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SUB-NATURAL-WIDTH *N*-RESONANCES OBSERVED IN LARGE FREQUENCY INTERVAL

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Abstract. Sub-natural-width *N*-type resonance prepared in Λ–system on the D_2 line of Cs atoms is measured by two, couple and probe monomode laser beams. The probe light is scanned over very large spectral interval of more than 40 GHz. Fixing the couple frequency within this interval provides observation of enhanced-absorption SNW *N*-resonance at various frequencies, as well as *N*-resonance couple with equal sign and well-known frequency difference, or even couple with reversed signs.

Key words: *N*-type resonance, sub-natural resonance, two-photon Raman process.

1. INTRODUCTION

Coherent laser spectroscopy of alkali vapor contained in thermal optical cells is widely used for various applications, including frequency references, atomic clocks, precise optical magnetometers, slow and stored light, and photonic sensors based on coherent population trapping (CPT) and electromagnetically induced transparency (EIT) resonances, etc. For those applications, various research groups are still exploring suitable approaches aimed at a profitable combination of the advantages of CPT/ EIT with other processes. Optical systems based on Rb atoms, in which narrow band *N*-type resonances appear, have been extensively studied recently [1–4]. Such *N*-resonances can be considered as a type of three-photon resonance where a two-photon Raman excitation is combined with a resonant optical pumping field.

Recently, in Cs vapor excited by fixed-frequency coupling and tunable probe fields, a sub-natural-width (SNW) *N*-resonance has been observed superimposed on the probe beam absorption profile of the $F_g = 4$ hyperfine transitions (D_2 line).

Three photon, bi-chromatic excitation of Cs vapor, contained in a 10 mm long cell with 20 Torr of neon has been performed and applied for measurement of magnetic fields over a large range [5]. For Cs, the coupling beam absorption measurements allow the observation of the SNW *N*-resonance on a flat low-level background, well outside of the D_2 line spectrum [6].

In this communication, we report the SNW *N*-resonances measured well outside or between the two absorption profiles of the D_2 line. The probe scan is over a spectral interval of more than 40 GHz. Fixing the coupling frequency within this interval provides observation of: (i) enhanced-absorption SNW *N*-resonance at various frequencies, (ii) two *N*-resonances with equal sign and well-known frequency difference, or (iii) even with reversed sign of the second resonance, *i.e.* two *N* resonances with enhanced and reduced absorption.

The richness of the SNW features can be advantageous for new frequency references elaboration. Moreover, the coupling absorption spectra demonstrate several new peculiarities that can be useful for study the light-atom interactions in cells with large pressure of buffer gas and different alkali atom densities.

2. EXPERIMENTAL SET UP

Figure 1 shows a schematic diagram of the experimental setup, similar to that used in Ref. [6]. Two narrow-band Distributed Feedback (DFBs) diode-laser systems, used in our experiment are built by means of two DFB diodes, both with an emission spectral width of about 2 MHz (FWHM). The two laser systems show mode hope free laser frequency detuning, that largely exceed the absorption spectrum of the Cs D_2 line. The coupling laser has a fixed frequency ν_c, while the probe one with frequency ν_p is tuned over the D_2 line. Both laser beams have equal spots (of 3 × 2 mm) that are carefully superimposed on a beam splitter, BS and then directed at the buffered cell. The polarizations of the coupling and probe lasers are linear and mutually orthogonal. The L = 1 cm long optical cell is filled with atomic Cesium with 20 Torr of Neon gas added that serves as a buffer. Part of the probe radiation was directed to additional cell with thickness $L = 6\lambda$, which was used as a frequency reference. In the experiments, the transmission of the coupling beam is registered with the probe beam scanned in a frequency interval over the entire D_2 line absorption. The probe beam is separated from the couple one by a polarizing beam splitter. The broad transmission spectrum of the coupling laser was measured with a SNW, two-photon resonance superimposed on it, for different frequency positions of the coupling.

