Controlling photons using electromagnetically induced transparency

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It is well known that a dielectric medium can be used to manipulate properties of light pulses. However, optical absorption limits the extent of possible control: this is especially important for weak light pulses. Absorption in an opaque medium can be eliminated via quantum mechanical interference, an effect known as electromagnetically induced transparency. Theoretical and experimental work has demonstrated that this phenomenon can be used to slow down light pulses dramatically, or even bring them to a complete halt. Interactions between photons in such an atomic medium can be many orders of magnitude stronger than in conventional optical materials.

Photons normally behave as non-interacting particles. This property ensures that information encoded in optical signals will be insensitive to environmental disturbances. As a consequence, optics has emerged as the preferred method for communicating information. In contrast, the processing of information requires interactions between signal carriers, that is, either between different photons or photons and electrons. Many other applications of optics, from medicine to spectroscopy, also rely on strong light–matter interactions. One of the main challenges of nonlinear optical science is the 'tailoring' of material properties to enhance such interactions, while minimizing the role of destructive processes such as photon absorption.

Electromagnetically induced transparency

The strength of the interaction between light and atoms is a function of the wavelength or frequency of light. When the light frequency matches the frequency of a particular atomic transition, a resonance condition occurs and the optical response of the medium is greatly enhanced. Light propagation is then accompanied by strong absorption and dispersion[2], as the atoms are actively promoted into fluorescing excited states.

Consider next the situation in which the atoms have a pair of lower energy states ($|1\rangle$ and $|2\rangle$ in Fig. 1a) in each of which the atoms can live for a long time. Such is the case for sublevels of different angular momentum (spin) within the electronic ground state of alkali atoms. In order to modify the propagation through this atomic medium of a light field that couples the ground state $|1\rangle$ to an electronically excited state $|3\rangle$ (red arrow), one can apply a second 'control' field that is near resonance with the transition $|3\rangle \rightarrow |2\rangle$ (black arrow). The combined effect of these two fields is to stimulate the atoms into a so-called coherent superposition of the states $|1\rangle$ and $|2\rangle$. Here the atoms can simultaneously occupy both states $|1\rangle$ and $|2\rangle$ with a definite phase relation between the two. In such a case, the two possible pathways in which light can be absorbed by atoms ($|1\rangle \rightarrow |3\rangle$ and $|2\rangle \rightarrow |3\rangle$) can interfere and cancel each other. With such destructive quantum interference, none of the atoms are promoted to the excited states, leading to a vanishing light absorption[3–5]. This is the essence of electromagnetically induced transparency (for reviews and references to early work on electromagnetically induced transparency (EIT) and so-called 'dark resonances' see refs 2–4).

Propagation in EIT medium

Many of the important properties of EIT result from the fragile nature of quantum interference in a material that is initially opaque. Indeed, the ideal transparency is attained only if the frequency difference between the two laser fields precisely matches the frequency separation between the two lower states. If matching is not perfect, the interference is not ideal and the medium becomes absorbing. Hence the transparency spike that appears in the absorption spectrum is typically very narrow (Fig. 1b). The tolerance to frequency mismatch can be increased by using stronger coupling fields, because then interference becomes more robust.

Atoms are decoupled from the light fields in an ideal EIT, so the refractive index at resonance is nearly equal to unity. This means that the propagation velocity of a phase front (that is, the phase velocity) is equal to that in vacuum. However, the narrow transparency resonance is accompanied by a very steep variation of the refractive index with frequency. As a result, the envelope of a wave-packet propagating in the medium moves with a group velocity v_g (ref. 6) that is much smaller than the speed of light in vacuum, c. We note that v_g depends on the control field intensity and the atomic density: decreasing the control power or increasing the atom density makes v_g slower.

