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Slow light in inhomogeneous and transverse fields

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Abstract. For all known massive particles, the value of the magnetic dipole moment is different from zero. In contrast, photons in vacuum have no magnetic moment. Here, we describe experimental studies that show that light, when transmitted through a dense atomic medium under the conditions of electromagnetically induced transparency (EIT), can behave as if it has acquired a magnetic dipole moment. In the area of solid-state physics, such effective particle properties (e.g. effective masses) are well known. In our experiments, slow light passing through a rubidium gas cell is deflected when exposed to a magnetic field gradient. The beam deflection is proportional to the propagation time through the cell and can be understood by assuming that dark-state polaritons have a nonzero effective magnetic moment aligned collinearly to the optical propagation axis. In more recent experiments, we have studied different dark-state configurations. We observe EIT, slow group velocities and stored light in a transverse magnetic field configuration, where the moving magnetic dipole is directed orthogonal to the optical propagation axis. The latter can be used for further studies of the quasiparticle properties of dark-state polaritons.

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Contents

1. Introduction

Electromagnetically induced transparency (EIT) enables light transmission through otherwise opaque media [1]. Destructive quantum interference of absorption amplitudes here gives rise to a (often only partial) suppression of light absorption. Media exhibiting EIT are known to have very interesting properties such as extremely slow group velocities [2]–[4]. Associated with slow propagation of light are the so-called dark polaritons that travel through the medium at the speed of the group velocity. The group velocity can even be reduced to zero in a controlled and reversible process, which allows for storage and retrieval of dark polaritons. An interesting issue is that in this way pure quantum states of light can be reversibly stored in the multiparticle ensemble of an atomic gas [5, 6]. It is, furthermore, known that the spectral position of dark resonances is extremely sensitive to magnetic fields, and both absorptive and dispersive resonance properties have been used for magnetometry [7]. In other work, the deflection of optical beams in media exposed to external fields has been studied. For example, deflection of light due to saturation effects and inhomogeneous optical pumping, or beam focusing due to pump beam-induced inhomogeneous refractive index modifications, have been observed [8]–[11].

We here report on experiments studying an effective magnetic dipole moment of dark polaritons that is due to the spin-wave contribution of the polariton, which develops on the entry of circular polarized light into the atomic medium. We first describe a recent experiment that gave experimental evidence for the existence of such an effective magnetic moment. Here, we studied the deflection of a beam under EIT conditions in a rubidium cell subjected to a Stern–Gerlach-like magnetic field gradient [12]. We observe an angle deflection of the transmitted beam that becomes increasingly pronounced for small optical group velocities. This deflection can be understood in a simple model by considering the mechanical force on the light–matter quasiparticle with magnetic dipole moment in the spatially inhomogeneous magnetic field, where the observed deflection is attributed to give evidence for the existence of such an effective dipole moment. In more recent experiments, we have investigated slow light in a configuration with an applied transverse magnetic field. Interestingly, the moving magnetic dipole can, here, also be directed transversely to the optical axis, whereas the angular momentum of the photon clearly cannot be aligned along this direction. At present, we have studied dark resonances and slow and stopped light in such a configuration. The driving optical beams here are linearly polarized and the polarizations are orthogonal to each other, while the magnetic field is parallel

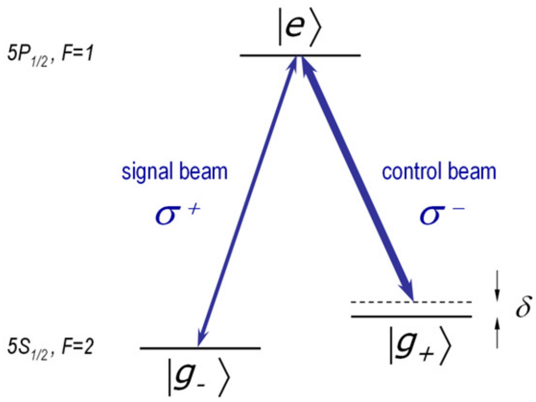


Figure 1. Simplified diagram of the Λ-type three-level system relevant to the experiments with longitudinal magnetic bias fields. Two ground states, $|g_-\rangle$ and $|g_+\rangle$, are coupled to the spontaneously decaying excited state $|e\rangle$ via a σ^+-polarized signal beam and a σ^--polarized control beam. δ denotes the two-photon detuning.