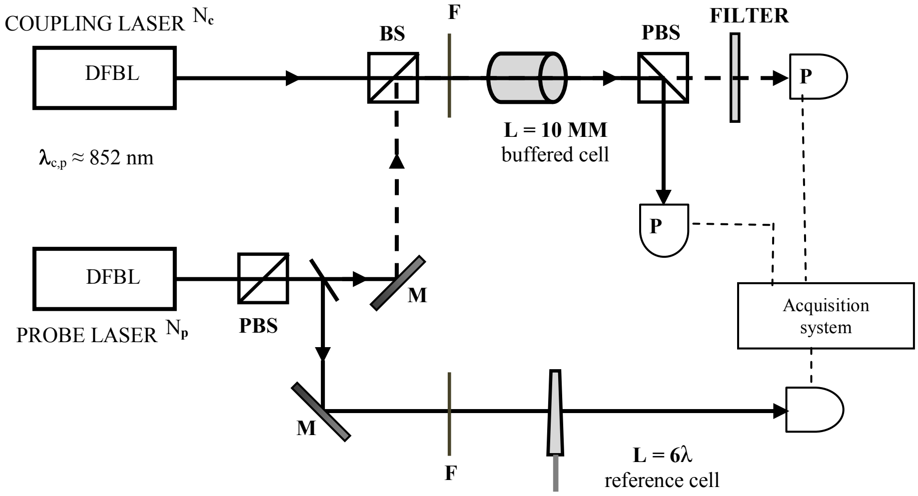

Fig. 1 – Schematic diagram of the experiment: DFBL – distributed feedback diode-laser: coupling and probe, PBS – polarizing beam splitters, P – photo diodes, M – mirrors, F – neutral optical filters, interference filter at the wavelength of 852 nm, and acquisition system. The SNW resonance is registered in the transmission of the L = 10 mm buffered cell.
The $L = 6\lambda$ cell provides a reference spectrum.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. FORMATION OF *N*-RESONANCE IN THE ABSORPTION OF THE FIXED FREQUENCY COUPLING BEAM

In the presented work, the absorption of the fixed-frequency couple beam is measured for constant Cs source temperature of $T = 72^{o}$ C and equal intensity of the coupling and probe beams of 500 mW/cm^2. The couple is fixed at different positions within the D_2 line and the parameters of the observed sub-natural-width *N* resonance, as well as other broader profiles in the couple absorption are discussed. Schematic diagram related to the *N*-resonance formation in ^{133}Cs atoms (D_2 line) is shown in Fig. 2a, where the coupling laser frequency is situated within the $F_g = 4$ reduced absorption profile. The involved atomic levels (the ground F_g = 3, 4 levels and the upper level $6P_{3/2}$, which consists of four hyperfine levels F_e = 2, 3, 4, 5), as well as the two-photon and the single-photon transitions, are shown. The probe laser frequency ν_P is scanned over a large spectral interval. As the coupling beam is in resonance with the absorption profile of the $F_g = 4$ set of transitions, Cs atoms are accumulated by the coupling light in the $F_g = 3$ level due to the hyperfine optical pumping. The accumulation is denoted by large gray circle.

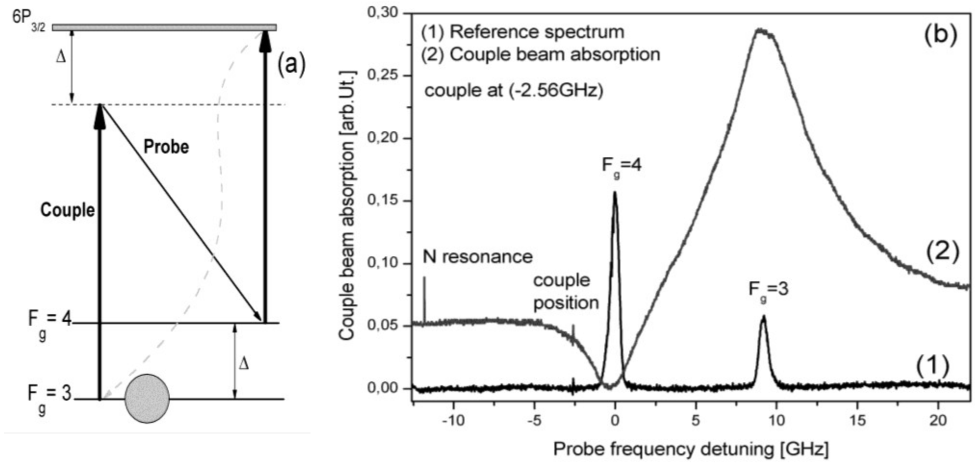

Fig. 2 – a) Probe frequency (ν_P) is scanned in large spectral interval, while the couple (ν_c) is fixed within the $F_g = 4$ set of transitions; b) the sub-natural-width *N* resonance in the low-frequency wing of the D_2 line absorption accompanied by two, more than two orders of magnitude broader absorption profiles: (i) about 3GHz width, reduced absorption profile (the $F_g = 4$ set of transitions) and (ii) about 10 GHz width enhanced absorption profile with maximum at the $F_g = 3$ set of transitions.

