed feedback diode-laser: coupling and probe, BS – beam splitter, PBS – polarizing beam splitter, interference filter at the wavelength of 852 nm. The \( L = 6\lambda \) cell provides a reference spectrum.

3. \( N_p \) resonance within \( F_g = 4 \) absorption profile

In this section, we will briefly discuss the N-resonance superimposed on the absorption profile of the \( F_g = 4 \) set of transitions (also reported in ref. [5, 6]). Because the resonance is observed in the probe-beam transmission, hereinafter it is referred to as \( N_p \) resonance.

A schematic diagram of the relevant atomic levels and optical transitions is shown in figure 2. The lower levels used to form the required \( \Lambda \) system are the two ground \( F_g = 3, 4 \) levels, the upper level being \( 6P_{3/2} \), which consists of four hyperfine levels \( F_c = 2, 3, 4, 5 \). The probe laser frequency \( \nu_p \) is tuned over the \( F_g = 4 \rightarrow F_c = 3, 4, 5 \) set of transitions, and the coupling laser frequency \( \nu_c \) is fixed. In the probe-beam transmission spectrum, an N-type resonance involving a two-photon process was
observed when the two-field frequency difference was $\nu_p - \nu_c = \Delta$, where $\Delta$ is the splitting ($\Delta = 9.2$ GHz) of the electronic ground state hyperfine levels. Figure 3 shows the experimentally observed $N_p$-resonances of enhanced absorption for two different frequency positions of the coupling beam. While the frequency of the coupling laser is fixed at two different positions within the lower-frequency wing of the $F_g = 4$ profile, the absorption of the probe laser is measured as a function of its frequency detuning. In both figures 3a and 3b, the $N_p$-resonance frequency position is shifted from that of the coupling laser by the electronic ground-state hyperfine level splitting $\Delta = 9.2$ GHz. Note that, although the coupling-beam frequency position is about 9.2 GHz lower than the $F_g = 4$ (and 18.4 GHz lower than the $F_g = 3$) set of transitions, the coupling demonstrates good-absorption Doppler-broadened profiles when the probe beam is in resonance with the $F_g = 4$ or $F_g = 3$ set of hyperfine transitions. Thus, the relatively strong laser intensity used, the high atomic source temperature and the buffer gas ensure efficient velocity-changing collisions and excitation transfer between Cs atoms.

**Figure 2.** Probe frequency $\nu_p$ is scanned over the $F_g=4 \rightarrow F_e=3,4,5$ transitions, while the coupling ($\nu_c$) is fixed at a lower frequency [5, 6].

**Figure 3.** Probe-beam spectrum of the $D_2$ line involving the $N_p$ resonance situated within the $F_g = 4$ absorption set and the fixed-frequency coupling-beam absorption, demonstrating two Doppler profiles. Fluorescence spectrum of the $L = 6\lambda$ cell used as a frequency reference. The coupling-beam frequency position is not shown, because it is well outside the probe frequency scan, in order to resolve the sub-Doppler features of the reference.

### 3. Theoretical simulation

To clarify the processes behind the $N$-resonance preparation and its dependence on the frequency positions of the coupling laser within the $D_2$ line of Cs, a theoretical modeling based on the Bloch optical equations is briefly described below.

Strong coupling and probe radiations are applied to a three-level atom (see figure 4a) with energy levels $(a, b, c)$. The coupling radiation has a fixed frequency $\omega_c$ corresponding to a transition from the lower level $b$ to a hypothetical level $h$ ($b \rightarrow h$), separated from the energy level $c$ by a gap $\Delta = E_b - E_c$. The probe frequency $\omega_p$ is tuned over a broad range of frequencies $(a \rightarrow c)$. When the probe frequency is such that the Raman condition $\omega_c - \omega_p = E_b - E_a$ is satisfied, a very sharp peak appears at the frequency $\omega_p = \omega_{bc}$.

The density matrix equations for the four-level system were written and the Bloch optical equations were solved numerically. As a result, we obtained a sharp resonance peak sitting on top of the $b \rightarrow c$
absorption transition from the $F_g = 4$ level, when the coupling frequency is tuned exactly to the $b \rightarrow h$ transition (figure 4b). This sharp peak moves away and weakens when the coupling frequency is moved away from the $b \rightarrow h$ transition to the $b \rightarrow c$ transition. Comparing the theoretical simulations with the experimental results show that the theoretical modeling proposed is in good agreement with the experimental observations, as its reproduces well the N-resonance position and its amplitude, depending on the coupling-beam frequency.

**Figure 4.** (a) Coupling and probe transitions for an N-type resonance observed in $F_g = 4$ absorption profile and (b) calculated sharp $N_p$ resonance on the $F_g = 4$ absorption peak ($b \rightarrow c$) for different values of the coupling frequency detuning: (1) $\omega_c = -9.192$, (2) $-8.992$ and (3) $-8.792$ GHz.

4. Conclusions
We studied a narrow $N_p$-resonance superimposed on the $F_g = 4$ profile of the $D_2$ line of Cs atoms in a cell with a thickness of 8 mm in the presence of neon at a pressure of 20 Torr. The behavior of the N-resonance was demonstrated in the absorption of the probe beam measured as a function of its frequency detuning. A theoretical modeling based on the Bloch optical equations was proposed in view of studying the formation of the $N_p$-resonance in the $F_g = 4$ absorption profile for different frequency positions of the coupling beam.

The observation of a very good contrast and a sub-natural-width $N$-resonance and the simplicity of the experimental realization can be of interest for a large variety of fundamental and applied problems in optics and laser spectroscopy.

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**References**
[1] Zibrov A S, Ye C Y, Rostovtsev Y V, Matsko A B and Scully M O 2002 Phys. Rev. A 65 043817/4
[2] Zibrov S, Novikova I, DPhillips D F, Taichenachev A V, Yudin V I, Walsworth R L and Zibrov A S 2005 Phys. Rev. A 72 011801(R)/4
[3] Novikova I, Phillips D F, Zibrov A S, Walsworth R L, Taichenachev A V and Yudin V I 2006 Opt. Lett. 31 2353-55
[4] Novikova I, Phillips D F, Zibrov A S, Walsworth R L, Taichenachev A V and Yudin V I 2006 Opt. Lett. 31 622-4

[5] Slavov D, Sargsyan A, Sarkisyan D, Mirzoyan R, Krasteva A, Wilson-Gordon A D and Cartaleva S 2014 J. Phys. B: At. Mol. Opt. Phys. 47 035001

[6] Krasteva A, Slavov D, Sargsyan A, Sarkisyan D, Wilson-Gordon A D and Cartaleva S 2015 J. Phys.: Conf. Series 594 012009

[7] Krasteva A, Gateva S, Sargsyan A, Sarkisyan D and Cartaleva S 2017 Rom. Rep. Phys. 69 202