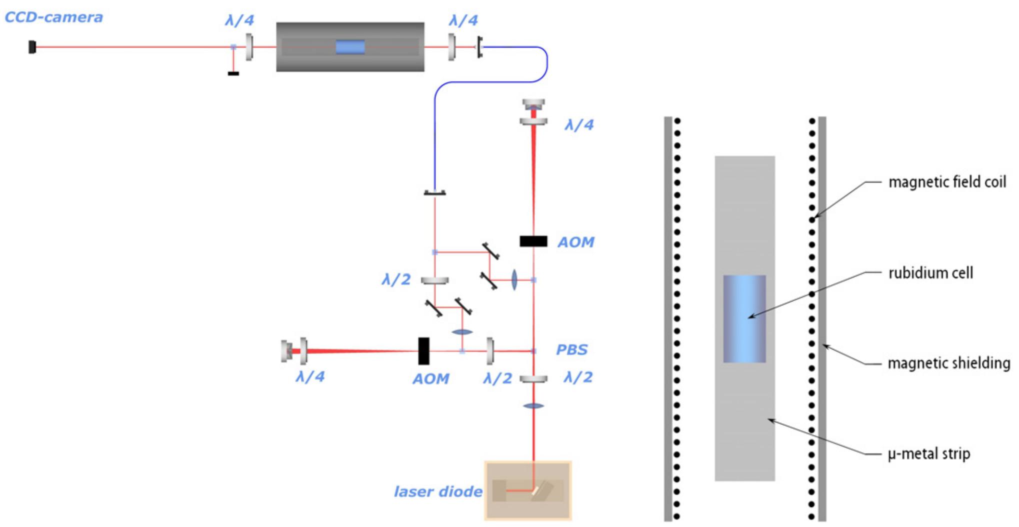
to the control field polarization axis. We also discuss future perspectives, which could include the observation of an Aharonov–Casher effect with slow light.

2. The Stern–Gerlach experiment for slow light

2.1. Experimental set-up

To study the deflection of slow light in a magnetic field gradient, we here use a heated rubidium buffer gas cell with light tuned to the ^{87}Rb D1-line near 795 nm. The magnetic dipole moment is directed along the propagation axis of the optical beams. A simplified level scheme of the used three-level system is shown in figure 1. Two optical fields of opposite circular polarizations are used: a weaker 'signal beam' and a stronger 'control beam'. These couple the two stable ground states $|g_+\rangle$ and $|g_-\rangle$, with magnetic quantum numbers m_F differing by two, via a spontaneously decaying excited state, $|e\rangle$. The two beams are derived from the original beam via a polarizing beam splitter (PBS), wherefore they possess orthogonal linear polarizations. They independently pass separate acousto-optical modulators (AOM), which allow for variation of the optical difference frequency. Subsequently, the beams are spatially overlapped and fed through a polarization-maintaining optical fiber, as shown in figure 2. Afterwards, the collinear beams are expanded to a diameter of 2 mm and converted to beams with opposite circular polarizations before they enter the rubidium cell apparatus. The apparatus consists of a magnetic shielding cylinder, which is used to eliminate the influence of magnetic stray fields on the highly sensitive medium, and a heated rubidium vapor cell with 20 torr Ne buffer gas pressure. The magnetic shielding cylinder also contains a magnetic field coil, which generates the homogeneous field oriented parallel to the optical beam.

Additionally, a μ-metal strip, which is considerably longer than the rubidium cell, is mounted parallel to the optical beam. In this configuration, a ferromagnetic material acts as a shortcut for the magnetic flux, leading to a magnetic field gradient, as depicted in figure 3.



(a) (b)

Figure 2. (a) The optical set-up. (b) Detailed view of the rubidium cell apparatus.

