Switching from "absorption within transparency" to "transparency within transparency" in an electromagnetically induced absorption dominated transition

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The absorption of a resonant coupling laser driving a closed degenerate two-level system in an atomic cesium beam was investigated as a function of the detuning of a second laser probing the same transition. The measurements were performed for four different polarization combinations of the two laser beams. Except for the beams of counterrotating polarizations all coupling-laser absorption profiles showed "absorption within transparency," i.e., the absorption in the region around the two-photon resonance was smaller than the absorption corresponding to the one-photon transition induced by the coupling laser, and an extra absorption peak was observed on this curve at the two-photon resonance. With regard to the beams of counterrotating polarizations we observed a switch from absorption within transparency to "transparency within transparency" when the probe-laser power exceeded the constant coupling-laser power. In other words, the cesium ensemble became mostly transparent to the coupling-laser beam at the two-photon resonance. © 2008 Optical Society of America

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Since the first detection of electromagnetically induced absorption (EIA) [1,2] much attention has been paid to the probe-laser absorption profile when both the probe and coupling lasers are linearly polarized with orthogonal polarizations. Publications also exist discussing the Hanle configuration (e.g., [3,4]) or the probe-laser absorption coefficient where at least one of the lasers' polarization is circular (e.g., [5–8]). However, few papers discuss experimental measurements of the coupling laser, all treating linear polarizations [9,10]. To our best knowledge, this Letter is the first comparison of coupling-laser absorption profiles taken at nearly identical laser powers but different laser polarizations.

All measurements were conducted in the cesium D_2 line hyperfine transition $6s\,{}^2S_{1/2}$, $F=4 \to 6p\,{}^2P_{3/2}$, $F=5$. The experimental setup (see Fig. 1) was similar to the one described in [9], the substantial difference being the polarization of the light. All lasers were stabilized by an external optical cavity. This resulted in laser linewidths narrower than 100 kHz. The coupling laser was locked to the atomic-transition frequency by frequency modulation spectroscopy. The other lasers were phase-locked to the coupling laser by a chain of phase-lock loops. The third laser (reference laser) was needed for phase-locking purposes only. It was 1 GHz detuned from the atomic transition frequency.

At first, all beams were linearly polarized. The probe-laser plane of oscillation was adjusted to be orthogonal to that of the coupling laser ($\pi \perp \pi$). All beams were superimposed by means of a beam splitter and then coupled into a single-mode fiber for mode-matching. The resulting beam had a waist of 1.1 mm in the interaction zone. The light crossed the

thermal atomic beam (atomic density $4 \times 10^{15}\,\mathrm{m}^{-3}$, beam diameter 5 mm) perpendicularly to its direction of propagation. Using six coils oriented in the three different spatial directions, the magnetic field in the interaction zone was suppressed below 0.6 μT. After passing this region the light was separated by a Wollaston prism and detected by photodiodes (PD^S). The signal-to-noise ratio of the signals was improved by dividing the signals registered after the interaction zone with reference signals taken before the interaction zone (at PD^R) [11].
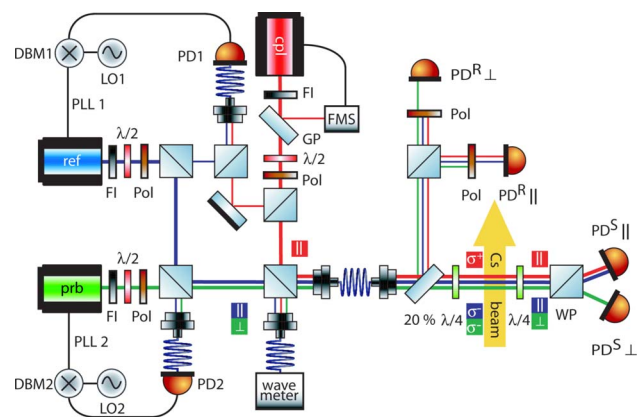

Fig. 1.   (Color online) Experimental setup for $\sigma^+\sigma^-$ polarized lasers. ∥, parallel polarization; ⊥, perpendicular polarization; σ, circular polarization; 20%, 20% beam splitter; cpl, coupling laser; prb, probe laser; ref, reference laser; DBM, double-balanced mixer; FI, Faraday isolator; FMS, frequency modulation spectroscopy; GP, glass plate; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; LO, local oscillator; PD, photodiode; PD^R, reference photodiode; PD^S, signal photodiode; PLL, phase-lock loop; Pol, polarizer; WP, Wollaston prism.

