

# Chasing ‘slow light’

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**Abstract.** A critical review of experimental studies on so-called ‘slow light’ arising due to the anomalously high steepness of the refractive index dispersion under conditions of electromagnetically induced transparency or coherent population oscillations is presented. It is shown that a considerable amount of experimental evidence of the observation of ‘slow light’ is not related to the low group velocity of light and can be easily interpreted in terms of a standard model of interaction of light with a saturable absorber.

## 1. Introduction

In the last decade, the topic of ‘slow’ and ‘fast’ light — a light pulse propagating in a medium with ultralow, or superluminal, or even negative group velocity — has gained particular popularity. The keen interest in this topic is related not so much to the possibility itself of varying in a controlled way the light group velocity in a medium, as to a huge scale of these variations (7 orders of magnitude and more) and to the claimed favorable prospects for applying ‘slow light’ in telecommunication and optical computing. As a result, in the late 90s, ‘slow light’, in fact, turned into a separate trend in physical optics. Several hundred publications have been

devoted to these problems. They are discussed at special topical meetings and workshops. The somewhat sensational character of the claimed achievements (including the effects of ‘stopped’ and ‘stored’ light) renders this topic popular not only in scientific literature, but also in the mass media.

Concurrently with the increased rate of publications on ‘slow light’ research, the quality of the publications has been getting noticeably poorer. The phenomenological simplicity of ‘slow light’ effects has made it possible to observe similar phenomena in relatively simple experimental conditions and to ascribe them to the ‘slowing down’ or ‘stopping’ of light without sufficient grounds.

In these notes, we critically analyze the publications on ‘slow light’ and demonstrate the inconsistency of a considerable number of arguments intended to provide evidence for dramatic changes in the group velocity of light.

## 2. From the history of the group velocity of light

The question of the slowing down of light in a medium has a long history, dating back to Newton’s *Optics*. Early in the last century, attention to the problem of the speed of light in a medium was attracted again in connection with the creation of the special theory of relativity, which limited, by its second postulate, the velocity of transfer of information to that of light in a vacuum ( $c$ ). The problem of the propagation of electromagnetic waves in real media was studied in the early 20th century by classics of physical optics. It is worth mentioning in this connection A Sommerfeld and his disciple L Brillouin, who summarized the results of these studies in the monograph [1]. Later on, the speed of light in a medium attracted the attention of researchers, mainly in those cases where it strongly differed from that in a vacuum. Forty years ago, a ‘superluminal’ group velocity of light was claimed to be observed in Ref. [2]. The studies were performed with light pulses propagating in an amplifying medium under conditions of strong nonlinearity related to the gain saturation under the action of the pulse. In this case, the shape of the

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pulse changed as it propagated through the medium, with its peak being shifted in the forward direction. By defining the group velocity of light as the velocity of motion of the pulse peak, the authors of Ref. [2] claimed to have observed a 9-fold higher speed of light in the medium over that in a vacuum. This phenomenon was, in essence, the inverse effect of the light pulse delay in a saturable absorber (see, e.g., Ref. [3]) and, therefore, was not of fundamental significance<sup>1</sup>.

A new splash of attention to this issue was associated with the *linear* propagation of optical pulses whose spectrum fell into the region of steep dispersion of the refractive index of the medium. In this case, in the standard formula for the light group velocity

$$V_g = \frac{c}{n + \omega \frac{dn}{d\omega}}, \quad (1)$$

the dispersion term starts to predominate. As a result, the motion of the light pulse in the medium slows down not so much due to the deviation of the refractive index  $n$  from unity (the resources of this slowing-down mechanism are rather limited) as due to the steep dependence of the refractive index on the frequency  $\omega$ . This dispersion-related contribution affects only the group velocity of light and does not change its phase velocity, controlled by the value of  $n$ .

It is noteworthy that the problem of definition of the light group velocity frequently becomes the subject of controversy. The notion of group velocity introduced in Ref. [1] is quite definite for a bi-frequency wave, being defined as the speed of motion of the beat envelope. This, rather abstract, field is evidently of limited interest for practice. As applied to a light pulse with a continuous spectrum, the problem of group velocity becomes more complicated, since the pulse, while traveling through a dispersive medium, changes its shape and the quantitative evaluation of its displacement in space becomes ambiguous. In what follows, we will understand the light group velocity as it is defined by Eqn (1). For transparent media, this definition corresponds to the velocity of motion of the pulse maximum and, in a certain approximation, with the velocity of motion of the pulse as a whole. It is known, for instance, that if the spectrum of the pulse fits into the region of linear dispersion of the refractive index, the original pulse of Gaussian shape will propagate through the medium practically without any distortion (see, e.g., Ref. [5]), provided that the absorption (gain) of the medium does not strongly change within the spectral width of the pulse (see also the experiment of Ref. [6]).