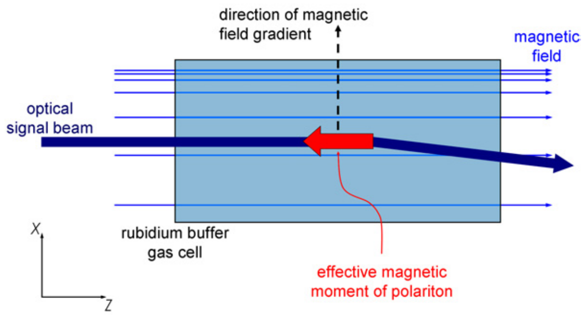


Figure 3. Schematical representation of a Stern–Gerlach experiment for slow light based on a magnetic bias field longitudinal to the beam propagation axis. The transverse magnetic field gradient causes a deflection of the signal beam, which is attributed to the dark polariton possessing an effective magnetic moment.

Subsequently, the control beam is removed, and the signal beam profile is mapped on a charge-coupled device (CCD) camera placed 2 m from the cell. The beam position is extracted from the obtained data using a center of intensity calculation for different values of the two-photon detuning while scanning through a dark resonance. Simultaneously, the corresponding signal beam intensity is measured and recorded.

2.2. Theoretical model

In the following, we will discuss a mechanical model used to describe the observed signal beam deflection as well as a model based on a quantum-mechanical description in terms of the motion of hybrid atom–light quasiparticles, the dark polaritons.

Provided the considered quasiparticle has a magnetic dipole moment different from zero, the expected angle deflection of a polariton traversing an inhomogeneous magnetic field region can be derived from the transverse magnetic force acting on $\mu_{\rm pol}$, the magnetic dipole moment of the dark polariton moving through the EIT medium with the group velocity $v_{\rm g}$. Assuming that the deflection angle α is small and that the dipole moment is aligned collinearly to the bias magnetic field, the expected deflection is given by $\alpha \cong F t_{\rm int}/p$, where the magnetic force F is $({\rm d}B_z/{\rm d}x)\cdot\mu_{\rm pol}$ and where $t_{\rm int} = L/v_{\rm g}$ denotes the interaction time and L the cell length, respectively. For the photon momentum $p = n\hbar k$ [13], the vacuum value of the photon momentum can be used, since the difference between the refractive index n of rubidium gas and unity is negligible. We easily find the expected deflection angle, which increases with longer interaction times:

$$\alpha \cong \frac{L}{v_{\rm g}}\frac{\mu_{\rm pol}}{\hbar k}\frac{{\rm d}B_z}{{\rm d}x}. \tag{1}$$

In contrast to the absolute value of the refractive index, which does not essentially differ from the refractive index of vacuum, the variation of the refractive index in the vicinity of the two-photon resonance is very steep, which gives access to a different description of the observed beam deflection based on a wave-optics model. These highly dispersive properties of EIT have been the subject of preliminary studies and have been demonstrated in different experimental configurations [2, 4]. By applying a magnetic field that is non-uniform transversely to the optical beam, a variation of the two-photon detuning is introduced in the system. At the same time, this causes a variation of the refractive index perpendicular to the optical beam axis, which results in an angle deflection of the optical beam, comparable to the deflection of a light beam passing through an optical prism. Due to the linear dependence of the deflection angle on ${\rm d}n/{\rm d}\omega$, the dependence of the observed beam deflection on the two-photon detuning is expected to show the shape of the derivative of a dispersion-like spectrum.

The two-photon detuning variation due to the presence of a magnetic field gradient can be expressed as $2g_{\rm F}\mu_{\rm B}\,{\rm d}B_z/{\rm d}x$, where the hyperfine g-factor for the used transition is $g_{\rm F} = 1/2$. If we further set $\mu_{\rm pol} = 2g_{\rm F}\mu_{\rm B}$ and use the relation $v_{\rm g} = c/(n + \omega({\rm d}n/{\rm d}\omega))$, the derived expression for the expected deflection angle is identical to the result obtained from the mechanical model, as shown in equation (1), for the case that $v_{\rm g} \ll c$.

