Narrowing of resonances in electromagnetically induced transparency and absorption using a Laguerre–Gaussian control beam

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ABSTRACT

We study the phenomenon of electromagnetically induced transparency and absorption (EITA) using a control laser with a Laguerre–Gaussian (LG) profile instead of the usual Gaussian profile, and observe significant narrowing of the resonance widths. Aligning the probe beam to the central hole in the doughnut-shaped LG control beam allows simultaneously a strong control intensity required for high signal-to-noise ratio and a low intensity in the probe region required to get narrow resonances. Experiments with an expanded Gaussian control and a second-order LG control show that transit time and orbital angular momentum do not play a significant role. This explanation is borne out by a density-matrix analysis with a radially varying control Rabi frequency. We observe these resonances using degenerate two-level transitions in the D2 line of 87Rb in a room temperature vapor cell, and an EIA resonance with width up to 20 times below the natural linewidth for the F = 2 – F = 3 transition. Thus the use of LG beams should prove advantageous in all applications of EITA and other kinds of pump–probe spectroscopy as well.

1. Introduction

The Laguerre–Gaussian (LG) beam, also known as a doughnut mode because the phase singularity of the electric field leads to a hole in the center, has found important applications in several areas of physics. For example, the orbital angular momentum associated with the photons in the LG beam [1] has been used to rotate optically trapped microscopic particles [2] or create quantized vortices in a Bose–Einstein condensate [3]. LG beams have been used to create a waveguide for atoms [4,5], and to reduce the linewidth of Hanle resonances [6]. Here, we show that the LG beam can be used to create narrow resonances at the line center of an optical transition with an unprecedented reduction in linewidth of 20 times below the natural linewidth. We use the LG beam as a control beam in the well-known phenomenon of electromagnetically induced transparency and absorption (EITA) [7–9], a phenomenon in which the strong control beam is used to modify the properties of a medium for a weak probe beam. We show that the LG control beam causes a significant narrowing compared to the usual Gaussian control beam. EIT has wide-ranging applications such as using degenerate two-level transitions in the D2 line of 87Rb in a room temperature vapor cell, and an EIA resonance with width up to 20 times below the natural linewidth for the F = 2 – F = 3 transition. Thus the use of LG beams should prove advantageous in all applications of EITA and other kinds of pump–probe spectroscopy as well.

The underlying mechanism for EITA is the shift of the energy levels of the atom away from line center through the AC Stark effect (creation of dressed states [18] and an Autler-Townes doublet). The shift is equal to the Rabi frequency of the control laser, therefore the EITA resonance is subnatural when the power in the control laser is sufficiently small—e.g. a resonance width of 0.25Γ has been seen with a control Rabi frequency of 0.3Γ [19]. However, a small control power implies a correspondingly low signal-to-noise ratio (SNR) in the probe spectrum. As a consequence, in the above observation of the 0.25Γ linewidth, the EIT dip is barely visible above the noise. The LG control beam is ideally suited to overcome these conflicting requirements; by aligning the probe beam to the center of the LG control beam, the control power can be increased for high SNR while maintaining a negligibly small power in the region of the probe required for the narrow resonance. Physically, the doughnut structure of the control beam leads to a spatial variation of the control Rabi frequency, with a low frequency in the region where the...
absorption of the probe beam is significant. This explanation is borne out by a density-matrix analysis (for a $A$-type system) using a radially varying control Rabi frequency, which shows that the LG profile gives a smaller linewidth compared to the Gaussian profile. The spatial separation of the intense part of the two beams also allows the probe beam to be detected with minimal contamination from the LG control, which is often a problem with a control beam that has a Gaussian profile. Thus, the use of an LG beam should prove advantageous in several other kinds of pump–probe spectroscopy as well.