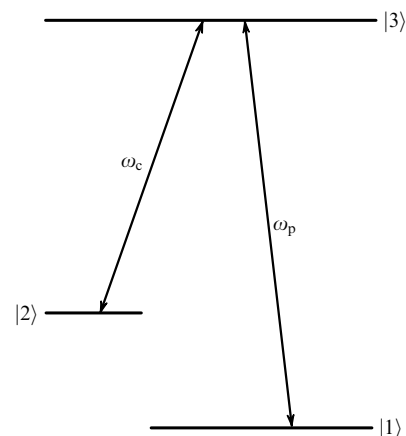
Thus, the group velocity in the sense of Eqn (1) is the speed of motion of the pulse maximum, but it does not mean that the opposite statement is also valid, i.e. that the speed of motion of the pulse maximum is always the group velocity of light. Definition (1) is applicable to a *transparent, linear*, and *stationary medium*, whose properties change, neither due to external perturbations nor due to the self-action of the light pulse, in the process of pulse propagation through the medium (i.e., the medium is supposed to be *linear* with respect to the probe pulse whose group velocity is measured). For absorbing, nonlinear, and nonstationary media, there may exist other mechanisms of the pulse maximum delay (e.g. of the time vignetting type), which have nothing to do with the dispersion of the medium and cannot be described

by Eqn (1). In our opinion, the delays of this kind cannot be attributed to changes in the light group velocity in the commonly accepted understanding of this notion.

### 3. ‘Slow light’ and the goal of this article

The real boom in publications devoted to anomalies in the light group velocity (or to ‘slow light’<sup>2</sup>) was associated with the realization of the electromagnetically induced transparency (EIT) [7], which has made it possible to combine two, previously exclusive, properties of the medium — a high steepness of dispersion and optical transparency. The effect is usually observed in systems with the energy-level diagram schematically shown in Fig. 1 (the so-called  $\Lambda$ -scheme). Two electromagnetic fields  $\omega_c$  and  $\omega_p$  are applied to induce transitions between two, usually closely spaced, sublevels of the ground state ( $|1\rangle$  and  $|2\rangle$ ) and the third common excited level  $|3\rangle$ . An excitation of this type is capable of inducing coherence between the two lower states. If the frequency  $\omega_c$  of one (usually stronger) field is fixed and the frequency  $\omega_p$  of the other (probe) field is being scanned, then, at the point of the two-photon resonance one will detect a dip in the absorption spectrum (‘transparency window’), corresponding to a destructive quantum interference of the transitions to the excited state via two alternative routes. In accordance with the Kramers–Kronig relations, a region of steep dispersion of the refractive index should correspond to this dip. The steepness may be extremely high due to the extreme narrowness of the coherence resonance of the ground state sublevels. Under these conditions, it appears possible to demonstrate anomalously high retardation of a light pulse in the medium [8–10]. The most impressive results — reduction of the light group velocity by more than seven orders of magnitude! — have been obtained using ultracold sodium atoms (in the vicinity of the Bose-Einstein condensation temperature) [11, 12].

In more recent experiments, the circle of mechanisms capable of providing ‘slow light’ was widened. The studies were performed, as a rule, in rather simple experimental



**Figure 1.** A model three-level energy diagram for observation of the electromagnetically induced transparency effect ( $\Lambda$ -scheme).

<sup>1</sup> It is noteworthy that neither in this paper nor in any other subsequent report on superluminal propagation of the light pulse do the authors claim to refute the special theory of relativity (see, e.g., review [4]).

<sup>2</sup> In what follows, for brevity the term ‘slow light’ is used in reference to all the phenomena associated with dramatic changes in the light group velocity due to steep dispersion of the refractive index, i.e. to the ‘slow light’, ‘fast light’, and the light with ‘negative’ group velocity.

conditions, and analyses of the results were made, in our opinion, not critically enough, attributing any apparent delay of the light pulse in the medium to its low group velocity. Some obviously erroneous works of this ilk were criticized in Refs [13–15]. However, the essence of the matter consists, in our opinion, not in the errors committed in certain papers, but rather in the inconsistency of the provided evidence. As a result, in the present-day situation, the reliability of the conclusions, in a considerable number of publications on 'slow light' is strongly in doubt.

In this article, we consider some effects of *incoherent* nonlinear optics which are phenomenologically similar to 'slow light' effects and should be necessarily observed in slow relaxing media with nonlinear absorption, while having nothing to do with 'slow light'. We draw attention to a number of commonly accepted pieces of evidence for 'slowing down' and 'stopping' light that cannot be used as such. We also discuss certain specific features of the 'slow light' effects that allow one to experimentally distinguish them from the effects of a 'slow medium' universally observable in resonance media with saturable absorption.