Let us now turn to a quantum-mechanical representation of the situation. Here, we consider the propagation of light through a medium under the conditions of EIT as the propagation of a quasiparticle that is a mixture of a photonic and an atomic contribution [14]. In this model, we consider an ensemble of N three-level atoms, with a classical control field used to couple the ground state $|g_+\rangle$ and the excited state $|e\rangle$ and a quantum-mechanically described signal field coupling the ground state $|g_-\rangle$ and $|e\rangle$. It has been pointed out in theoretical work [14, 15] that the group velocity can be expressed as $v_{\rm g} = c\cos^2(\Theta)$, where the mixing angle between the photonic and atomic contributions is defined as $\tan(\Theta) = g\sqrt{N}/\Omega$. Here, Ω denotes the Rabi frequency of the control field and g is the coupling constant of the signal field. In terms of a collective atomic state $|g_-\cdots g_-\rangle$ with all atoms in the ground state $|g_-\rangle$ and a state $|n\rangle_{\rm elm}$ denoting a state of the photonic contribution with n photons in the mode representing the signal beam, a polariton 'vacuum state' $|0\rangle_{\rm p} = |0\rangle_{\rm elm}|g_-\cdots g_-\rangle$ can be constructed. In this way, a one-polariton state can be generated by applying the polariton creation operator on the polariton

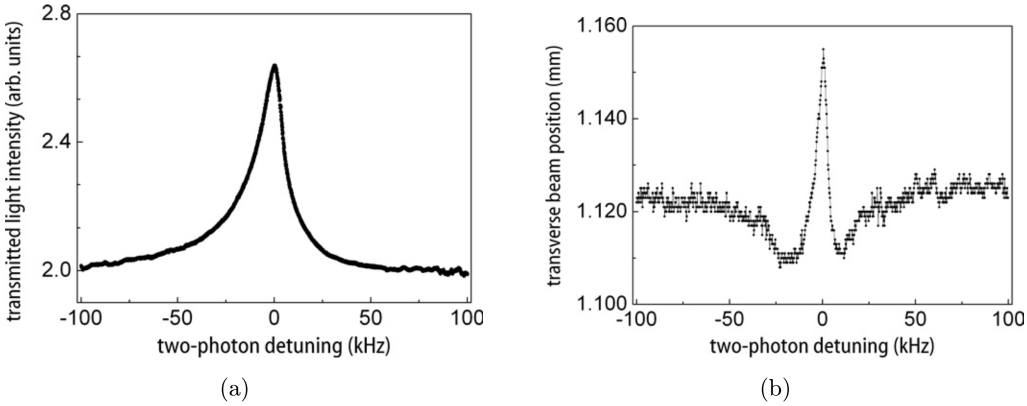


Figure 4. (a) Signal beam transmission spectrum. The two-photon detuning is given by $\delta = \omega_S - \omega_C + \mu_B \cdot B$, with the optical frequencies of the signal and the control beam, ω_S and ω_C, the Bohr magnetron μ_B and the magnetic bias field B. (b) Signal beam position transverse to the optical axis. For a two-photon detuning near zero, a clear deflection of the signal beam is observed.

vacuum state. The polariton creation operator

$$\Psi^\dagger = \cos(\Theta)\hat{a}^\dagger - \sin(\Theta)\frac{1}{\sqrt{N}}\sum_j^N \hat{\sigma}_{-+}^j$$

contains $\hat{a}^\dagger$, an operator for the generation of a photon in the signal mode and the operator $\hat{\sigma}_{-+}^j$, which flips the state of the jth atom from $|g_-\rangle$ to $|g_+\rangle$. The one-polariton state is then given by: $|1\rangle_p = \Psi^\dagger|0\rangle_p$. Using this description, it is possible to derive the expected force that a dark polariton would experience under the influence of an external magnetic field gradient by calculating the spin expectation values S_z for the polariton vacuum state and for the one-polariton state, respectively. The magnetic moment of a dark polariton is then given by the following expression:

$$\mu_{pol} = \mu_B({}_p\langle 1|\, S_z\, |1\rangle_p - {}_p\langle 0|\, S_z\, |0\rangle_p) = \mu_B(m_1 g_1 - m_2 g_2)\sin^2(\Theta).$$

For the involved rubidium transitions in our experiment and for the case $v_g \ll c$, we obtain a magnetic moment of the dark polariton of $\mu_{pol} = 2g_F\mu_B$. This result is consistent with the expression obtained from the above described classical model.