Figure 2 illustrates the dynamics of light propagation in EIT medium. Initially the pulse is outside the medium in which all atoms are in their ground states ($|1\rangle$). The front edge of the pulse then enters the medium and is rapidly decelerated. Because it is still outside the medium, the back edge propagates with vacuum speed c. Thus, upon entrance into the cell the spatial extent of the pulse is

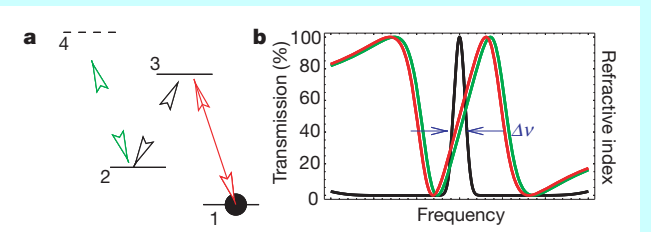

Figure 1 Electromagnetically induced transparency. **a**, Prototype atomic system for EIT and nonlinear optics. **b**, Spectrum of transmission and refractive index corresponding to EIT. Rapid variation of the refractive index (red curve) causes a reduction of group velocity. A control field (black arrow) is used to modify the propagation of weak resonant field (red) or to induce its interaction with another weak field (green). The presence of a second weak field causes an effective shift of the resonant frequency (green curve), which results in a corresponding change of the refractive index.

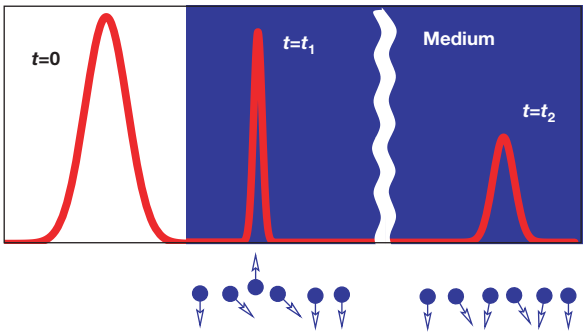

Figure 2 Schematic of spatial compression exhibited when a light pulse (red curve) enters the slow medium (blue). Photons are converted into flipped spins (blue arrowed circles), and the slow photonic and spin waves then propagate together. For long distances ($t_2 \gg t_1$), the lossless propagation is limited by the spreading of the pulses owing to the narrow bandwidth of the transparency window.

Box 1
Slow velocities versus narrow lines

Consider a generic dispersive optical element (for example, narrow atomic resonance, optical cavity, and so on) that is characterized by the common lorentzian input–output relation: $E_{out}(\omega) = T_l(\omega)E_{in}(\omega)$ with spectral response function $T_l = (1 + i(\omega - \omega_{res})/\Delta\nu_l)^{-1}$. Here, $\Delta\nu_l$ is the linewidth of the dispersive element and ω_{res} is the resonance frequency of the optical element. For $\omega \approx \omega_{res}$, this response corresponds to a group delay $\tau_l = 1/\Delta\nu_l$. Hence narrow resonances lead to long group delays, but the latter does not exceed the reciprocal linewidth. In contrast, the response near an EIT resonance is given by[11]: $T_{EIT}(\omega) = \exp(i\omega\tau - \omega^2/\Delta\nu^2 + O(\omega^3))$, with the corresponding bandwidth $\Delta\nu = 1/\tau \times \sqrt{T}$. Here $T = N\sigma L/2$ is the optical depth of the medium, with N and σ being the atomic density and absorption cross-section.

The importance of a product with a large-delay bandwidth can be emphasized by noting that the spatial length of light pulse inside a medium is v_gT. Hence in order to localize the pulse inside a medium of length L and to contain its spectrum within the transparency linewidth, $\Delta\nu \times \tau \gg 1$ is required.

compressed by the ratio c/v_g, whereas its peak amplitude remains unchanged. Clearly the energy of the light pulse is much smaller when it is inside the medium. The rest of the photons are being expended to establish the coherence between the states $|1\rangle$ and $|2\rangle$, or in other words to flip atomic spins, with any excess energy carried away by the control field. The wave of flipped spins now propagates together with the light pulse. The two form a combined excitation of photons and spins called a dark-state polariton[7]. The group velocity of this polariton is proportional to the magnitude of its photonic component. As the pulse exits the medium its spatial extent increases again and the atoms return to their original ground state; the pulse however, is delayed as a whole by $\tau = (1/v_g - 1/c)L$, where L is the length of the medium.

