

METHODOLOGICAL NOTES

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On electromagnetically induced transparency in the degenerate Λ-scheme

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Abstract. **Using an experimental work on 'stopped light' as an example, we show how a classical phenomenon of linear optics, the interference of polarized light, can imitate the effect of electromagnetically induced transparency.**

After the first impressive experiments on the so-called 'slow light' [1, 2], works have appeared where equally spectacular results were obtained under much simpler experimental conditions. In one of the most popular of those publications [3], the symptoms of a retarded polarization-optical response of an atomic medium were regarded as manifestations of the 'slow' and 'stopped' light effects. Criticism of this paper can be found in [4]. In the present note, we attract attention to an instructive aspect of the misinterpretation in [3], which, in fact, resulted from erroneous identification of the interference of polarized beams as the effect of electromagnetically induced transparency (EIT).

We recall that in its simplest form, the EIT effect [5] is revealed when a sufficiently strong resonant field acts on a three-level quantum system with a Λ-type energy diagram (Fig. 1). It turns out that the action of the pump (control) field E_c in one arm of the Λ-scheme (with both the initial and final levels of the appropriate transition being empty) renders the system transparent for the weak probe (signal) field E_s acting in the second arm if the frequency difference between the two fields coincides with the frequency of transition between the two lowest levels.

The narrow dip formed under these conditions in the absorption spectrum of the system (in the channel of the probe light $|1\rangle - |3\rangle$, Fig. 1) ensures a high steepness of the refractive index dispersion in the vicinity of the transparency point and can be revealed, in particular, as a giant reduction of the group velocity of light propagating in this medium. This is the gist of the EIT-based 'slow light' effect.

Turning to the physical content of EIT, we can recall that this effect is, in essence, a strongly asymmetric case (with respect to the intensities of the two fields) of the effect of coherent population trapping [6], which is usually detected as a dip in the luminescence excitation spectrum under comparable intensities of the fields. In turn, the effect of coherent population trapping is the direct development of the effect of optically driven spin precession [7], with magnetic sublevels of the ground state serving as the lowest levels of the Λ-scheme. Eventually, the effect of the optically driven spin precession is nothing but the effect of optical orientation (or optical alignment) in a rotating coordinate frame [8]. Therefore, without restraining the specificity of EIT, which is the only 'linear' effect among all the coherence resonances mentioned above, we can say that EIT is just a modification of the generalized optical alignment effect. In [3], the attempt was made to realize the EIT effect, so to say, on the lowest step of the above hierarchy, when the lowest levels of the Λ-scheme are *degenerate magnetic sublevels* of the ground state.

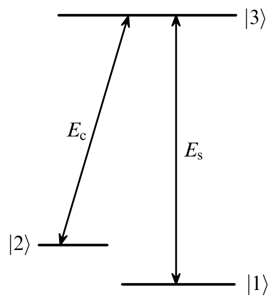

Figure 1. Energy level diagram (Λ-scheme) illustrating a common approach to the observation of the coherence resonance of states $|1\rangle$ and $|2\rangle$. A specific feature of the EIT effect is that it is observed at $E_c \gg E_s$ and is linear in the probe field E_s, while the effects of coherent population trapping and optically driven spin precession are observed in the fields of comparable amplitudes (more precisely, of comparable Rabi frequencies at the transitions $|1\rangle \to |3\rangle$ and $|2\rangle \to |3\rangle$).

The experiments in [3] were performed on the transition $5^2S_{1/2}$, $F = 2 \to 5^2P_{1/2}$, $F = 1$ of ^{87}Rb using a tunable diode laser as a light source and a Pockels cell for controlling the beam polarization. A specific feature of the experiment was that orthogonal polarization components of the same laser beam were used as the control and signal (probe) beams. In other words, real variations in the polarization of the light beam passing through the cell were produced using the Pockels cell and were considered a result of admixing of the orthogonally polarized probe beam to the control beam. A simplified schematic of the experimental setup is shown in Fig. 2. The strong (control) and weak (signal) beams are combined on the input polarizing beamsplitter and then, after passing through the atomic system, are split again on the same polarization basis and are registered by two photodetectors.

The basic experimental fact reported by the authors of [3], which, in their opinion, should serve as a direct manifestation of the EIT effect, is that the system under study is opaque for

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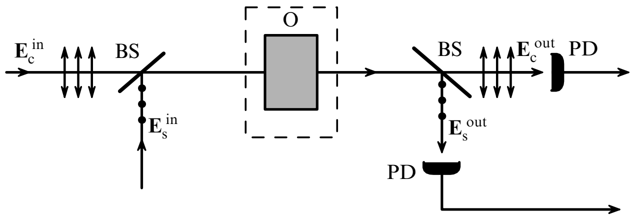

Figure 2. Simplified schematic of the experimental setup for observation of the EIT effect in the degenerate Λ-scheme. E_c and E_s are the control and probe (signal) beams, BS are polarizing beamsplitters, PD are photodetectors, and O is the object under study.