2.3. Experimental results

In preparatory measurements, we have recorded transmission spectra of the signal beam for different transverse positions with respect to the optical axis in order to characterize the magnetic field gradient in our set-up. A typical transmission spectrum is depicted in figure 4(a), which shows the enhancement of light transmission near the center of the dark resonance. In subsequent experiments, we have monitored the position of the signal beam on a CCD camera placed 2 m away from the rubidium cell. We observe a beam displacement near resonance, and figure 4(b) shows the observed position as a function of two-photon detuning. The line shape

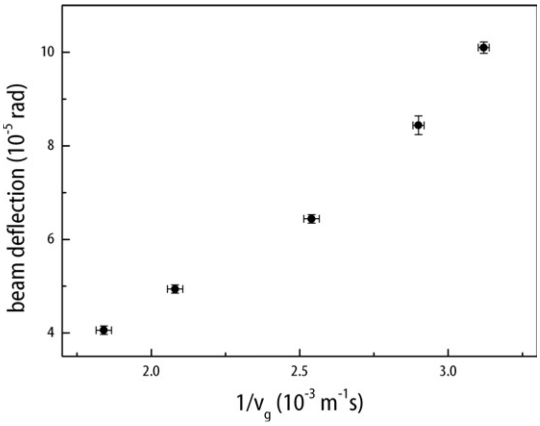


Figure 5. Dependence of the deflection of the signal beam on two-photon resonance on the inverse group velocity.

here qualitatively resembles the derivative of a dispersion curve, in accordance with theoretical considerations described in the previous section.

In the vicinity of the Raman resonance, a deflection angle of approximately 2×10^{-5} rad has been measured in agreement with theoretical predictions for dark-state polaritons with a nonzero magnetic moment. In other measurements recording the beam position at different focal planes and verifying the absence of a displacement at no field gradient, we have ascertained that field gradients indeed give rise to an angle deflection of the signal beam. As discussed earlier, the magnitude of this deflection is also determined by the time it takes a polariton to traverse through the rubidium cell and hence by the group velocity of slow light. In order to verify the predicted increase in the deflection angle with slower group velocities, we have carried out measurements where the beam position has been measured for different group velocities. The beam deflection on two-photon resonance was indeed found to increase with larger values of $1/v_g$, as shown in figure 5.

From the observed beam deflection shown in figure 5, we can also derive an experimental value of the magnetic dipole moment, which yields an estimated value of $5.1 \times 10^{-24}\,\mathrm{J\,T^{-1}}$ [12]. This value is a factor 1.8 lower than the theoretically expected value of one Bohr magnetron in the slow light limit $v_g \ll c$, and thus of the correct order of magnitude. We believe that for the future a more detailed theoretical model accounting for the finite control beam intensity and linking the effective polariton interaction time with the used pulsed group velocity measurement should be carried out. The deviation from the predicted value is attributed to coherence loss mechanisms present in our measurements due to the transverse variation of the two-photon detuning over the optical beam diameter, and to the finite spectral width of the optical pulses in our pulsed group velocity measurement. Both effects cause loss of coherence of the dark state and nonlinearities of the dispersion. The experiment we have described can give access to studies of particle properties of the dark-state polaritons.

3. Slow light in transverse magnetic field configurations

Until now, we have discussed experiments for slow light carried out in magnetic field gradients oriented transversely to the optical beam axis. The observed beam deflection is attributed to the influence of an external magnetic field gradient on an effective magnetic dipole moment of the dark polariton, which is oriented along the bias magnetic field and parallel to the optical beam axis.

An interesting question now is whether this moving quasiparticle with a nonzero effective magnetic moment can exhibit an Aharonov–Casher phase shift. In the slow light limit, this effect would be non-dispersive. The Aharonov–Casher effect has been predicted in earlier theoretical work [16] and experimentally verified in different configurations and for different particles, including neutrons, calcium atoms, thallium fluoride and rubidium atoms [17]–[20]. It has been pointed out that a neutral particle taken around a charged wire on a closed path C should acquire a phase shift

$$\Phi_{\mathrm{AC}} = \frac{1}{\hbar c^2} \oint_C \vec{\mu} \times \vec{E}(\vec{r}) \cdot \mathrm{d}\vec{r},$$

provided that the moving particle has a magnetic moment different from zero. Interestingly, the magnitude of the acquired phase shift does not depend on the velocity of the particle. The Aharonov–Casher phase shift does not only occur for closed paths around charged wires, but also for particles traveling on a straight trajectory through constant electric field regions, as pointed out by Anandan [21] and Casella [22].