Since the problems of interpretation of experimental observations considered here are of a conceptual nature, and the effects of incoherent nonlinear optics that mimic 'slow light' are known well enough and have been repeatedly described in the literature, we consider it possible to restrict ourselves to a qualitative level of their treatment without reproducing the known theoretical derivations (which, if needed, can be found in the references).

#### 4. Subject of study — nonlinear absorber

The simplest (and chronologically the first discovered) effects of nonlinear optics were related to resonance perturbation of populations of quantum states (effects of saturation) [16]. For sufficiently long relaxation times, these *incoherent* nonlinear effects can be, in principle, observed at arbitrarily low light intensities. The opposite side of the high nonlinearity of such 'slow' systems is a certain sluggishness of their optical response and, therefore, their limited applicability to the up-to-date broadband systems of optical information processing. These effects, as a whole, are naturally considered to be well known and, perhaps for this reason, are not given sufficient attention.

The effects of saturation in their simplest form are known to emerge when the time of interaction of the light with the nonlinear medium substantially exceeds the transverse relaxation (dephasing) time of the resonance oscillators and when the rate of the light-induced transitions becomes comparable to that of the population relaxation. In this case, this means the populations of the system and, hence, the absorption of the medium change. Most frequently, the absorption of the medium drops with increasing light intensity (the medium is bleached). But there also exists the opposite situation, when the absorption of the medium increases with light intensity. The appropriate nonlinear absorbers are called *inverse*. For practical applications (mainly in laser techniques), diverse optical media, like dye solutions, doped crystals and glasses, dielectrics with semiconductor nanocrystals, etc., are used as saturable absorbers. A typical 'slow' saturable absorber is the ruby crystal, where the coherence of the light-induced excitation of the medium in the blue-green spectral range is rapidly destroyed by the fast relaxation from the excited state of the  $\text{Cr}^{3+}$  ions to

metastable levels, whose long lifetime provides retardation of the optical response of the crystal.

The most perfect saturable absorber model is, however, provided by the optically pumped atoms of alkali metals, which are also characterized by fairly long ground-state population relaxation times but, in addition, show one more important property: in the absence of an external magnetic field, their anisotropy is entirely controlled by the anisotropy of the acting light (see, e.g., Ref. [17]). As a result, in the field of polarized light, these systems may be considered as *polarization* saturable absorbers, which differ from conventional ones by additional degrees of freedom — polarization of the exciting light and anisotropy of the medium. These degrees of freedom considerably widen the range of phenomena observed under conditions of optical pumping.

Below, we will dwell in more detail upon the properties of these 'slow' saturable absorbers, which are the basic subjects of 'slow light' experiments. We will consider the effects that should necessarily be observed in 'slow' nonlinear absorbers regardless of the spectral features of the medium's dispersion and variation of the light group velocity. All the effects considered below are, in fact, combinations of the elementary properties of a saturable absorber and none contains anything essentially new. Still, it is exactly these effects that are frequently considered as manifestations of 'slow light'.

#### 5. On the capabilities of a saturable absorber

So, the question is: What is to be expected from a saturable absorber under conditions of optical excitation typical for 'slow light' experiments and what really new has been found in those experiments?

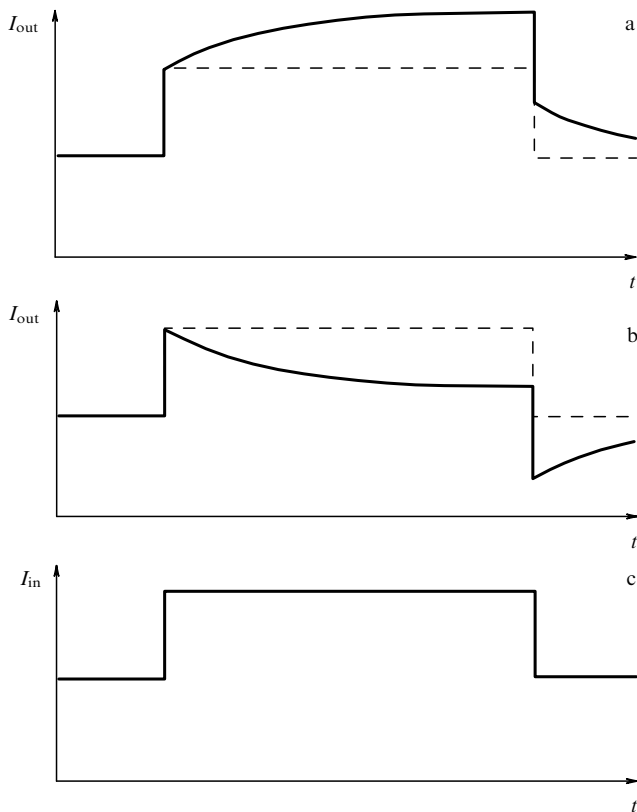
##### 5.1 Time-domain response

The simplest property of the saturable absorber is related to the dynamics of its response to a change in the incident light intensity. When the light intensity at the input changes in a step-wise way, the light intensity at the output, evidently, experiences a jump, corresponding to the linear light transmission, and an exponential growth (or exponential fall for the inverse saturable absorber), corresponding to the process of establishing steady-state populations of the system (Fig. 2).