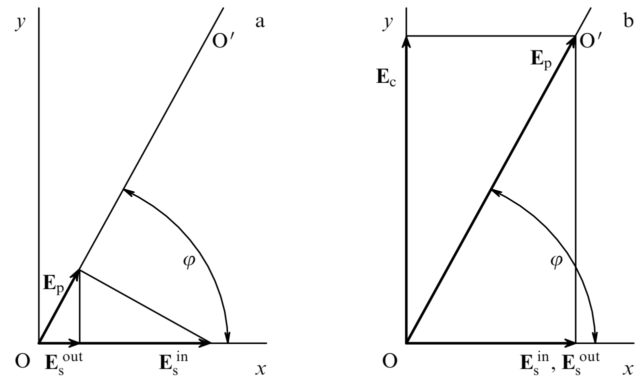

Figure 3. Vector diagram describing transformation of the probe wave field E_s in the arrangement of Fig. 2 with a polarizer in the 'black box' in the absence (a) and in the presence (b) of the control field E_c. The fields E_s and E_c are polarized along the x- and y-axes, respectively. The line OO′ corresponds to the polarizing direction of the polarizer. $\mathbf{E}_s^{in}$ and $\mathbf{E}_s^{out}$ are the probe field vectors at the entrance and at the exit of the optical system.

the probe light in the absence of the control beam and becomes virtually completely transparent in its presence. The authors interpret this effect as that of *nonlinear optics*, controlling transmission of the medium by light. At first glance, this looks convincing. But is this actually the case? Is it necessary that the optical element placed into the 'black box,' outlined in Fig. 2 by the dashed line, be nonlinear to demonstrate the above effect of 'controlling light by light'? We show that it is not.

We assume that the control and probe beams are polarized not circularly as in [3] but linearly. This changes absolutely nothing from the standpoint of physics (because the system under study is amenable both to orientation and alignment), but makes the treatment more visual.

We also assume that the mutually coherent fields are in-phase, and hence, being summed at the input beamsplitter, they form linearly polarized light. The angle φ between the plane of polarization of this light and that of the probe beam is evidently equal to $\arctan(E_c/E_s)$, where E_c and E_s are the amplitudes of the control and probe waves (Fig. 3).

We replace the cell with rubidium vapor in the 'black box' by a linear polarizer with its polarizing direction making the same angle φ with the polarization plane of the probe. As a result, in the absence of the control field, the probe beam, on its way to the detector, is first attenuated by this polarizer (according to the Malus law, the attenuation factor is $\cos^2\varphi$) and then attenuated to the same degree by the output beamsplitter (Fig. 3a). It is clear that total attenuation of the probe beam, given by the factor $\cos^4\varphi$, can formally be arbitrarily large if the angle φ is sufficiently close to 90°.

Thus, transmission of the probe beam by the 'black box' is rather low. We turn the control light on. Now the light coming out of the input beamsplitter is again linearly polarized, but its polarization plane exactly coincides with the polarizing direction of the polarizer in the black box, and the light passes through the polarizer without any attenuation or any change in its polarization state. In other words, with the control beam on, the black box becomes transparent for the whole incident light and, in particular (most importantly for us), for its horizontal polarization component, i.e., for the probe beam.

This is practically an exact copy of the EIT effect described in [3] (neglecting the dynamics of the process). In reality, the medium studied in [3] is indeed nonlinear, and hence the pump beam aligns it optically and thus controls its anisotropy. This means that the azimuth of the transmission axis of the black box is actually set not manually, as in our hypothetical experiment, but by the light itself. For this reason, there arise some apparent discrepancies between the picture described above and the observations in [3]. For instance, in our simplified arrangement, when the control light is on, the probe light is present at the exit of the setup, even being absent at the entrance. However, as can be easily seen, this is exactly what is observed in [3] in the demonstrations of stopped light, when, after preliminary manipulations with polarization of the light beam and subsequent dark pause, the signal in the channel of the probe light is observed with no probe light at the entrance. In the experiment, this signal cannot be observed for a long time because, after a certain time interval, the control beam aligns the atomic system along its polarization plane or, in other words, properly sets the polarizer of the black box ($\varphi = 90°$, Fig. 3), and the projection of the control beam onto the probe light channel vanishes. In our model, the position of the black box polarizer is fixed, and therefore the signal of the probe light cannot disappear.

Thus, we see how easily the EIT effect can be simulated by the interference of polarized beams when the 'control' and 'probe' fields are just two orthogonal polarization components of the same beam.

However, a question arises: Perhaps this is not an imitation of the EIT effect but the EIT effect itself or, better to say, what it has become in the degenerate Λ-scheme. To a certain extent, this is the case indeed. But, first of all, there are no grounds to rename old, well-known effects of classical optics unless we have discovered something new. Second, and most important, is that 'freezing' the phase difference between the probe and control waves in the degenerate Λ-scheme changes the *symmetry* of the problem. In the standard nondegenerate case of EIT, the anisotropy of the medium is provided exclusively by the control light, while the weak probe light monitors it in a nonperturbing way. In the degenerate Λ-scheme considered here, the probe light of an arbitrarily low intensity affects the anisotropy of the medium (in a way that depends on the value of the 'frozen' phase) and is therefore fundamentally unable to fulfill its function of *probe*. In addition, an optical medium with the anisotropy axis OO′ cannot be characterized by any optical constant for the probe light polarized along the x axis, and, correspondingly, no phase or group velocity can be assigned to this light [4, 9]. In fact, the standard model of the EIT effect becomes inapplicable when the inverse frequency spacing between levels $|1\rangle$ and $|2\rangle$ becomes comparable with the time of measurement.

We note in conclusion that the apparent effect of controlling light by light in a single interference order is a trivial phenomenon. As applied to the polarization geometry under consideration, this effect can be comprehensively described by the standard operation of multiplying the Jones vector of the input light by the matrix of the linear polarizer. Still, in some experimental situations, recognition of this phenomenon appears to be not so trivial. At least, paper [3], in which exactly this error was made, has gained unquestioning recognition by the scientific community and to date remains widely cited in publications on slow light. This is why we considered this story instructive and deserving additional attention.

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