Electromagnetically induced transparency: controlling light with light

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Abstract
In this paper an introduction to the principles of electromagnetically induced transparency (EIT) is given. Two experiments on EIT are discussed: one from the review of A. André et al. [1] on quantum memory, and another more recent article [7] about single atom EIT in a cavity. Finally, the four questions on blackboard are adressed.

1 Introduction

1.1 What is EIT?
Electromagnetically induced transparency is an optical phenomenon that can make a medium transparent, when two laser beams are interacting with the medium. The common energy level scheme for EIT is shown in figure 1. The two frequencies $\omega_p$ and $\omega_c$ indicate the frequency of the probe field, and of the control field. The transitions from $|1\rangle$ to $|3\rangle$ and from $|2\rangle$ to $|3\rangle$ are dipole allowed transitions; the remaining transition, from $|1\rangle$ to $|2\rangle$ is dipole forbidden. When the probe field is applied to an optically dense gas consisting of three level atoms, nothing will happen: it will partially get absorbed, and a small part is transmitted. Applying a control field that is tuned at the transition from $|2\rangle$ to $|3\rangle$ changes the behaviour completely. Suddenly the fraction of transmitted light goes to one: the medium has become transparent. This transparency only occurs when the frequencies of the probe beam and coupling field correspond exactly to the transition from $|1\rangle$ to $|3\rangle$ and from $|2\rangle$ to $|3\rangle$.

The physics behind EIT can be explained in several ways [2]. The simplest explanation is given by the ‘multiple routes to excitation model’, which is analogous to the young's slits model for interference of light. In this model EIT is the interference between two excitation pathways to the upper probe level. The two pathways are the direct excitation from $|1\rangle$ to $|3\rangle$ and the excitation from $|1\rangle$ to $|3\rangle$ to $|2\rangle$ to $|3\rangle$. The combined effect of the two light fields brings the atom in a dark superposition of the $|1\rangle$ and $|2\rangle$ states, determined by the amplitudes and phases of the coupling and probe laser fields.
Figure 1: The lambda energy level scheme, most often used in EIT experiments. The transitions from $|1\rangle$ to $|3\rangle$ and from $|2\rangle$ to $|3\rangle$ are dipole allowed transitions, but the transition from $|1\rangle$ to $|2\rangle$ is forbidden. The frequencies $\omega_p$ and $\omega_c$ indicate the frequency of the probe field, and of the control field.

In this superposition none of the atoms is brought into the excited state as destructive interference between these excitations cancels the original absorption from $|1\rangle$.

To achieve cancelation it is necessary that the atomic states are coherent, just as coherence is needed in young’s slit model: for this reason only laser light can be used. The coherence of the atomic states relaxes due to for example collisions. In solids the dephasing rate is large which is one of the reasons (next to the large transition linewidths in solids) why mainly mainly gases are used as media, such as rubidium, caesium and hydrogen.

For the case when the coupling field is strong and constant in time, and the probe field is weak, the linear susceptibility $\chi(\omega)$ is given by [1]

$$\chi(\omega) = g^2 N \left( \frac{\gamma_{12} + i\omega}{(\gamma_{13} + i\omega)(\gamma_{12} + i\omega) + |\Omega|^2} \right)$$

(1)

where $g$ is an atom-signal field coupling constant, $\gamma_{ij}$ is the relaxation of the $|ij\rangle$ coherence, $\Omega$ is the rabi frequency of the control field and $N$ is the number of atoms in the sample. The imaginary part of the susceptibility describes the absorption of the medium, the real part determines the refractive index, according to:

$$T(\omega) = e^{-Im[\chi(\omega)kL]}$$

(2)

with $L$ the length of the medium, and

$$n(\omega) = 1 + Re[\chi(\omega)/2]$$

(3)

In figure 2 the refractive index and the transmitted intensity as a function of the frequency detuning $\omega_p - \omega$ is shown.