To observe a possible Aharonov–Casher effect for atom–light quasiparticles, the product $\vec{\mu} \times \vec{E}(\vec{r}) \cdot \mathrm{d}\vec{r} = \vec{\mu} \times \vec{E}(t) \cdot \vec{v}\, \mathrm{d}t$ must be nonzero, which requires that the magnetic moment be directed transversely to the optical propagation direction. We are aware that it is not obvious whether an Aharonov–Casher phase shift can exist for polaritons in EIT, since no physical particles are moving here. Instead only the spin wave travels through the atomic medium. We nevertheless consider dark polaritons with a transversely directed spin wave component as a very interesting subject for an experimental investigation. Note that the photon spin cannot be directed along this axis due to the absence of a longitudinal optical polarization.

To obtain a magnetic dipole moment directed transverse to the beam propagation axis, we apply a magnetic bias field along this transverse direction. The stronger control beam of frequency ω_{C} is polarized along the direction of the magnetic bias field, i.e. π-polarized, while the weaker signal beam with frequency ω_{S} is polarized transversely to the direction of the magnetic bias field, so that both σ^+ and σ^- polarization components are present. A corresponding level diagram is shown in figure 6(a). The desired transverse orientation of the magnetic dipole moment of the polariton spin wave can be obtained when the difference in signal and control beam optical frequencies is resonant to a transition with $\Delta m_F = 1$. Note that one of the circular polarization components of the signal beam is now off-resonance. The σ^--polarized signal beam component and the π-polarized control beam can optically pump the ground states $|g_0\rangle$ and $|g_+\rangle$ into a dark coherent superposition of ground states. Figure 6(b) illustrates the corresponding experimental configuration. Note that for an $F \rightarrow F' - 1$ level scheme with $F > 1$ this state is not completely dark, but only gray for the light field.

Our optical fields were tuned to the $F = 2 \rightarrow F' = 1$ component of the rubidium D1-line. In the measurements, the control field was always much stronger than the signal field. Most relevant atoms were thus in the $F = 2, m_F = 2$ ground state. The states $|g_-\rangle$, $|g_0\rangle$ and $|g_+\rangle$ thus correspond to the $m_F = 0, m_F = 1$ and $m_F = 2$ sublevels of the $F = 2$ ground state. The linearly polarized control beam drives the $F = 2, m_F = 1 \rightarrow F' = 1, m_{F'} = 1$ transition, and the σ^--polarized portion of the signal beam couples the $F = 2, m_F = 2 \rightarrow F' = 1, m_{F'} = 1$ transition.