For measurements with the beams of counterrotating circular polarizations ($\sigma^+\sigma^-$) two quarter-wave plates were inserted: one just in front of the interaction area and the second directly behind it. To study the coupling-laser absorption profile of a circularly polarized coupling laser and a linearly polarized probe laser ($\sigma^+\pi$) a quarter-wave plate was put in the coupling-beam path before superposing it with the other lasers. With the insertion of a quarter-wave plate in the probe-beam path rather than in the coupling-beam path experiments with a linearly polarized coupling and a circularly polarized probe laser ($\pi\sigma^-$) were conducted. To detect the coupling-laser absorption profile in this configuration an additional quarter-wave plate after the interaction region was needed. In any circular-linear polarization configuration only one of the PD^S (and, respectively, PD^R) was used.

We studied the coupling-laser absorption profile for four different polarization combinations at a comparable coupling-laser power ($113-125\,\mu$W) as a function of the probe-laser detuning δ from the atomic resonance frequency at various probe-laser powers. The results of our measurements when at least one laser was linearly polarized are presented in Figs. 2(a)–2(c). All curves show absorption within transparency: the absorption coefficient α around the two-photon resonance is smaller than that at the one-photon resonance; at the two-photon resonance itself there is an absorption peak.

The coupling-laser absorption profiles for $\sigma^+\sigma^-$ polarized light were fundamentally different from all other cases of laser polarization. As depicted in Fig. 3, we detected a switch of the two-photon resonance peak from absorption to more transparency. This happened when the varied probe-laser power exceeded the coupling-laser power. The same flip was observed at several other coupling-laser powers between 100 and 250 μW whenever the probe-laser power became greater than the power of the coupling laser. We called this phenomenon a switch from absorption within transparency to transparency within transparency.
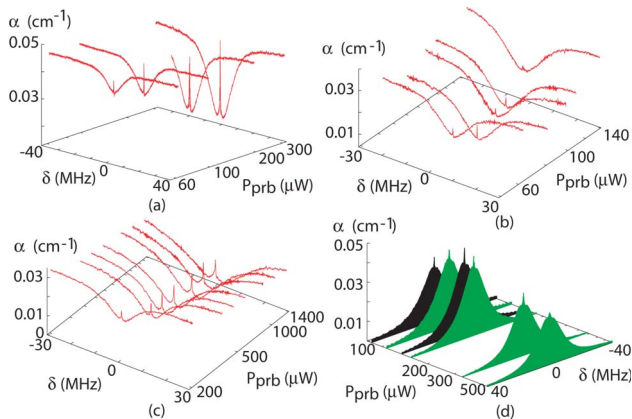

Fig. 2.   (Color online) Absorption coefficient of the coupling (a)–(c) and probe laser (d) for the following polarizations and coupling-laser powers: (a) $\pi\perp\pi$, 125 μW; (b) $\pi\sigma^-$, 113 μW; (c) $\sigma^+\pi$, 118 μW; (d) $\sigma^+\sigma^-$, 122 μW.
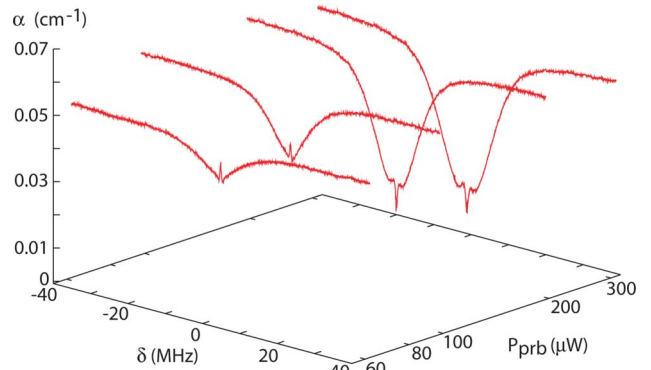

Fig. 3.   (Color online) Absorption coefficient of the coupling laser. Both laser beams are counterrotatingly polarized. The coupling-laser power amounts to 125 μW.

To explain this behavior, one has to keep in mind the conditions for EIA [1,12]: At least two levels in both the excited state and the ground state are needed to spontaneously transfer coherence. Consequently, the simplest system showing EIA is an N-system. During our measurements we worked in a closed two-level system of multiple degeneracy. One could assume that this system consisted of a combination of numerous subsystems. Depending on the lasers' powers the role of the N-systems or that of the V-systems was preponderant.