1.2 Special properties of EIT

Making a material transparent is one feature of EIT but there are many more interesting properties. Looking at figure 2 one can see that the refractive index changes steeply with detuning. This in its
Electromagnetically induced transparency: controlling light with light

Figure 2: The above graph shows the transmission and the lower graph shows the refractive index as a function of detuning. At resonance the transmission is perfect, and the refractive index is 1. The refractive index changes strongly near resonance.

turn gives rise to a very small group velocity. The group velocity is given by $v_g = \frac{d\omega}{dk}$. The dispersive and absorptive properties of the medium are not independent and to calculate the group velocity the *kramers-kronig* relations have to be used [3]. Using equation 1 for the susceptibility, this gives [1]

$$v_g = \frac{c}{1 + \frac{g^2 N}{|\Omega|^2}}$$

(4)

As can be seen, when the rabi frequency of the control field goes to zero, the group velocity will go to zero. As the rabi frequency is proportional to the electric field, this implies that turning of the control field can bring a light pulse to a stop. This has already been demonstrated to work [10]. One prerequisite for this to work is that the control field has to be turned off adiabatically, in order to ensure that there is no loss and coherence is maintained.

When the probe light enters the medium it will get decelerated and the pulse gets compressed:
when entering the medium the front edge of the pulse travels slowly but the tail still travels at normal speed. One would expect the energy density to increase greatly as well as all the energy is concentrated in a smaller volume. This does not happen: energy is needed to establish coherence between state $|1>$ and state $|2>$, or in other words, to flip atomic spins as shown in figure 3 [6].

Figure 3: The schematic illustrates spatial compression of a light pulse (red curve) that enters the slow medium (blue). Photons are converted into flipped spins (blue arrows) and the photonic and spin waves propagate together. For long distances (leftmost picture) the pulse spreads. This is because at higher densities or propagation distances the medium becomes more opaque at frequencies around the resonance frequency and the transparency window becomes smaller. To preserve the pulse, the bandwidth of the pulse has to be smaller than the transparency bandwidth.

In the medium there is a strong coupling between the photons in the pulse and the atoms. This coupling results in a quasiparticle called a dark-state polariton, which can be considered to be a combined excitation of photons and spins. If a light pulse is brought to a halt the dark state polariton becomes purely atomic. The photonic quantum state is mapped onto spin states of atoms. The photonic state can also be retrieved by turning the control field back on. This shows that in theory it is possible to store and retrieve light pulses. What is even more interesting is that the retrieved light pulse has the same shape and in addition preserves phase coherence [4]. Thus with EIT it is possible to store information contained in light. During the storage time, information about the amplitude of the probe field is contained in the population amplitudes of the atomic dark states and information about the mode vector of the probe field is contained in the relative phase between different atoms in the macroscopic sample.

Light is a reliable carrier of quantum information, but it is not possible to do quantum information processing tasks with light alone. With EIT it is possible to temporarily store information contained in light pulses, in atomic states. Thus EIT is an attractive candidate to make possible quantum memory in computing [5]. Some other uses of EIT are enhancement of non-linear processes with low light intensities, electromagnetically induced focussing, inversionless lasing [12][13] and even manipulation of diffraction [11].
2 Experiments

Electromagnetically induced transparency is not just an interesting theoretical concept but has also been experimentally verified and investigated. In this section two experimental results will be given. The first result is from the review of André et al [1] and is about using EIT for Quantum memory, the second result is from a recent article (June 2010) on EIT with a single atom in a cavity [7].

2.1 Quantum memory

The coherent and reversible storage of photon states in matter currently presents a problem for the practical realization of many basic concepts in quantum information processing. Photons are the fastest and simplest carriers of quantum information, but they are difficult to localize and store. EIT offers the possibility to use photons as information carriers but use atoms as quantum memory elements. This storage process has been demonstrated experimentally, e.g. by Liu et al [9]. They have brought laser pulses to a complete stop in a magnetically trapped, cold cloud of sodium atoms by instantaneously turning off the coupling laser. The authors use cold atoms to reduce the doppler effect as it tends to spread out the energy of the atomic states.