EITA is usually studied in three-level or multilevel systems, with the control and probe lasers on separate dipole-allowed transitions. We have recently shown that this can be observed in a degenerate two-level system [9], i.e. one in which both lasers are on the same transition and no third level is involved. Of course, each (degenerate) level is composed of multiple magnetic sublevels thus making it a “multilevel system”, but this is true of all EITA experiments, even those that are called three-level experiments, even those that are called three-level systems for example. In our earlier work using a Gaussian control beam [9], we demonstrated the subnatural features on the $^{87}\text{Rb}$ $D_2$ line, and showed that the narrow resonance appears as enhanced absorption (EIA) for the $F=2\rightarrow F'=3$ transition, and enhanced transparency (EIT) for the $F=1\rightarrow F'=0$ transition. Density-matrix analysis showed that the EIA feature in the $2\rightarrow 3$ transition was due to the formation of N-type systems, involving four sublevels. Here also we observe the same linewidth but the features are much narrower. For the $F=2\rightarrow 3$ transition, the EIA resonance has a full width that is 20 times below the natural linewidth, which as far as we know is the narrowest feature ever observed for a probe laser on a dipole-allowed transition. Considerable effort has been made to account for the control laser by a polarizing beam-splitter cube, and only the probe beam arriving after the cells is sent through an acousto-optic modulator (AOM) into a saturated-absorption spectrometer. The frequency of the AOM is modulated at 30 kHz to generate the error signal for locking the laser to a peak. Frequency modulation using the AOM rather than by direct modulation of the diode current is important in keeping the laser linewidth as small as possible, and observing the narrowest features. The two beams are linearly polarized in orthogonal directions so that they can be mixed and separated using polarizing beam-splitter cubes, and only the probe beam can be detected.

The probe beam is expanded to a large size and then apertured to a diameter of about 1 mm. This ensures that the intensity is roughly constant over this size. The total power in the beam entering the cell is 6 $\mu$W. It is aligned to the central hole of the LG control beam, as shown in the figure. The two beams co-propagate through a room temperature vapor cell of size 25-mm diameter $\times$ 50-mm long. The cell contains pure Rb (both isotopes in their natural abundances and with no buffer gas), and has a multilayer magnetic shield around it.

Before turning to the results, we first demonstrate the advantages of scanning the control laser while keeping the probe laser locked. Any spectrum is obtained by measuring the response of a locked probe laser on a dipole-allowed transition. Conventional two beam EIT spectroscopy is performed using polarizing beam-splitter cubes, and only the probe beam arriving after the cells is sent through an acousto-optic modulator (AOM) into a saturated-absorption spectrometer. The frequency of the AOM is modulated at 30 kHz to generate the error signal for locking the laser to a peak. Frequency modulation using the AOM rather than by direct modulation of the diode current is important in keeping the laser linewidth as small as possible, and observing the narrowest features. The two beams are linearly polarized in orthogonal directions so that they can be mixed and separated using polarizing beam-splitter cubes, and only the probe beam can be detected.

The experimental schematic, shown in Fig. 1, is similar to that in our earlier work [9], except that the control beam has an LG profile. It is generated by diffracting the Gaussian beam output of a grating-stabilized diode laser [21] through a computer-generated transmission hologram [22,23]. The laser frequency is scanned by electronically varying the angle of the grating using a piezoelectric transducer. The control beam power in the experimental cell is 0.3 mW and its waist size is 1.4 mm. The probe beam is derived from a similar but independent diode laser system. Part of the beam is sent through an acousto-optic modulator (AOM) into a saturated-absorption spectrometer. The frequency of the AOM is modulated at 30 kHz to generate the error signal for locking the laser to a peak. Frequency modulation using the AOM rather than by direct modulation of the diode current is important in keeping the laser linewidth as small as possible, and observing the narrowest features. The two beams are linearly polarized in orthogonal directions so that they can be mixed and separated using polarizing beam-splitter cubes, and only the probe beam can be detected.

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Before turning to the results, we first demonstrate the advantages of scanning the control laser while keeping the probe laser locked. Any spectrum is obtained by measuring the response of a system while scanning the input frequency. Most EIT spectra are obtained by looking at probe transmission while scanning its frequency, while the control beam is locked [19]. Instead, we use a technique where the probe laser is locked on resonance while the
detuning of the control laser is scanned [17]. This is a technique
that we have developed to overcome the first-order Doppler effect
so that the spectrum appears on a flat background. The under-
lying reason is that the locked probe beam addresses only the
zero-velocity atoms, and its absorption remains Doppler free until
it is modified by the control beam. This advantage is seen clearly
in Fig. 2. The probe-transmission spectrum for the $F = 2 \rightarrow 1$
transition is obtained either with control scanning makes the
maximum Rabi frequency at the center of the beam of 2.5$\Gamma$.

![Fig. 2. Advantage of scanning the control laser. The spectrum obtained by
scanning the probe laser with a locked control [shown in (a)] appears on a
Doppler background, whereas the spectrum obtained by scanning the control laser
with a locked probe [shown in (b)] appears on a flat Doppler-free background. Both spectra are on the $F = 2 \rightarrow 1$ transition with a Gaussian control with maximum Rabi frequency at the center of the beam of 2.5$\Gamma$.]