For $\sigma^+\sigma^-$ polarized light and a coupling-laser power larger than that of the probe laser the atomic transition was dominated by an N-system, thus showing EIA and absorption within transparency. When the probe-laser power was increased, the degree of openness of the system started to play a crucial role. In the $\sigma^+\sigma^-$ configuration transfer channels between the various N-systems were present (e.g., the decay from level 2 to level 5 in Fig. 4). In this way the oscillating population of the initial N-system decreased, and the coherence between state 2 and state 4 was reduced. Hence, the spontaneously transferred coherence into the superposition of levels 1 and 3 diminished. As long as the probe-laser power was weaker than the coupling-laser power the effect was too small to have a bearing on the absorption spectra. When the probe-laser power became larger than the coupling-laser power, the population reshuffled from the initial N-system to N-systems and V-systems. According to [12] a V-system shows transparency at the two-photon resonance. This publication also illustrates that an absorption spectrum of an atomic transition is given by individual contributions of each subsystem (see also [13]). In agreement with this idea, in
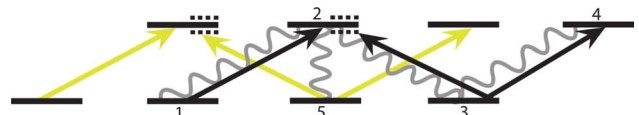

Fig. 4.   (Color online) Schematic of an open N-system. Curves symbolize spontaneous emission processes. Arrows represent laser transitions; dark lines build the so-called "initial" N-system (see text), and light-colored arrows picture another N-system. The coupling laser is σ^+ polarized; the probe laser is σ^- polarized.

our experiment we observed a superposition of several subsystems that led to an increase of transparency at the two-photon resonance for probe-laser powers larger than that of the coupling laser.

The switch from absorption to more transparency could only be measured for the beams of counter-rotating circular polarizations because the system was the most open one. For $\pi \perp \pi$ light the system was completely closed at any power of the two lasers; i.e., all Zeeman sublevels were connected by electromagnetic radiation. In the $\sigma^+ \pi$ case the initial N-system became open only when the probe-laser power was comparable to that of the coupling laser. At these powers the distribution of population in the Zeeman sublevels was similar to that of the $\pi \perp \pi$ configuration. Consequently, it did not result in a switch of the two-photon absorption peak. An analogous discussion applies to the $\pi \sigma^-$ case.

To investigate variations in the absorption profile for the four polarization combinations in more detail we fitted to each measured curve the function

$$f(x) = C_0 + \frac{C_1 \cdot G}{G^2 + (x - O_1)^2} + \frac{C_2 \cdot K}{K^2 + (x - O_2)^2}. \qquad (1)$$

C_0 is a constant shift; the second and third terms describe Lorentz profiles. The second term was fitted to the broader absorption curve induced only by the probe laser. G is the half-width at half maximum (HWHM) of that line. The third term was fitted to the two-photon resonance peak with HWHM K. C_1 and C_2 are constant scaling factors. The factors O_i ($i = 1, 2$) account for the detunings from the two-photon resonance.

For all polarizations the HWHM of the two-photon absorption peak broadened for enhancing probe-laser powers ($0.04 - 1.10$ MHz) except for the $\pi \sigma^-$ case, where it remained constant within the error limits. The broadest signals were obtained for $\sigma^+ \sigma^-$ polarized light. By dividing C_2 by K we obtained the absolute height of the two-photon resonance absorption peak. A comparison showed no correlation between incident polarization and peak height for probe-laser powers below 190 μW. Above this power the peak height increased for $\pi \perp \pi$ and $\sigma^+ \pi$ and decreased for $\sigma^+ \sigma^-$ polarized light. The largest signals were detected for pure linearly polarized light. At comparable probe-laser powers they were twice as high as the signals in the $\sigma^+ \pi$ case.

After discovering the polarization-and-power-dependent switch of the two-photon absorption peak for the coupling laser in the $\sigma^+ \sigma^-$ adjustment, we were interested in the behavior of the probe laser in that configuration. Therefore, measurements with $\sigma^+ \sigma^-$ polarized lasers and a constant coupling-laser

power of 122 μW were conducted, while the probe laser was changed over a wide interval in power around 122 μW. In doing so we obtained the probe-laser spectra pictured in Fig. 2(d). The probe laser showed EIA for all probe-laser powers. Hence, a change in the absorptive behavior of a coupling laser did not imply a modification of the probe-laser spectra as also theoretically demonstrated in [12].

In conclusion, we have investigated the coupling-laser spectra for four coupling-and-probe-laser polarizations ($\pi \perp \pi$, $\pi \sigma^-$, $\sigma^+ \pi$, and $\sigma^+ \sigma^-$) at comparable, constant coupling-laser powers and over a comparable range of probe-laser powers in a degenerate two-level system. When at least one laser was linearly polarized exclusively absorption within transparency was observed. However, still showing the probe-laser EIA, we detected a switch from absorption within transparency to transparency within transparency for the coupling laser when both lasers were counterrotatingly polarized and the varied probe-laser power exceeded the constantly held coupling-laser power. It remains an open question whether a corresponding switch from positive to negative parametric dispersion may be observed.

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