The cloud consists of 11 million sodium atoms and is cooled to 0.9 mK. The cloud has a length of 339 mm in the z direction, a width of 55 mm. The atoms are prepared in state $|1\rangle$. First the atomic cloud is illuminated by the coupling laser, a few microseconds before turning on the probe laser, (resonant with the transition $|2\rangle$ to $|3\rangle$) so that the atoms start out in a dark state. When the probe pulse enters the cloud it will get spatially compressed and the pulse, initially 3.4 km long, is compressed to within the cloud. All of the probe energy at this point has been transferred to the coupling field and the atomic medium: coherent optical information has been imprinted onto the atoms. To stop the probe pulse, and keep the information in place, the control field is abruptly turned off. By turning the control field back on, the information can be read out again and the probe pulse emerges from the medium.

The authors have simultaneously measured the intensity of the probe and coupling field. The results are shown in figure 4.

The open circles show reference pulses recorded in the absence of atoms. The dashed curves and filled circles show intensities of coupling and probe pulses under EIT conditions. In figure 4a the time delay of the probe pulse upon entering the medium is shown. In 4b and 4c the control beam is turned of and on for two different time lags. As can be seen the normalized probe intensity goes from 0.85 to 0.3 and back again, corresponding to the storage and retrieval of information. Figure 4d shows the transmission of the probe pulse as a function of the storage time. As expected, the retrieved signal is deteriorated for longer storage times, due to relaxation of coherence. A $1/e$ decay time of 0.9 ms for the atomic coherence is found.

These results convincingly demonstrate that coherent optical information can be stored in an atomic medium and subsequently read out by using the effect of EIT.
Figure 4: The open circles show reference pulses recorded in the absence of atoms. The dashed curves and filled circles show intensities of coupling and probe pulses under EIT conditions. The measured probe intensities are normalized to the peak intensity of the reference pulses. In a) the probe pulse is delayed by 11.8ms. The arrow at 6.3ms indicates the time when the probe pulse is spatially compressed and contained completely within the atomic cloud. Figure b) and c) show the revival of a probe pulse after the coupling field is turned off at \( t=6.3 \mu s \) and turned back on at \( t=44.3 \mu s \) and \( t=839.3 \mu s \), respectively. During the time interval when the coupling laser is off, coherent information imprinted by the probe pulse is stored in the atomic medium. When turning on the coupling field again, the probe pulse is regenerated through coherent stimulation. Figure 4d) shows the transmission of the probe pulse as a function of the storage time. As expected, the retrieved signal is deteriorated for longer storage times, due to the relaxation of coherence.

2.2 Single atom EIT in a cavity

In a recent article [7] Mücke et al demonstrate EIT with a single atom quasi-permanently trapped inside a high-finesse optical cavity. The authors use a cavity to enhance the matter-light interaction, needed to scale the experiments down to just one atom. Using high reflectivity mirrors not only enhances the pathlength, but also increases the coupling (the factor \( g \) in equation 1).

In addition the authors investigate the scaling of EIT with increasing atom number, and show that the measured spectra agree with theory.

In figure 5 the energy levels and experimental protocol is shown. In figure 5a) the atoms are shelved into the \( F=2 \) state. A weak probe beam at near resonance with the transition from \( F=1 \) to \( F'=1 \) will in this case pass right through the cavity as if there are no atoms: this signal is used as a reference.
Figure 5: The energy level scheme of rubidium is shown on the left. a) b) and c) show the three distinct physical conditions for which the spectra are measured. The procedure is repeated at a repetition rate of 25 Hz, for different detuning frequencies, such that three entire spectra are obtained in one measurement.

Subsequently, the atom is brought into the F=1 state (see figure 5b), coupling the atom to the cavity. The atom now acts as a two level system. In the third step, a control field is applied (figure 5c) that couples F=2 to F’=1. This situation corresponds to the Λ level scheme that should give the characteristic EIT spectrum.

These three steps are repeated at a rate of 25 Hz, where for every cycle the probe frequency is slightly altered. In this way it is possible to record three spectra simultaneously (the reference spectrum, corresponding to an empty cavity, the spectrum with a two level atom without EIT, and the spectrum with EIT).