The above description is an ideal scenario. In practice, two main limitations have to be taken into account. First, the lifetime of the coherence created between different spin states is always finite (τ_{coh}). This implies that after a characteristic time τ_{coh} the atoms will end up either in state $|1\rangle$ or $|2\rangle$; the transparency will then be lost and the polariton will disappear. Second, even for infinite τ_{coh}, the pulse delay is limited by the bandwidth of the transparency window, which decreases with propagation distance. This is because at higher densities or propagation distances the medium becomes increasingly opaque at frequencies other than the line centre; as a result the available transparency window becomes smaller. After a sufficiently long propagation this results in spreading of the pulse (see Fig. 2). In order to preserve the pulse, its bandwidth $1/T$ should be smaller than the transparency bandwidth $\Delta\nu$. This puts a limit on the ratio of delay and pulse duration, which can exceed unity only if an optically dense medium is used (see Box 1).

Early experimental work demonstrated these unusual properties of EIT[8–11]. For example, group velocities of $c/165$ were measured in lead vapour[9]. Even in these early experiments, delays considerably exceeding the pulse duration were observed. The subject was then brought into focus by the remarkable experiments of ref. 12. An ultracold gas of Na atoms was used to slow light pulses to 17 m per second. The pulses were entirely localized inside the medium owing to its large density. Experimental work on slow group velocities in hot atomic vapour[13,14] rapidly followed.

Nonlinear optics based on EIT

The large body of work on EIT was motivated by the realization that nonlinear optical effects can be enhanced when resonant absorption is eliminated. The key idea[15] is that in an EIT medium the atoms are very sensitive to processes that create or alter the coherent superposition between states $|2\rangle$ and $|1\rangle$. As an illustration, we consider the process where an optical field with amplitude E_s (green arrow in Fig. 1a) is used to modify the properties of the medium by coupling to a third optically allowed transition between states $|2\rangle$ and $|4\rangle$. This off-resonant field effectively changes the energy of the metastable state $|2\rangle$ by an amount that is proportional to the intensity E_s^2. This shift, in turn, modifies the refractive index of the probe field. When the dispersion of refractive index is very steep (Fig. 1b), small energy shifts due to weak optical fields result in a large index change. This is the essence of the resonantly enhanced Kerr effect[16].

Modification of the refractive index of one field by another can be viewed as resulting from a photon–photon interaction that preserves the intensity of each field mode. This process is also referred to as cross-phase modulation: the two-field interaction gives rise to a nonlinear phase shift that is proportional to the group delay (that is, the interaction time of the slow pulse with matter). Hence for given field intensities, increasing the interaction time between light and matter can result in more efficient nonlinear optical effects.

This is just an example of how nonlinear optics based on EIT works. By now related ideas have been explored for a variety of nonlinear phenomena ranging from phase conjugation[17] to acousto-optics[18] and have already been shown to work very well for a number of potential practical applications. This is perhaps best illustrated by experimental work[19] that used EIT to obtain extremely efficient frequency up-conversion into the extreme ultraviolet. An extension of this work to molecular systems allowed the generation of a comb of phase modulated signals with a frequency span corresponding to subfemtosecond pulses[20,21].

We note in particular the recent work on nonlinear optics involving very weak light fields. For example, in the experiment on slow light propagation[12], an optical Kerr effect that is several orders of magnitude stronger than that in usual resonant systems was inferred. In another recent experiment[22], an efficient nonlinear process involving mixing of four waves was initiated by optical pulses with tiny energies in the nanojoule range.

Given the rapid progress of studies on EIT-based nonlinear optics it is natural to ask about the ultimate limits. For example, in cross-phase modulation[16] how much energy in one pulse is required, under optimal conditions, to change the phase of another pulse by π? This problem was studied[23] for the case involving one 'slow' pulse that is subject to EIT and another 'fast' pulse that propagates at c. In this case the interaction time is limited by the duration of the fast pulse (T), and the efficiency of various processes scales proportionally to the

number of photons n in the pulse per cross-section of a single atom. Specifically, an optical pulse containing few photons can be used to change significantly the phase of another field. Ref. 24 extended these studies by considering two interacting slow pulses. In this case, the interaction time is determined solely by the group delay τ. As τ can exceed the pulse length T in an optically dense medium (see Box 1), this approach in principle allows one to induce a large nonlinear phase shift, even when the energy of each input pulse is less than that of a single photon per atomic cross-section.