In the couple beam absorption spectrum, an *N*-resonance involving a two-photon process will be observed if the two-field frequency difference is $\nu_C - \nu_P = \Delta$, where Δ is the splitting ($\Delta = 9.2$ GHz) of the ground-state hyperfine levels. Thus, as the probe laser frequency decreases to $\nu_P = \nu_C - \Delta$, a bright *N*-resonance occurs, characterized by a sub-natural-width increase in absorption.

In Fig. 2b, the experimentally observed couple beam absorption A_c is shown as a function of the probe beam frequency ν_p detuning for a couple frequency fixed outside of the $F_g = 4$ absorption profile of the reference beam ($\nu_C = -2.56$ GHz). In case of two-photon Raman resonance, the atoms accumulated in the $F_g = 3$ level are transferred back to the $F_g = 4$ level by the coherent two-photon process, and are detected as enhanced absorption of the coupling beam, forming the *N* resonance situated on very low level flat background. During the probe beam detuning in resonance with the $F_g = 4$ set of transitions, when the Raman condition is not fulfilled, the couple beam experiences the lowest absorption $(A_c)^{min}$, due to the simultaneous depleting of $F_g = 4$ level by the couple and probe lights. Further rising of the probe light frequency results in increasement of the couple beam absorption. The maximal absorption of the couple $(A_c)^{max}$ is observed at the probe light frequency detuning to the $F_g = 3$ set of transitions (Fig. 2b). This can be attributed to the strong atomic accumulation in the $F_g = 4$ level when the probe beam frequency is detuned to the $F_g = 3$ set of transitions.

3.2. BRIGHT *N*-RESONANCE AND NEW FEATURES, FIXING COUPLE FREQUENCY AT DIFFERENT POSITIONS AROUND THE $F_g = 4$ OR $F_g = 3$ SET OF TRANSITIONS

In this section, we will take into account the couple frequency position fixed close to the maximum and in the wings of $F_g = 4$ (Fig. 3) or $F_g = 3$ (Fig. 4) absorption profiles. First, let's discuss the couple beam absorption at three different couple frequency detunings: (i) in the lower frequency wing of the $F_g = 4$ reference cell Doppler profile with $\nu_C = -1.52$ GHz (Fig. 3a), (ii) within reference cell profile at $\nu_C = 0.24$ GHz (Fig. 3b) and in the higher frequency wing of the reference cell profile, at $\nu_C = 1.4$ GHz (Fig. 3c).

At all three positions of the couple frequency, we observe very well pronounced bright SNW *N*-resonance. But the situation is different for the remaining part of the couple absorption profile. When the couple beam frequency ν_c is closer than in Fig. 2b to the $F_g = 4$ set center but still it is outside of the absorption profile of the reference cell, the couple absorption exhibits broad (about 10 GHz-width) enhanced absorption profile for the ν_p scanned in the region of the $F_g = 3$ set of transitions (Fig. 3a). However superimposed on it, a dip (denoted as *R* resonance) in the absorption profile appears (of approximately 0.8 GHz width) centered at the $F_g = 3$ set position. Similar is the case when the ν_c is fixed on the opposite slope of the $F_g = 4$ reduced absorption profile (Fig. 3c). Reduced absorption *R* resonance is reported earlier in Ref. [6], where it is shown that the resonance amplitude is influenced by the couple frequency detuning, but the resonance central frequency does not follow the shift of the frequency of the couple beam. Our systematic study shows that the *R* resonances are observed for the ν_c fixed in two narrow spectral intervals on both slopes of the reduced absorption profile of the couple, centered at $F_g = 4$. Hence, the conditions for the *R* resonance formation are rather critical.

