

Nonlinear Behavior of Circularly Polarized Laser Beams Propagating through Sodium Vapor

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A variety of surprising effects arise from the nonlinear light-matter interaction of circularly polarized laser light propagating through sodium vapor. We present experimental evidence for an asymmetry in the absorption of left hand and right hand circularly polarized light as well as for the creation of a collimated light beam of apposite polarization within the light-matter interaction region. Both effects are not yet explained by common theories.

The propagation of intense laser light through a nonlinear medium shows interesting and unexpected phenomena such as self induced transparency, self focusing and defocusing, spontaneous pattern formation, symmetry breaking, nonlinear wave guiding, transverse mode excitation, optical bistability, intensity oscillations and transition to chaos, self pulsing or four wave mixing [1]. Only a few experiments investigated the propagation of circularly polarized laser beams in atomic vapors which can give rise to surprising spatio-temporal intensity and polarisation patterns depending on the specific experimental arrangement.

In our experiments we have used two co-propagating circularly polarized laser beams tuned to the atomic D1 transition of sodium. Their nonlinear interaction can lead to “beam bouncing” [2], “beam switching” [3] and “beam splitting” [4]. In contrast to earlier work by Tam and Happer [5] we use buffergas which allows us to describe the sodium D1 transition in terms of a homogeneously broadened four level system and to assume polarized sodium atoms to be confined to the laser beam region [6].

In the course of investigating these effects we found that even one circularly polarized laser beam can show unexpected nonlinear behavior, which is not yet explained by common theories. Here we present experimental evidence for a nonlinear dependence of the absorption profile on power and polarization of the input beam, atomic density of sodium and magnetic fields.

Absorption profiles for different values of input beam power are shown in Fig. 1 a for right hand circularly polarized light (σ_- , electric field vector rotates anti-clockwise in an observer plane viewed along the beam propagation direction, photon spin anti-parallel to the propagation direction of the laser beam) and in Fig. 1 b for left hand circularly polarized light (σ_+). At

low input powers, where both absorption profiles for left and right hand circularly polarized input beams are identical. The point of maximum absorption (symbol Δ) is shifted towards lower frequencies in a) and towards higher frequencies in b) as the input beam power is increased.

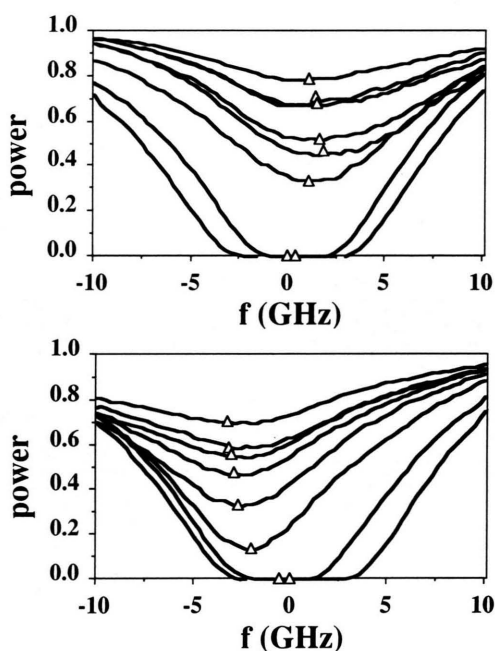


Fig. 1. Absorption profiles at different input beam powers (from bottom to top 0.2 mW, 0.5 mW, 1 mW, 1.6 mW, 2 mW, 3.1 mW, 3.4 mW, 4 mW), a) for right hand circularly polarized input beam σ_- and b) for left hand circularly polarized input beam σ_+ . Zero frequency indicates the frequency of maximum absorption at low input powers, where both absorption profiles for left and right hand circularly polarized input beams are identical. The point of maximum absorption (symbol Δ) is shifted towards lower frequencies in a) and towards higher frequencies in b) as the input beam power is increased.

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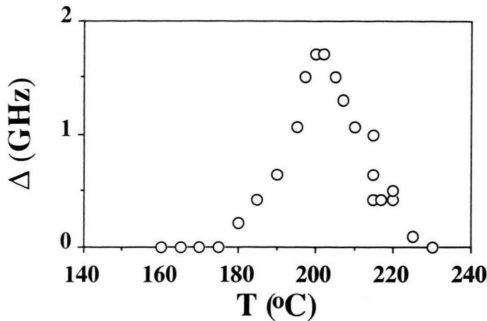


Fig. 2. Frequency difference Δ as a function of sodium cell temperature. Corresponding densities of sodium atoms are $3.4 \cdot 10^{17} \text{ m}^{-3}$ at 160°C , $3.3 \cdot 10^{18} \text{ m}^{-3}$ at 200°C and $2.5 \cdot 10^{19} \text{ m}^{-3}$ at 240°C . Power of input beam: 2 mW, beamwaist at cell input window: $80 \mu\text{m}$.