Experimental dependences of this kind are reported, for instance, in Ref. [18], where the probe-pulse shape distortion is ascribed to the effect of the steep material dispersion in the region of resonance of the electromagnetically induced transparency and electromagnetically induced absorption. Such temporal dependences in pure form, being of no interest, are not usually presented in papers on 'slow light'. We mention this type of response only for the sake of completeness and in order to move to the next, more important type of response.

##### 5.2 Frequency-domain response

The Fourier-transform of the above time dependences yield their frequency-domain representation, which can be easily obtained experimentally by measuring the frequency dependence of the amplitude and phase of oscillations of a modulated light beam transmitted through a saturable absorber. Figure 3 shows what the dependences of this kind look like for a bleachable absorber. As expected, the frequency dependence of the response displays a peculiarity in the range of low frequencies comparable to the inverse



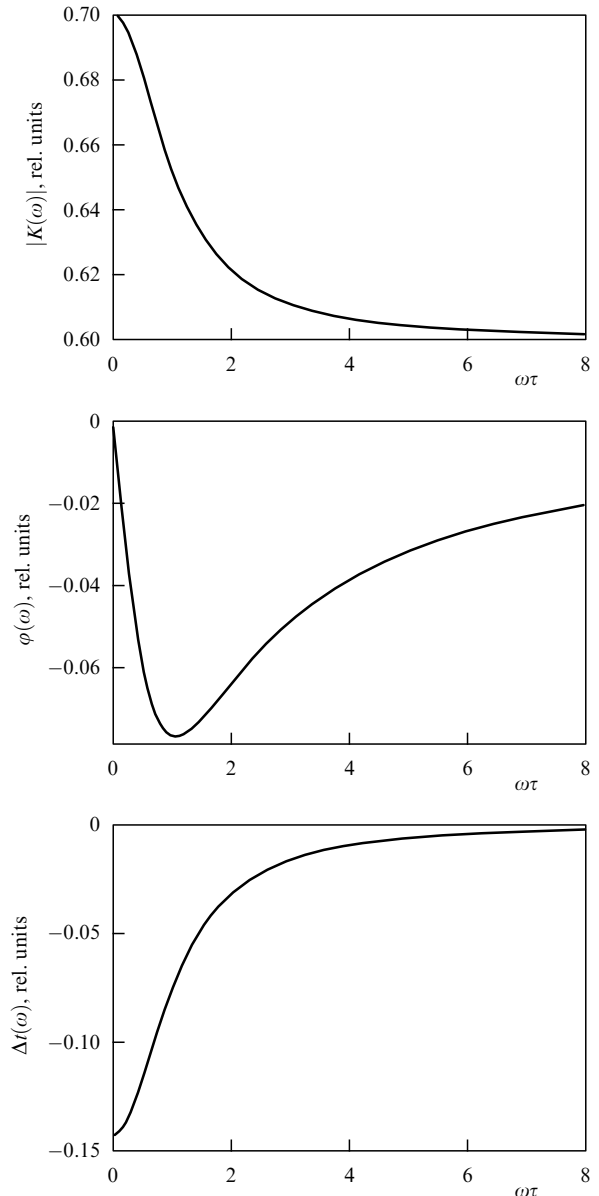
**Figure 2.** Schematic depiction of the time dependence of light intensity at the output of an ordinary (a) and inverse (b) saturable absorber for a step-wise change in the intensity at the input (c).

population relaxation time of the absorber. The absolute time delay  $\Delta t(\omega)$  of the intensity modulation signal is seen to be the greatest in the region of lowest frequencies, while the relative (i.e. phase) delay  $\varphi(\omega)$  reaches its maximum at frequencies  $\omega \sim 1/\tau$  and does not exceed a small fraction of the oscillation period.

In Refs [19–24], these simple properties of nonlinear absorbers (crystals with paramagnetic impurities) have been erroneously ascribed to the reduction of the group velocity of light due to spectral hole burning under conditions of coherent population oscillations. Full agreement of the experimental data obtained in those papers with the prediction of the simple model of the saturable absorber was shown in Refs [15, 25], where one can find a more detailed criticism of the publications [19–24]. The same perverse interpretation of the effects of delayed photoresponse in a saturable absorber has received further development in experiments with bacteriorhodopsin molecules in a polymer film [26].