3. Results and discussion

The EIA experiments were done on the $F = 2 \rightarrow 3$ transition. A typical probe-transmission spectrum is shown in Fig. 3. The spectrum is normalized to make the signal equal to 1 away from line center, corresponding to absorption by zero-velocity atoms, but otherwise arbitrary depending on the gain of the photodiode.

The general structure is the same as in our earlier work with a Gaussian control beam in Ref. [9], with a broad optical-pumping peak around line center (due to population redistribution among the magnetic sublevels), and a narrow EIA dip exactly at line center. The full width at half maximum (FWHM) of the EIA dip is only 0.3 MHz—an unprecedented factor of 20 below the natural linewidth—which is 6 times narrower than that obtained with the Gaussian control laser [9]. The maximum Rabi frequency of the control beam, corresponding to $\Omega_0$ in Eq. (1), is given by $\Omega_0 = 2.5\Gamma$. Considering that the rms linewidth of our free-running laser is of order 1 MHz [21], the fact that we can see such a narrow feature means that the linewidth of the laser when it is locked is considerably smaller. It also appears that the width of the EIA dip can be reduced further if the linewidth of the laser can be reduced, using well-established techniques such as by locking to a high-finesse cavity.

The signal-to-noise ratio (SNR) of the spectrum is very good. It is comparable to the one in our earlier work, where the maximum Rabi frequency at the center of the Gaussian control was slightly smaller 1.3$\Gamma$. Despite the larger Rabi frequency, the EIA dip is much deeper and narrower in the present case.

In our earlier work [9,24], we have contrasted the narrow EIA feature seen by us with enhanced-absorption features seen in the earlier work of Ref. [25], which is akin to the phenomenon of coherent population trapping (CPT) with phase-coherent beams. What we can add here is that the mutual coherence between the two lasers used in this study has been measured to be 1.4 MHz (over the duration of the experiment), measured by beating the two beams on a photodiode. Therefore, CPT-type effects do not play a significant role in the narrowing. Furthermore, CPT experiments require sufficiently large power in both beams (and not the weak probe–strong control used here), so it is unlikely the use of an LG control (with negligible power in the region of the probe) will cause a reduction in the linewidth of the CPT resonance.

We next turn to an EIT spectrum observed on the $F = 1 \rightarrow 0$ transition. A typical probe-transmission spectrum is shown in Fig. 4. The spectrum is again normalized to unit absorption away from line center. The polarization of the two beams has been changed from linear to circular, i.e. from lin $\perp$ lin to $\sigma^+ \sigma^-$, implemented by putting $\lambda/4$ waveplates on either side of the cell. This is because this polarization configuration results in the magnetic sublevels forming a $\Lambda$-type system, which is known to give EIT. The control power is increased so that $\Omega_0 = 3.2\Gamma$, which gives better SNR. In this case, optical pumping by the control laser
The polarizations of the two beams are changed to circular (\(\sigma^+\sigma^-\)), and the control power is increased so that \(\Omega_B = 3.2\Gamma\). The broad dip around line center is due to optical pumping and population redistribution by the control.

near line center increases the population in the \(m_F = \pm 1\) sublevels and hence causes a decrease in probe transmission, as explained in our earlier work [9]. This broad optical-pumping dip is slightly smaller for the LG control than seen earlier with the Gaussian control, which is to be expected because the LG control is weaker in the region of the probe. The higher control power gives higher SNR, but it also results in an increase in the linewidth of the resonance, so that the improvement compared to the Gaussian-control result shown in our earlier work (obtained with a maximum Rabi frequency of 1.05\(\Gamma\)) is reduced to a factor of 2.

One possible explanation for the linewidth reduction is that the LG beam carries orbital angular momentum (OAM), and hence provides a torque on the atomic trajectory within the beam. This increases the transit time and can result in a narrowing of the resonance if the transit time limits the linewidth. To understand the role of transit time in more detail, we have studied the EITA phenomena with an expanded Gaussian control beam, which should increase the transit time directly. The expanded Gaussian beam is 2.5 times larger, and has the same power as before. This means that the transit time is increased by this factor, while the control Rabi frequency is reduced by the same factor. Both these effects should cause a decrease in the linewidth, instead we observe a 20% increase, and a simultaneous decrease in SNR. And this change is there for both EIA resonances (\(F = 2 \rightarrow 3\) transition) and EIT resonances (\(F = 1 \rightarrow 0\) transition). This shows that transit time does not limit the observed linewidth.