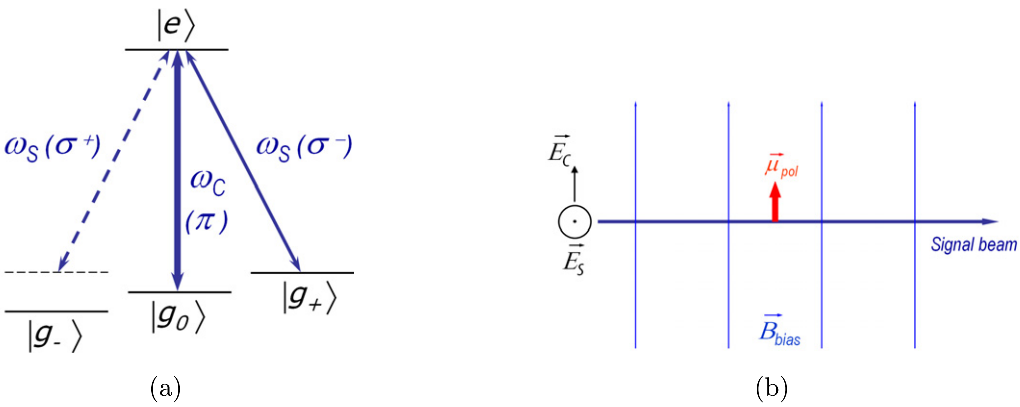


Figure 6. (a) Simplified level scheme for a configuration with a transverse magnetic field. The ground states are denoted by $|g_-\rangle$, $|g_0\rangle$ and $|g_+\rangle$, differing each by 1 in their magnetic quantum number. The resonant σ^- component of the signal beam has an optical frequency of ω_S, which equals the optical frequency of the off-resonant σ^+ component. The frequency of the π-polarized control beam is ω_C. (b) Corresponding experimental configuration, where $\vec{E}_S$ and $\vec{E}_C$ denote the electric field orientations of signal and control beams, respectively.

As we have seen, the magnetic moment of the dark state polariton is given by $\mu_B(m_1 g_1 - m_2 g_2)$, for the case $v_g \ll c$, and is hence determined by the transitions used to establish EIT. In contrast to our previous configuration, involving a $\Delta m_F = 2$ coherence of ground states, where the magnitude of this quantity was μ_B, the expected effective magnetic moment in this Λ-type system with $\Delta m_F = 2$ is $1/2 \cdot \mu_B$.

In earlier experimental work, EIT with transverse magnetic field orientations has been observed in samarium vapor [23]. In our experiment, we have recorded dark resonances and slow and stopped light with such a transverse magnetic field configuration in a ^{87}Rb buffer gas apparatus. To test our system, dark resonance transmission spectra have been recorded for both longitudinal and transverse magnetic bias fields, where all the parameters except for the optical polarizations and the magnetic field orientation were identical. Additionally, the corresponding group velocities have been determined, by irradiating the atomic vapor cell with pulsed signal light and measuring the observed pulse delay.

The dark resonances shown in figure 7(a) are separated by the frequency corresponding to the Zeeman splitting of the ground state components and are attributed to dark resonances driven by the linearly polarized control field and the σ^+ and σ^- components of the signal field for the two observed peaks, respectively. The linewidths of the transitions are slightly broadened compared to the dark resonance depicted in figure 7(b), which was recorded using a longitudinal magnetic field configuration. We have observed slow light propagation for both polarization configurations, and find that in the first case the group velocity with a value of $1600\,\mathrm{ms}^{-1}$ is larger than the result of $1160\,\mathrm{ms}^{-1}$ measured for the latter configuration.

With the transverse field configuration, we have carried out a storage of light experiment, which extends the work of [5, 6] towards transversely directed polariton spin wave states. The corresponding experimental data are shown in figure 8 for a light storage time of $50\,\mu$s. The polariton is here stored in a (transversely directed) spin wave. At the end of the storage time, the optical group velocity again reaches a nonzero value and the reaccelerated signal beam