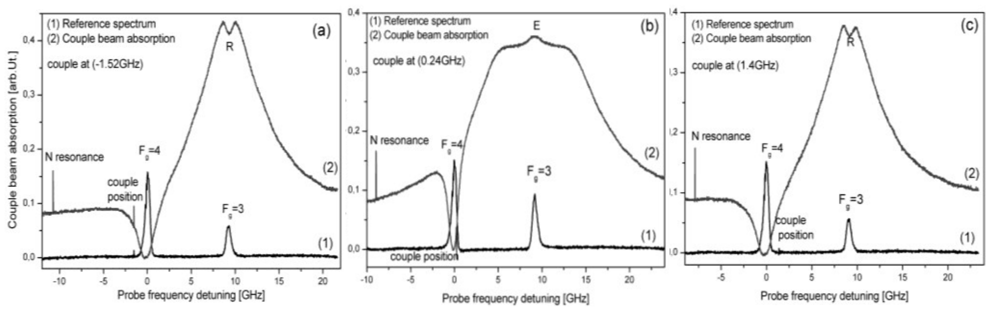

Fig. 3 – Absorption spectrum of the couple beam when its frequency is fixed at three different positions from the $F_g = 4$ absorption profile maximum, while scanning the probe one over spectral interval of more than 40 GHz. The positions of the couple beam frequency are: a) $\nu_c = -1.52$ GHz; b) $\nu_c = 0.24$ GHz; c) $\nu_c = 1.4$ GHz.

Surprisingly when the ν_c is fixed within the F_g = 4 absorption profile measured for the reference cell, the reduced absorption resonance *R* transforms into enhanced absorption resonance E (Fig. 3b). Note that in the last case, the reduced absorption profile (at F_g = 4) shows some narrowing (1.2 GHz width) while the enhanced absorption region is much broader (more than 17.5 GHz) than in Fig. 3a and Fig. 3c. The E resonance formation can be related to more effective optical pumping by the probe beam of the F_g = 4 level, for couple beam frequency fixed very close to the F_g = 4 set absorption center. In such a case more effective atomic population cycling between F_g = 4 and F_g = 3 levels can be reached in a spectral interval of the order of Doppler broadening.

Furthermore, we discuss the case where the coupling laser frequency is fixed within the absorption region of the F_g = 3 absorption profile. The related atomic levels, two-photon transition and the single-photon transitions are shown in Fig. 4. In this scheme, as the coupling beam is in resonance with the absorption profile of the F_g = 3 set of transitions Cs atoms are accumulated by the coupling light in the F_g = 4 level. In case of two-photon Raman resonance, the atoms accumulated in the F_g = 4 level are transferred back to the F_g = 3 level by the coherent two-photon process, and are detected as enhanced absorption of the coupling beam, forming the SNW bright *N* resonance observed this time at the high-frequency wing of the D_2 line. In this case, a broad enhanced absorption profile with maximum at the F_g = 4 set of transitions is formed (Fig. 5). During further probe beam detuning, the F_g = 3 level is strongly depleted by both beams, resulting in minimal couple beam absorption.

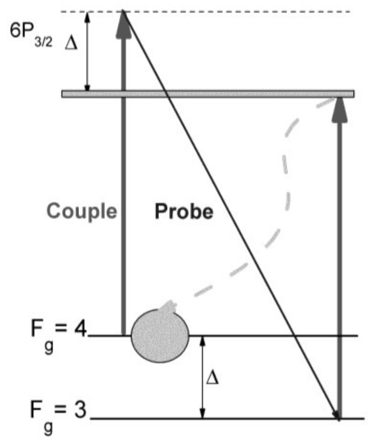

Fig. 4 – Probe frequency (ν_P) is scanned in large spectral interval, while the couple (ν_c) is fixed within the F_g = 3 set of transitions.

When the couple beam frequency ν_c is fixed at the wings of the reference cell profile, the couple absorption exhibits well pronounced dip *R* at the center of the F_g = 4 group absorption profile (Fig. 5a,c). For couple frequency detuned within the reference cell profile of the $F_g = 3$ set of transition (Fig. 5b), analogically to Fig. 4b we observed E peak at the center of the F_g = 4 profile.

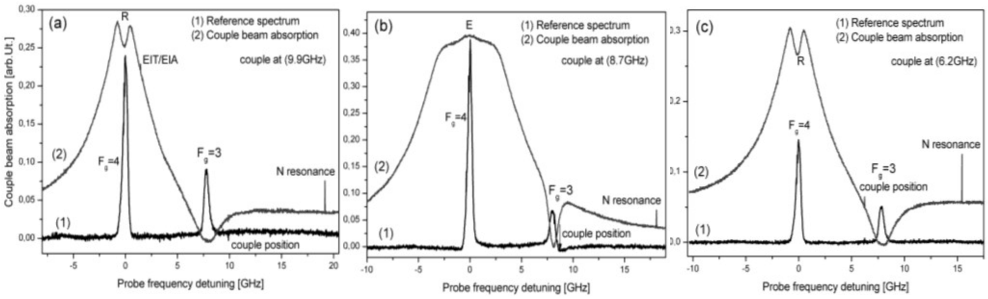

Fig. 5 – Absorption spectrum of the couple beam when its frequency is fixed at three different positions from the F_g = 3 absorption profile maximum, while scanning the probe one over spectral interval of more than 40 GHz. The positions of the couple beam frequency are: a) ν_c = 9.9 GHz; b) ν_c = 8.7 GHz; c) ν_c = 6.2 GHz.