From EIT to quantum memory

It is now widely accepted that quantum mechanics allows for fundamentally new forms of communication and computation[25]. To implement these ideas, information should be encoded in delicate quantum states, such as single-photon states, and subsequently manipulated without being destroyed. Photons are the fastest and simplest carriers of quantum information, but they are difficult to localize and process. It appears that an ideal solution would be to store and process quantum information in matter that forms the nodes of a quantum network, and to communicate between these nodes using photons[26].

A way of achieving this goal by transferring or mapping quantum information reversibly between light and matter was proposed in ref. 27. The idea is closely related to the dark-state polariton concept[7]. When a polariton propagates in an EIT medium, its properties can be modified simply by changing the intensity of the control beam. As the control intensity is decreased the group velocity is slowed, which also implies that the contribution of photons in the polariton becomes purely atomic, and its group velocity is reduced to zero. At this point, quantum information originally carried by photons is mapped onto long-lived spin states of atoms. As long as the trapping process is sufficiently smooth (that is, adiabatic[28]), the entire procedure has no loss and is completely coherent. The stored quantum state can easily be retrieved by simply re-accelerating the stopped polariton. This is illustrated in Fig. 3, which shows the evolution of the 'signal' light pulse, spin coherence and polariton when the control beam is turned off and on. The amplitude of the signal pulse decreases as it is being decelerated whereas the spin coherence grows; the procedure is reversed when the control beam is turned back on.

We note here that the essential point of this technique is not to store the energy or momentum carried by photons but to store their quantum states. In fact, in practice almost no energy or momentum is actually stored in the EIT medium. Instead, both are being transferred into (or borrowed from) the control beam in such a way that an entire optical pulse is coherently converted into a low-energy spin wave. This is the key feature that distinguishes the EIT approach from earlier studies in optics (involving, for example, traditional photon echo techniques[1]) or nuclear physics[29]; it also makes possible applications in quantum information science. A different technique, to 'freeze' light pulses, was suggested in ref. 30.

We have already argued that for EIT to be effective in eliminating dissipation, the light pulse spectrum should be contained within a relatively narrow transparency window (Fig. 1b). A vanishing control beam intensity implies that the transparency window would become infinitely narrow and eventually disappear. The essence of adiabatic following in polaritons is that a dynamic reduction in group velocity is accompanied by narrowing of the polariton frequency spectrum, such that it is not destroyed even if $v_g = 0$. The conditions for adiabatic following are very simple: the entire pulse should be within the medium at the beginning of the trapping procedure and its spectrum should be contained within the original transparency window. Once again, these conditions are satisfied only if the medium is optically dense.