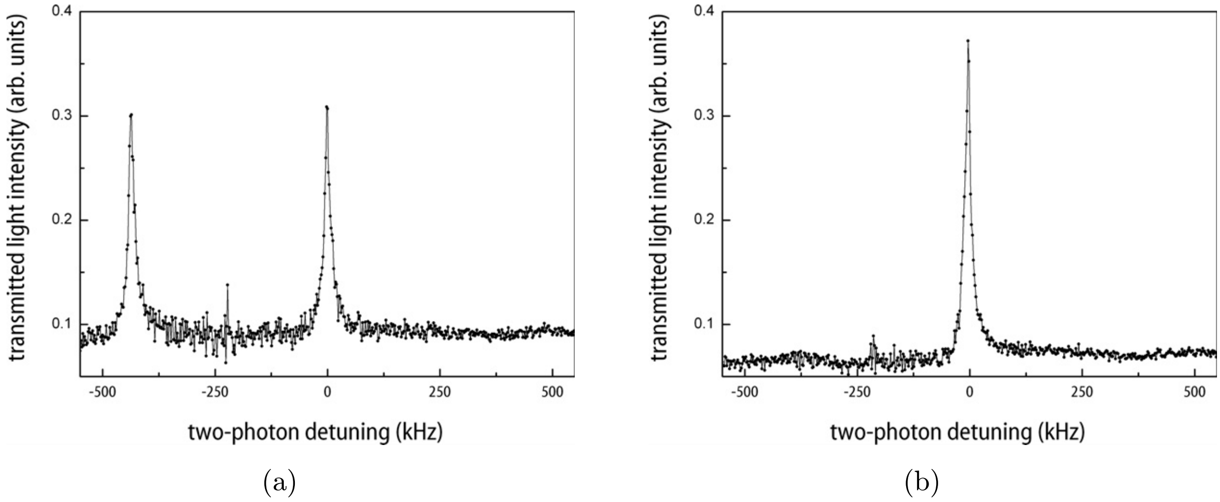


Figure 7. Signal beam transmission spectra. Each spectrum is the average of ten measurements. (a) The magnetic field is oriented transversely to the optical beam axis (see figure 6). The signal and control beams are linearly polarized, where the polarization of the control beam is aligned collinear to the magnetic field. (b) Corresponding spectrum for a longitudinal magnetic field configuration and opposite circular polarizations of the optical beams, as has been shown in figure 1.

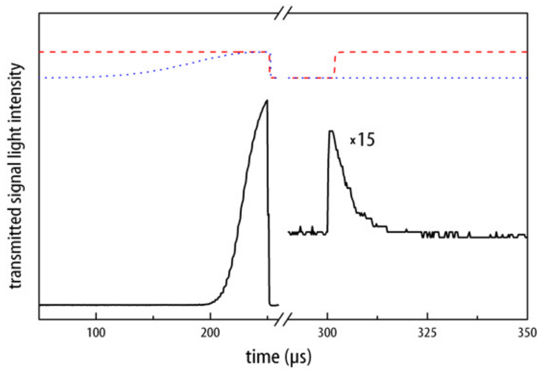


Figure 8. Stored light measurement carried out in the transverse magnetic field configuration. The signal background due to residual control beam transmission has been subtracted from this plot. The transmitted signal beam intensity is averaged and the signal of the retrieved pulse is magnified by a factor of 15. Above the data, the representations of signal (dotted line) and control (dashed line) beam intensities are shown.

pulse component is detected subsequently at the cell output. Note that only the optical dipole component directed transversely to the propagation direction can contribute to the remission of the signal beam. This intrinsically results in an additional loss of signal beam intensity, since the equally large longitudinal component cannot radiate into the beam propagation axis. It is clearly interesting to observe that a σ^+–σ^--polarized signal beam can be partially stored into a

σ^--polarized spin wave, which after a second axis projection can be accelerated again into the original polarization direction.

For the future, it will be interesting to test whether an applied electric bias field can induce an Aharonov–Casher phase shift. The field here should be aligned transversely to both the optical axis and the effective polariton magnetic moment, i.e. point out of the plane of figure 6(b). We are at present working on the implementation of a corresponding test experiment, where instead of detecting the absolute Aharonov–Casher phase shift, a beam deflection is searched for in the presence of an applied electric field gradient. In the case the dark polariton gives rise to a moving magnetic moment, the expected deflection would be of the order of magnitude of some 10 nm for an electric field gradient of approximately $1\,\mathrm{kV\,cm^{-2}}$. The deflection angle would be expected to rise linearly with the magnitude of the electric field and, due to the non-dispersive properties of the effect, show no variation in the group velocity, provided the dark polaritons are sufficiently slow, i.e. $v_g \ll c$.

4. Summary

We have described experiments investigating the particle nature of the dark polariton, which is the relevant atom–light quasiparticle in slow light propagation. In a first series of experiments carried out with a longitudinal magnetic bias field, we observed an angle deflection of a circularly polarized optical beam traversing a rubidium cell under the conditions of EIT and subjected to a Stern–Gerlach magnetic field gradient. The observed beam deflection is attributed as evidence for the dark polariton possessing an effective magnetic dipole moment.

We have proposed an experiment investigating the existence of a possible Aharonov–Casher phase shift of slow light, where a beam deflection is searched for in the presence of an electric field gradient. We also report on experiments studying dark polaritons with a transversely directed spin wave, in which dark resonances and slow and stopped light are observed.

Acknowledgments

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