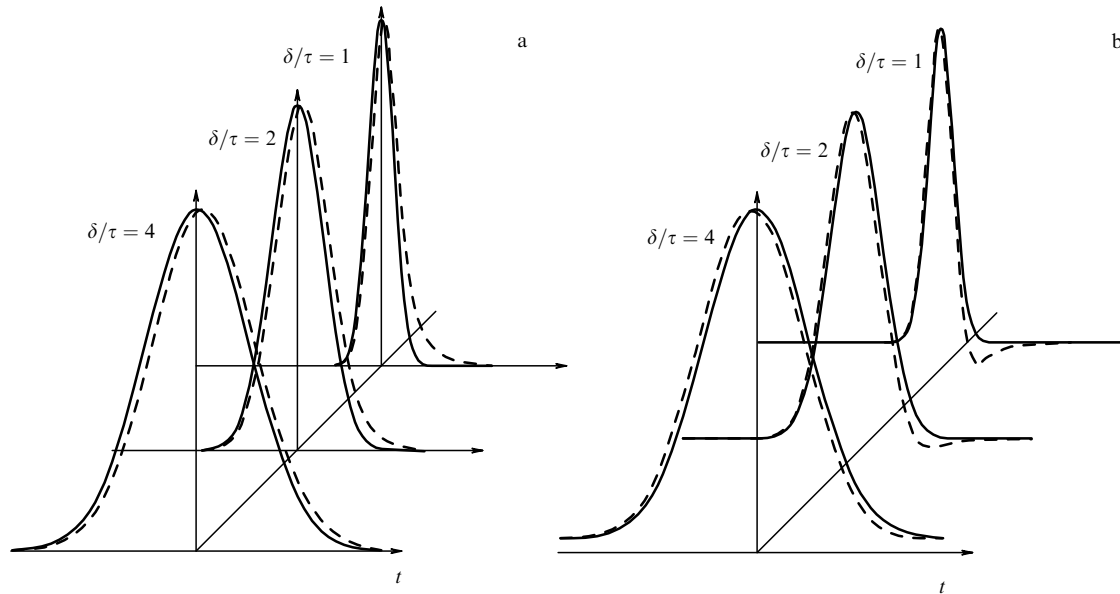
### 5.3 Light pulse delay

When a light pulse travels through a saturable absorber, the absorption of the medium generally changes in the process of its propagation. This leads not only to a change of the pulse amplitude, but also to a distortion of the pulse shape. If the shape of the pulse is smooth and its width is comparable to or exceeds the relaxation time  $\tau$ , then the distortion of its shape appears to be small and, to a first approximation, is reduced to a pure shift in time. Note that the sign of the delay is positive for the usual bleachable absorber and negative for the inverse saturable absorber. This effect was studied as far back as the 1960s (see, e.g., Refs [3, 27]). To the same category of



**Figure 3.** Typical frequency variations of the amplitude  $|K(\omega)|$ , phase  $\varphi(\omega)$ , and time delay  $\Delta t(\omega)$  of intensity oscillations of a light beam passed through a saturable (bleachable) absorber.

effects can be attributed the effect (already mentioned above) of the apparent increase in the light group velocity in a ‘saturable amplifier’ [2, 28] when, as in the inverse saturable absorber, the pulse is distorted in favor of its front edge. Figure 4 shows the calculated curves that illustrate the pulse ‘delay’ for the usual (a) and inverse (b) saturable absorber for different ratios of the pulse width  $\delta$  and relaxation time  $\tau$  [15]. Note that the illusion of the pulse delay arises, in this case, due to the amplitude normalization of the output pulse. With no normalization, the output pulse, in this figure, would always lie *inside* the input one. The light pulse delay in the saturable absorber, evidently, is not related to the dispersion of the refractive index. This delay is a consequence of the light-induced nonstationarity of the medium and, in essence, is not a delay as such. In the papers on hole-burning under conditions of coherent population oscillations mentioned in Section 5.2, this delay of the light pulse, with no additional



**Figure 4.** Normalized Gaussian pulses  $I(t) \sim \exp[-(t/\delta)^2]$  propagating through an ordinary (a) and inverse (b) saturable absorber for different ratios between the pulse width  $\delta$  and the relaxation time of the absorber  $\tau$ . Solid lines are the pulses at the input, dashed lines are the pulses at the output [15].

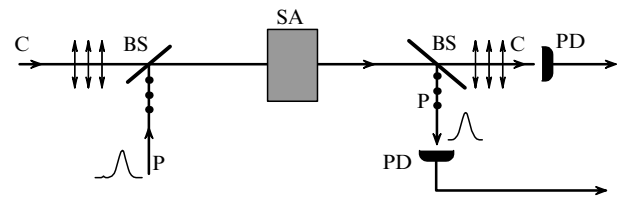
justification, was ascribed to 'slow light' (see, e.g., Refs [2, 26]).