The measured spectra for 15 atoms and for one atom are shown in figure 6. The blue curves are for the cavity EIT case, the black curves are the reference empty cavity spectra, and the red curves corresponds to the two-level atom case, where the atoms start out in the F=1 state. The solid lines are theoretical curves, the dots are the measured data. The EIT effect is clearly resolved as the blue curve shows a very narrow transmission linewidth.

For one atom (see figure 6b) the spectrum also clearly shows a narrowed spectrum and nearly perfect transmission, and again a good agreement between theory (solid blue line) and experimental data (dotted line) is found. The red curve, for the two level situation, is different from that for 15 atoms, which is a consequence of the atomic motion that effectively reduces the coupling.
Figure 6: Figure a) shows the empty cavity spectrum (black), two level spectrum (red) and the EIT spectrum (blue) for 15 atoms. The solid lines are theoretical curves and the dots are experimental results. The characteristic narrow transmission window is obvious. Figure b) shows the same spectra for just one atom. The transmission window is less narrow but still corresponds to theory and again there is nearly perfect transmission at resonance. The dotted red line is a theoretical curve obtained from semi-classical theory in the limit of weak probe fields and assuming that almost all the population is in the atomic level F=1. The solid red curve is a more accurate theoretical curve taking into account additional effects, and matches the results well. The inset shows a CCD image of the atom showing that there is one atom present in the cavity.

The difference between the maxima of the red curve (control field off) and blue curve (control field on) at resonance is about 20% of the maximum of the blue curve. A quantum-optical transistor with an on/off contrast of about 20% is realized, admitting or rejecting the passage of probe photons through the cavity. This is a clear evidence of EIT in just one atom.
3 Questions

The questions on blackboard assume that the given article [1] presents a new result but the article on blackboard is more of a review article as it presents an overview of recent work on EIT. Instead of answering the questions for that article I will answer them for the article in Nature of Mücke et al[7] that was treated in the previous section.

1. **What is new in the article?**
   The authors report the control of the optical response of a single atom with EIT. This is entirely new: optical control with one atom had already been done before, but no one before had ever observed electromagnetically induced transparency with just one atom.

2. **How does it relate to other work in the same field?**
   EIT is a very active field of research, and a lot of different experiments are presently being done (e.g. on EIT with multilevel atoms). The work of Mücke et al follows a general trend in the field of EIT of scaling the control of light into the quantum domain with one (or a few) particles of light and matter. This down scaling could in the future allow for the implementation of quantum computing with atoms and photons and many other novel applications. The authors state that merging EIT with cavity quantum electrodynamics and single quanta of matter will be likely to become the cornerstone for novel applications.

3. **Does the work really present a breakthrough in the field?**
   The authors have demonstrated EIT with a single atom by making use of a high finesse optical cavity. The authors do not demonstrate an entirely new concept, and single atom optical control has been done before. However, single atom electromagnetically induced transparency has not been achieved up until now, and therefore I think the work does represent a breakthrough. The experiment of Mücke et al opens a whole range of new possibilities. Some of these have already been reviewed very shortly after the publication in another publication in june 2010 in Nature by Scott Parkins [8]

4. **Do the results presented in the article support the claims made in the introduction of the article?**
   The authors claim to have demonstrated EIT with a single atom quasi-permanently trapped inside a high-finesse optical cavity. They plotted the transmission as a function of detuning (see figure 6), for 15 atoms and for one atom. For one atom the EIT effect is much less pronounced but still the graphs show a convincing
correspondence to the theoretical curve. Moreover, the 20 % contrast is a convincing demonstration of EIT. The CCD image shown in the inset of figure 6 proves that there is really just one atom present. Thus the results support the claim given in the introduction.

4 Summary

A brief introduction on EIT has been given, and two experiments have been discussed. The review of André et al gives a broad overview of experiments on stokes-anti stokes pulses, single photon generation, nonlinear optics, stationary pulses with counterpropagating beams, and generation of non classical states (such as fock states) but these subjects have not been discussed here. The area of EIT is very broad and by far too much to summarize in a short paper.

A recent experimental result showing the possibility of manipulating an individual atom with EIT has been discussed. This is an exciting development and shows that EIT has the potential to become a cornerstone in many applications. However, many questions have yet to be answered to make real applications possible.

References