3.3. DOUBLE BRIGHT *N*-RESONANCES FOR COUPLE FREQUENCY FIXED BETWEEN F_g = 4 AND F_g = 3 ABSORPTION PROFILES

Different is the case when the couple frequency is fixed between the F_g = 4 and F_g = 3 sets of transitions. Here for single probe frequency scan, two SNW bright *N* resonances are observed – one red frequency detuned from the F_g = 4 set profile and the other blue detuned from the F_g = 3 set profile. The corresponding atomic levels, the couple of the two-photon transitions and four single-photon transitions are shown in Fig. 6a. The coupling beam is between the two sets of hyperfine transitions. Under this condition, a small number of Cs atoms are accumulated by the coupling laser in the F_g = 4 and F_g = 3 levels. The small atomic accumulations are denoted by small gray circles in Fig. 6a.

During the probe beam detuning, one after the other both two-photon Raman resonances occur resulting in two enhanced absorptions of the coupling beam. In this way, namely two SNW bright *N* resonances are formed shown in Fig. 6b.

For the first N^1 resonance, the frequency of the probe beam ν^1_p at which the resonance is observed can be determined by the expression $\nu^1_p = \nu_c - \Delta$. In the case of second N^2 resonance formation, the respective probe frequency is $\nu^2_p = \nu_c + \Delta$. Note that the absorption spectrum of the couple beam differs significantly from those presented in Figs. 2, 3 and 5. The first difference is related to the much lower maximal value of the couple beam absorption shown in Fig. 6 than those shown in previous figures. In Fig. 6, the absorption rate of the coupling beam is low due to its frequency position (in far wings of absorption profiles of both sets of hyperfine transitions).

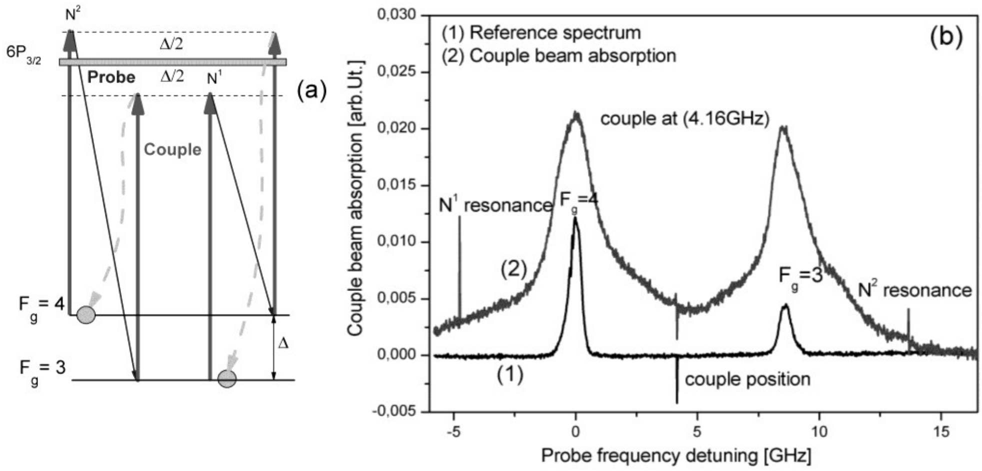

Fig. 6 – a) Probe frequency (ν_P) is scanned in large spectral interval, while the couple (ν_c) is fixed between the $F_g = 4$ and $F_g = 3$ absorption profiles; b) two sub-natural-width N resonances are observed – one red frequency (N^1) detuned from the $F_g = 4$ set profile and the other blue (N^2) detuned from the $F_g = 3$ set profile.