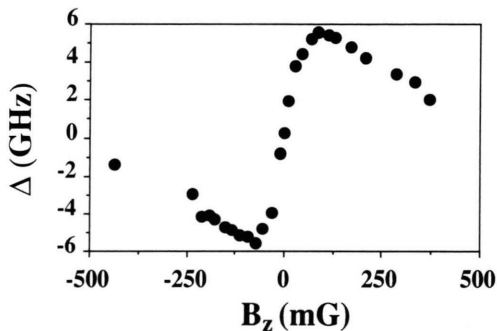


Fig. 3. Frequency difference Δ as a function of the external magnetic field B_z along the laser beam propagation direction. Cell temperature 210°C , power of input beam: 2 mW, beamwaist at cell input window: $200 \mu\text{m}$.

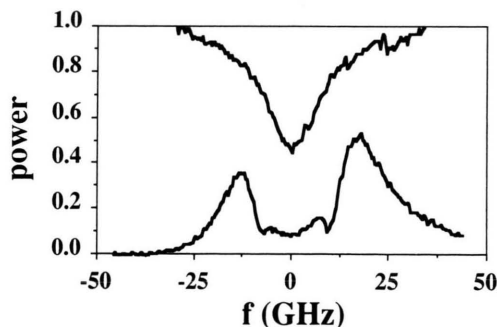


Fig. 4. Comparison of laser beam absorption profile (top) and power of created beam with opposite polarization leaving the sodium cell (bottom). The power transmitted through the cell is measured in relative units, where 1.0 equals 4 mW for the top curve and $16 \mu\text{W}$ for the bottom one. The maximum power of the created beam of $9 \mu\text{W}$ occurs at a frequency detuning of 18 GHz. $B_z = 0$, cell temperature 210°C , power of input beam: 4 mW, beamwaist at cell input window: $200 \mu\text{m}$.

0.2 mW input power the absorption profiles for both polarizations are identical. As the beam power is gradually increased up to 4 mW the maximum absorption peak is shifted towards higher frequencies in the case of σ_- and towards lower frequencies in the case of σ_+ radiation. The frequency difference Δ (frequency of absorption maximum of σ_+ in Fig. 1a minus frequency of absorption maximum σ_- in Fig. 1b) is about 4 GHz at 2 mW input beam power. This clearly demonstrates an intensity and polarization dependent nonlinear response of the system.

One can also observe a density dependent nonlinear response (Fig 2) as the density of sodium atoms in the cell is varied between $3.4 \cdot 10^{17} \text{ m}^{-3}$ (at 160°C cell temperature) and $2.5 \cdot 10^{19} \text{ m}^{-3}$ (at 240°C). The frequency difference Δ gradually increases up to a maximum at about $3.3 \cdot 10^{18} \text{ m}^{-3}$ (at 200°C) and decreases until it reaches zero at about 230°C . Below 170°C and above 230°C no frequency difference occurs.

For input beam powers and atomic densities where Δ is large we investigate the nonlinear dependence on an external longitudinal magnetic field B_z while the transverse magnetic components are compensated to zero. Figure 3 shows no frequency difference for an exactly compensated longitudinal field $B_z = 0$. At about $B_z = \pm 100 \text{ mG}$ maximum frequency differences Δ occur where Δ is positive for longitudinal fields pointing along the laser beam propagation direction. We like to point out that the observed frequency differences in the order of GHz can not be simply explained by Zeeman level shifts since applied magnetic fields of about 100 mG only account for about 100 kHz Zeeman shifts in sodium. A most surprising aspect of this effect, which is not predicted by common theories, is the possibility of distinguishing between σ_+ and σ_- radiation by simply applying a small magnetic field.

Another interesting nonlinear effect is shown in Figure 4. For one circularly polarized input beam of about 4 mW, a co-propagating beam of the opposite circular polarization can be observed at the cell output. This effect also depends on input beam power, polarization, atomic density and magnetic field. However at large atomic densities the dependence on the longitudinal magnetic field disappears. Since the same behavior (independence of magnetic field at large atomic densities) has also been seen for the frequency difference Δ the question arises whether both effects are correlated. On the other hand Δ can become zero at $B_z = 0$ where

as the production of the opposite polarization component remains, even at zero magnetic field.

The existing model [6] accounts for optical pumping, saturation and vector properties of light. However, it assumes homogeneous line broadening, and the role of isotropic, spontaneously emitted radiation as well as collisions of excited Na atoms with Ar buffergas atoms are neglected. We therefore explore whether collisional mixing of excited states combined with the amplification of spontaneously emitted radiation may be a possible explanation for the observed creation of orthogonal polarized radiation. For the explanation of the polarization dependent shift of maximum absorption we are searching for a possible magnetic field dependent asymmetry e.g. of the colli-

sion process between Ar and Na in either of the groundstates. If this is the case we may apply concepts used in collision theory which are able to explain shifts, broadening and asymmetry of atomic absorption profiles depending on the kind of collision partners [7].

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