#### 5.4 Dynamics of polarization response

Under the action of resonance polarized light, the polarization saturable absorber, mentioned in Section 5.3, becomes dichroic. In accordance with the general laws of symmetry (Neumann's principle), the type of light-induced dichroism (linear, circular, or elliptical) should correlate with polarization of the acting light. As is known, these properties are displayed, in particular, by the optically pumped atomic systems, in a zero magnetic field, amenable both to orientation and alignment (this fact was recently demonstrated once again in Ref. [29]). In the case of a bleachable absorber, the light-induced dichroism of the medium corresponds to its bleaching in the polarization of the acting light. When polarization of the incident light is changed, the anisotropy of the nonlinear medium and the light polarization at the output of the medium follow these changes with a certain time delay controlled by the intrinsic relaxation constants of the absorber (for more details, see Ref. [14]).

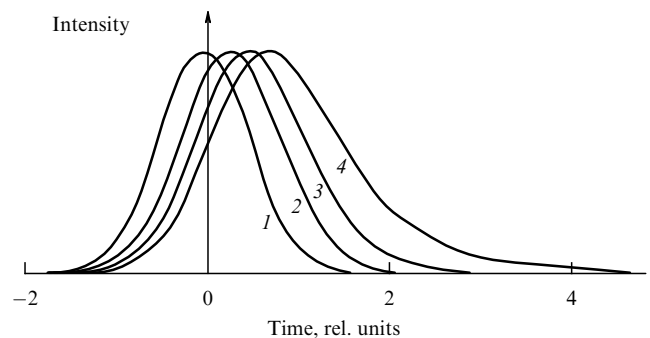
A pulse of polarization modulation can be formally represented as a pulsed admixture of the orthogonally polarized component to a polarized beam (in practice, this is usually made by shifting the phase of the components in a single beam with the aid of polarization modulators like, for instance, a Pockels cell). The polarization dynamics of the pulse at the output of the medium can also be monitored by detecting this orthogonal component of the output beam (Fig. 5).

Figure 6 shows what the weak pulse of the orthogonally polarized component looks like at the output of a saturable (bleachable) absorber for different ratios between the pulse width  $\delta$  and relaxation time  $\tau$ . As is seen from the figure, the distortion of the pulse shape at the output (as for the case of pure intensity modulation, see Section 5.2) decreases with increasing pulse width, gradually approaching a pure shift. For the bleachable polarization absorber, this shift is positive



**Figure 5.** The pump-probe configuration, popular in the 'slow light' experiments with coherent orthogonally polarized beams from a single source ('degenerate'  $\Lambda$ -scheme). C — pump (coupling) beam, P — probe beam, SA — saturable absorber, BS — polarization beamsplitter, PD — photodetector.

(delay), and for the inverse absorber, negative (advance). In this configuration of the experiment, in contrast to the case of a 'single-channel' scheme described in Section 5.2, the observed delay in the polarization component, as one can see by comparing Figs 4 and 6, may be fairly large. In addition, the delay, in this case, is not apparent, but real in the sense that the signal at the output can be observed after



**Figure 6.** The shape of a 'probe' pulse (in the setup shown in Fig. 5) at the input (1) and at the output (2–4) of a medium for different ratios of the pulse width  $\delta$  and relaxation time of the absorber  $\tau$ :  $\tau = \delta/2$  (2),  $\tau = \delta$  (3), and  $\tau = 2\delta$  (4) [15].

completion of the input signal (due to the permanent presence of the original polarization component transformed by the perturbed nonlinear medium).

The nature of the above delay of the polarization pulse in a ‘slow’ nonlinear absorber evidently reflects only the retarded dynamics of the medium and has nothing to do with variation of the light group velocity in terms of Eqn (1). However, in the works on ‘slow light’, a delay of this kind is usually ascribed to the group velocity reduction (see, e.g., Refs [30, 31]). Note also that the above scheme with admixing of the orthogonal polarization component and its separation at the output (Fig. 5) makes it possible to monitor the polarization dynamics of the light at the output of the absorber, but does not allow one, by any means, to *probe* the medium with this polarization component (no matter how weak it is), because the anisotropy of the absorber, under the action of the polarization pulse, varies in time, and the initial polarization components cease to be independent (normal) modes. Therefore, the delay of the pulse of one polarization component, in this experimental configuration, cannot be ascribed to the low group velocity of light for the additional reason that the notion of velocity cannot be introduced for a component that is not a normal wave of the anisotropic medium [32].

### 5.5 Intensity-related characteristics of the response

At low light intensities, the relaxation rate of the saturable absorber (exponential regions in Fig. 2) is intensity-independent and is determined by the ‘dark’ population relaxation time  $T_1$ . With increasing intensity, the effective population relaxation rate  $\tau^{-1}$ , controlled by the sum of the dark and light-induced relaxation processes, grows in a linear way (see, e.g., Ref. [16]), whereas the delay time of the pulse or of the light intensity oscillations (at sufficiently low frequencies, see Section 5.3), accordingly, decreases hyperbolically. For this reason, the dependence presented in Fig. 7 demonstrates the standard properties of a saturable absorber and, taken alone, cannot be used to confirm the ‘slow light’ model, as is done in [33].