Hence, the optical pumping of the $F_g = 4$ and $F_g = 3$ levels by the coupling beam is very low. This accordingly results in low repopulation by the probe light when it is in resonance with $F_g = 4$ or $F_g = 3$ sets of transitions. Thus, the absorption of the couple beam remains very low along the entire detuning of the probe light excepting two small-absorption bumps at the $F_g = 4$ and $F_g = 3$ croups of hyperfine levels. As a second difference we underline the possibility of producing of two sub-natural-width enhanced absorption resonances with large and known frequency difference. Such result has a potential for the N resonance application as a frequency reference.

3.4. BRIGHT AND DARK *N*-RESONANCES AT LARGE COUPLE FREQUENCY DETUNING FROM THE $F_g = 3$ ABSORPTION PROFILE

Figure 7 concerns the case where the coupling laser frequency is fixed higher than the $F_g = 3$ absorption profile. The related atomic levels and transitions are shown in Fig. 7a. When coupling light is blue detuned in far wing of the absorption profile of the $F_g = 3$ set of transitions, a small amount of Cs atoms are accumulated by the coupling light in the $F_g = 4$ level. If the Raman condition is not fulfilled, the $F_g = 3$ level will be slightly depleted by the coupling beam providing some accumulation of atoms to the $F_g = 4$ level. In case of two-photon Raman resonance, the atoms accumulated in the $F_g = 4$ level are transferred back to the $F_g = 3$ level by the coherent two-photon process, and are detected as enhanced absorption of the coupling beam resulting in the bright N^1 resonance. However, the situation is different when the probe beam approaches the $F_g = 4$ set of transitions. Here the left couple in Fig. 7a is already with extremely low absorption rate and its optical pumping to $F_g = 3$ level is negligible. Due to this at the two-photon Raman resonance, the $F_g = 3$ level suffers some population loss that results in formation of dark N^2 resonance. Thus, the last *N* resonance is of opposite sign to all resonances previously discussed in this work.

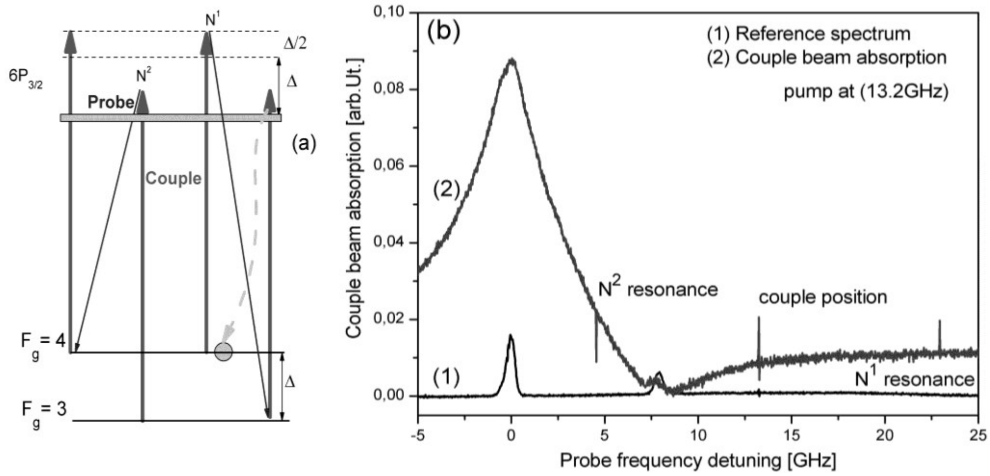

Fig. 7 – a) Probe frequency (ν_p) is scanned in large spectral interval, while the couple (ν_c) is fixed higher than the $F_g = 3$ absorption profile at $\nu_c = 13.2$ GHz; b) bright and dark sub-natural-width *N* resonances are observed – one of enhanced absorption of the coupling beam (N^1) and the other of opposite sign (N^2).

4. CONCLUSIONS

Systematic experimental study of sub-natural-width *N* resonance observed on the D_2 line of Cs vapor is presented. Three-photon, bi-chromatic excitation of Cs atomic vapor buffered by 20 Torr of neon is performed. The bi-chromatic excitation involves a fixed-frequency coupling beam and scanning the probe beam across the D_2 line. The absorption of the coupling beam is measured as a function of the probe frequency detuning. The probe light frequency is scanned in a large spectral interval (more than 40 GHz) that allows not only to observe single and double *N* resonances, but also to clarify the conditions for observation of two Doppler broadened features: reduced absorption *R* and enhanced absorption *E* resonances. Still the physical processes behind the two last resonances are not clarified. Further theoretical analysis will be performed to study the optical pumping by the couple and re-pumping by the probe beams and their influence to the constant frequency coupling laser.

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