We have further studied the role of OAM by using a second-order LG beam. This doubles the torque on the atoms and hence increases the time spent by the atoms within the control beam. Under the same conditions of total power, the spectra obtained with the LG\(^2\) control show the same linewidth as that obtained with the LG\(^1\) control, for both the EIA and EIT features. With higher total power, the linewidth increases. We thus conclude that the OAM carried by the LG beam plays a negligible role in the linewidth reduction.

In our previous work with Gaussian control beams [9], we had done a complete density-matrix analysis of the sublevel structure to support the observations, especially the fact that we get EIA for the \(F = 2 \rightarrow 3\) transition and EIT for the \(F = 1 \rightarrow 0\) transition. The qualitative reason for this difference was shown to be the various sublevels coupled by the two beams—EIA was due to the formation of several N-type systems, while EIT was due to the formation of a \(A\)-type system. Since this does not depend on the intensity profile of the control beam, the same difference also

appears in our present work. However, there is a marked difference in the linewidth of the resonances, which is obviously related to the profile of the LG over the Gaussian. Our experiments with the expanded Gaussian also show that a weaker control beam with the same Gaussian profile will not narrow the resonance. Therefore, the particular spatial profile of the LG mode appears important for the narrowing.

To verify this explanation, we have done a density-matrix calculation with the two profiles for the \(F = 1 \rightarrow 0\) transition, which as mentioned before forms a \(A\)-type system (as shown in the inset of Fig. 5) when the beams have \(\sigma^+\sigma^-\) polarizations. The \(A\)-type system has been widely studied in the literature, and there is an analytic expression for probe absorption in the weak-probe regime [26,27]. The spectra are calculated for a radially varying control Rabi frequency—varying either as Gaussian or LG—which leads to a radial dependence of probe absorption. The results for the two profiles are shown in Fig. 5. In the calculation done in Ref. [5] to explain atom waveguiding by an LG beam, the spatial variation in Rabi frequency included both the amplitude and phase of the electric field. But our experiments with the LG\(^2\) beam show that the phase (and resulting OAM) does not play a significant role. Therefore, the calculations are done with only the amplitude variation of the electric field. The value of \(w_0\) for both profiles is taken to match the experimental value of 1.4 mm. The maximum control Rabi frequency is taken to be 0.66\(\Gamma\). This is smaller than the experimental value because the calculation does not take into account Doppler averaging, which we have shown results in a further narrowing of the EIT resonance [27].

The figure shows clearly that there is significant narrowing with the LG control, exactly as seen in our experiments. The calculation does not capture the phenomenon of optical pumping, because, in the steady state, the control laser will cause complete population transfer due to optical pumping and suppress any other feature. Neither can it capture the signal-to-noise ratio, which plays an important role in our experiment. Nevertheless, it shows that LG profile (without OAM) causes narrowing compared to the Gaussian profile.

4. Conclusion

In conclusion, we have studied the phenomenon of electro-magnetically induced transparency and absorption using a control beam with a Laguerre–Gaussian profile instead of Gaussian, and find a marked reduction in the width of the control-induced resonances. We study these resonances using two-level hyperfine
transitions on the D2 line of 87Rb. The system is two level in the sense that both the control and probe lasers are on the same transition and no third level is involved, but each level has multiple magnetic sublevels, so that optical pumping and population redistribution by the strong control laser. We see a narrow EIA resonance for the $F = 2 \rightarrow F = 3$ transition, and a narrow EIT resonance for the $F = 1 \rightarrow F = 0$ transition; a difference that was explained earlier using density-matrix analysis of the various sublevels coupled by the two lasers [9]. We find the same difference here, but the resonances are significantly narrower. For the $F = 2 \rightarrow 3$ transition, we obtain a width that is 20 times below the natural linewidth. The physical explanation for the narrowing is the almost negligible control power for the LG beam in the region where the probe absorption is high. We show that transit time and the OAM carried by the LG beam do not play a significant role in the narrowing. This explanation is verified by a density-matrix calculation for the $F = 1 \rightarrow 0$ transition with the two profiles. We have further studied the effect of an LG control beam for EIT in the more conventional 3-level $A$-type systems. Such systems can also be formed in the D2 line of 87Rb using the levels F = 1 → F = 1 → F = 2 or the levels F = 1 → F = 2 → F = 2 [27]. We again see a reduction in linewidth compared to the use of a Gaussian beam. Similarly, the use of an LG control beam has been shown to cause a reduction in linewidth of the Hanle resonance [6]. Therefore, it seems that the use of an LG beam could prove advantageous in several kinds of pump–probe spectroscopy experiments.

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References