### 5.6 ‘Storage’ of the light-induced anisotropy

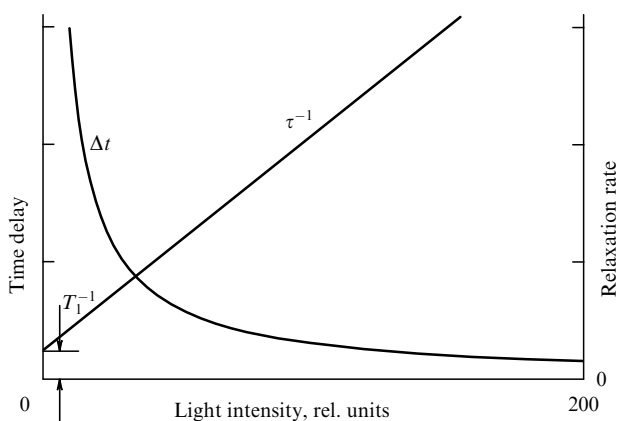
The *real* delay of the polarization pulse at the output of a nonlinear absorber with respect to the input pulse signifies, in particular, that the contribution to the anisotropy of the

medium, induced by the polarization pulse, persists for some time after the end of the pulse. This time is evidently determined by the relaxation parameters of the medium, which, as pointed out in Section 5.5, depend on the light intensity. For this reason, by switching off the light beam immediately after completion of the polarization pulse, we can ‘freeze’ the residual anisotropy induced by the polarization pulse and ‘store’ it during the *dark* relaxation time  $T_1$ , which may be rather long. If, after such a pause, we again switch the light beam on, then, to within the relaxation during the pause, we will reproduce the situation that existed at the moment of switching the light off. This means that the light beam will continue a ‘readout’ of the anisotropy of the medium induced by the polarization pulse, and at the output of the medium we will detect the ‘tail’ of this process (Fig. 8). The dependence of the relaxation rate on the light intensity will be evidently revealed in the fact that the length of this ‘tail’ will vary with the pump beam intensity (see, e.g., Ref. [34]). In our opinion, this natural manifestation of the relaxation properties of a polarization nonlinear absorber may be considered as the effect of polarization memory, but there are no grounds to consider it as ‘stopped light’ as it is done in many papers on ‘slow light’ where a *degenerate*  $\Lambda$ -scheme is used (see, e.g., Refs [30, 31, 35–37]; for more details see Refs [13, 14]).

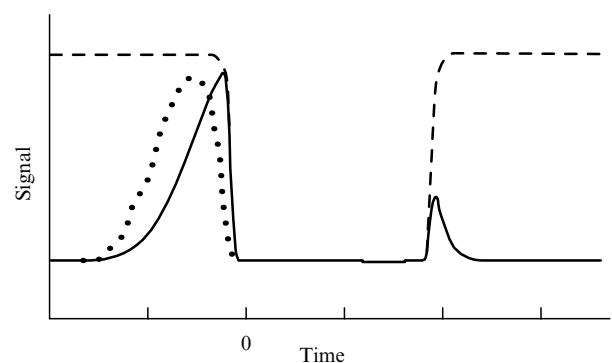
### 5.7 Polarization-interference paradoxes

Let us turn again to the polarization scheme shown in Fig. 5, where the polarized light passing through a nonlinear absorber composed of two mutually coherent and orthogonal polarization components is analyzed, at the exit of the medium, on the same polarization basis. Let these components, for definiteness, be linearly polarized and in-phase, so that, being superimposed, they form the light of linear polarization. Consider the case when, as in the effect of electromagnetically induced transparency (EIT), one of the beams (the pump, or coupling beam) is strong, whereas the other (probe) beam is weak. Then we come to the effect which may seem, at first sight, to be paradoxical and which is widely exploited in ‘slow light’ studies.

Under the action of only the strong pump beam, the medium is bleached and the beam propagates over its own polarization route (C–C in Fig. 5). The weak probe beam, in the absence of the pump, also propagates along its own route



**Figure 7.** Standard dependence of the pulse (or intensity oscillation) delay time at the output of a nonlinear absorber and of the absorption relaxation rate on the light intensity.



**Figure 8.** Standard time dependence of the ‘probe’ beam intensity (solid line) in demonstrations of ‘stopped light’ in the arrangement shown in Fig. 5. Dotted line — intensity of the ‘probe’ beam at the input, dashed line — intensity of the pump beam at the input.

(P–P), but, being unable to bleach the medium, experiences strong absorption and appears to be strongly attenuated at the output. However, if we measure transmission of the probe light in the *presence* of the pump, we will find that the system is transparent for it. Therefore, in this experimental arrangement, bleaching of the medium in one polarization makes it bleached for an arbitrarily weak beam of orthogonal polarization. Paradoxically, the probe beam, as it may seem, should be a *normal* wave of the medium whose anisotropy is formed by the beam of orthogonal polarization and should be able to *probe* the medium in conformity with all laws of polarization optics.