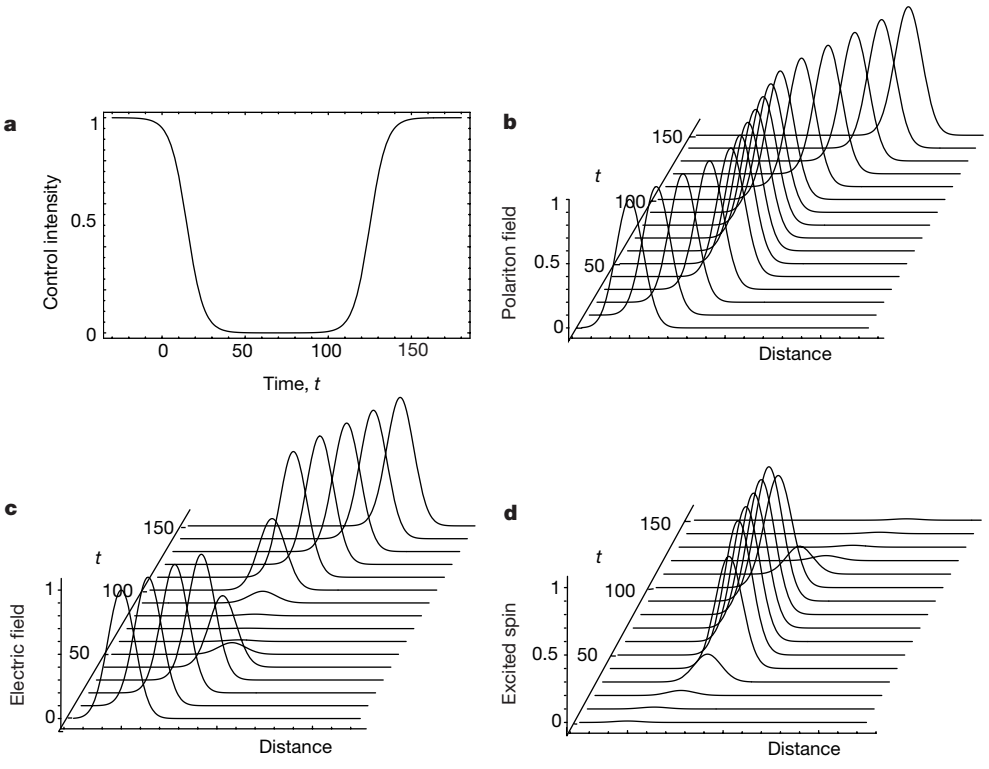

Figure 3 Dark-state polaritons. A dark-state polariton can be stopped and re-accelerated by ramping the control field intensity as shown in **a**. The coherent amplitudes of the polariton Ψ, the electric field E and the spin components S are plotted in **b** to **d**.

Recent experiments have already verified the basic concept of dynamic trapping in polaritons, by showing that the weak laser pulses are not destroyed during the trapping and release processes. In the experiment of ref. 31, a light pulse was slowed and then 'trapped' in an ultracold atomic sample for up to 1.5 ms. The experiment of ref. 32 used Zeeman sublevels of the electronic ground state of warm Rb atoms to demonstrate a trapping time of about 0.5 ms. Extension of the latter work recently demonstrated the phase coherence of the trapping process[33].

Outlook

Even though EIT has already made a major impact in nonlinear optical science, commercial applications have not yet emerged. One potential area is all-optical switching and signal processing in optical communication. The most serious roadblocks on this front are materials and speed issues. Good optical control requires long coherence times, and for this reason the majority of experiments made use of atomic vapours that have relatively slow response. For practical communication systems, solid state devices are desirable because of their low cost and the possibility of integration with existing technologies. Work on implementing EIT in solids is currently in progress[34,35].

Photon–photon interactions enabled by EIT can fulfil the stringent requirements on precision and efficiency imposed by quantum information processing. In particular, optical materials with large nonlinearities and low loss could be indispensable for the controlled generation of entangled states and for quantum logic operations. Several avenues for using EIT in this area have already been explored. Earlier proposals involved the use of a coherent medium to enhance photon–photon interactions in optical cavities. The key idea is that a single photon can shift the resonant frequency such that the following photon is out of resonance and is therefore reflected[36]. The resulting 'photon blockade' effect can form the basis of a quantum switch. However, the requirement of a high-quality cavity is a disadvantage from a practical point of view. Subsequent work has predicted the efficient generation of entangled photons on the basis of resonant mixing of four waves[37]. Using EIT-based phase modulation for two slowly propagating pulses, ref. 24 predicted the possibility of generating macroscopic quantum states (so-called 'Schrödinger's cat' states) of light. However, the application of this idea to quantum logic operations is complicated by the evolution of pulse envelopes in nonlinear process. Nevertheless, a scheme for complete quantum teleportation using this technique has recently been proposed[38].

We also note that once a dark-state polariton is converted into a purely atomic excitation in a small-sized sample, logic operations can be accomplished by promoting atoms into excited states with strong atom–atom interactions, as suggested in ref. 39. Here the ability to interconvert quantum information between photons and atoms is essential for performing operations involving distant units and for the scalability of such systems. Likewise, important potential applications such as quantum communications over long distances might be implemented by combining an EIT-based memory with linear optical elements[40].

Experiments in the coming years will undoubtedly shed new light on the opportunities and practical limitations for classical signal processing and for quantum-state manipulation using EIT. Nevertheless, it seems safe to predict that some of the techniques described here will find important uses in optical science and technology. □

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