Of course, there is no riddle here. On the one hand, this is a simple combination of nonlinear absorption with the effect of interference of polarized rays. If we trace the *amplitudes* of the two fields (which is exactly what should be done when analyzing interference effects), we will see that addition of the probe-field component gives rise to a slight rotation of the polarization plane of the acting field. Due to the high intensity of the field, the anisotropy (dichroism) axis of the medium follows this rotation virtually with no delay, and the medium remains bleached for the new polarization of the pump. As a result, the beam (and each of its components) passes through the medium with no attenuation. On the other hand, this is a sort of play on words. We tacitly assumed that the weak beam *probes* the medium, while, as was already pointed out, this is not correct (to really probe the medium by this beam, it suffices to switch the pump off; we will see that the medium is opaque). And eventually it will be correct to say that this is the EIT effect or what this effect turns into in the degenerate  $\Lambda$ -scheme. However, while for unequal frequencies of the beams in the nondegenerate  $\Lambda$ -scheme, when the measuring time is much longer than the beat period, the scheme in Fig. 5 is consistent in the sense that the probe beam, corresponding to a normal wave of the medium, is really able to *probe* it, for equal frequencies this approach is physically inappropriate. For this reason, in the degenerate polarization  $\Lambda$ -scheme, the notions of the 'probe' and 'pump' beams are improper. This reasoning refers to all the papers on 'slow light' that used the popular degenerate configuration described in Ref. [30].

### 5.8 A saturable absorber in a rotating frame of reference

We have already mentioned that optically pumped atoms in a zero magnetic field may serve as an adequate model of the saturable absorber. The absorption saturation of the system corresponds, in this case, depending on the light polarization, to either orientation, alignment, or a combination of the two. In the presence of an external magnetic field, the light-induced ordering of atomic moments appears to be hampered by their precession. However, as is known (see, e.g., Ref. [17]), by modulating the intensity or polarization of the light at the frequency of the precession, one can realize the orientation (or alignment) *in the rotating frame*. Thus one comes to numerous effects of quantum and nonlinear optics treated in terms of coherent population trapping, double microwave-optical resonance, beat resonances, superposition of quantum states, stimulated Raman scattering, electromagnetically induced transparency, a 'dark' polariton, etc. (see, e.g., Ref. [38]). The EIT effect is most frequently implemented in a 3-level  $\Lambda$ -scheme with a relatively small distance between the two low levels formed by the Zeeman or hyperfine interaction (Fig. 1). To observe the EIT effect, a strong pump beam is applied to one of the arms of the  $\Lambda$ -scheme (with the depleted low level), and a weak probe

beam is applied to the other arm. The pulse of this probe light is used to observe the effect of the group velocity reduction. The effect is detected when the frequency difference between the two fields is exactly equal to that of the transition between the two low levels  $|1\rangle$  and  $|2\rangle$ . "Exactly" means to within the width of this transition, which determines the spectral width of the 'transparency window' and may be extremely small. From the narrowness of the transparency window it is concluded that the spectral dependence of the dispersion of the medium at the frequency of the probe beam (at resonance) may be extremely steep, and the group velocity (due to the *normal* spectral dependence of the dispersion) may be extremely low.

Experiments on 'slow light' frequently use phase-correlated light beams obtained either by shifting the frequency of a single laser source or by phase-locking their difference frequency. Under these conditions, observation of the EIT resonance by scanning the *frequency difference* between the beams (i.e., the fact that the resonance is observed in the low-frequency  $|1\rangle$ – $|2\rangle$  transition domain) does not mean that such a narrow resonance is present in the *optical* spectrum in the vicinity of the resonance  $|1\rangle$ – $|3\rangle$ . Moreover, when the spectral width of the laser source substantially exceeds that of the EIT resonance (which is frequently the case), such a narrow resonance in the optical range cannot exist in principle. In other words, under these conditions, the medium is *probed* by the difference frequency, whose high monochromaticity provides the small width of the instrumental function of this spectroscopic technique in the relevant frequency range.

This circumstance is often overlooked in theoretical studies of the EIT effect performed in terms of monochromatic waves. In this case, scanning one of the frequencies is evidently identical to scanning the difference frequency, and the question about phase succession of the beams no longer makes sense. At the same time, this circumstance is, in our opinion, highly important for interpretation of experiments on 'slow light' because in a considerable number of these studies the narrow resonances of the effects of EIT and coherent population oscillations are observed under conditions of scanning of the difference frequency. In this case, the conclusion about a narrow resonance in the optical spectrum can be made only when reliable information about the spectral width of the light beams is available. This remark may be addressed both to most papers on 'hole burning' under conditions of coherent population oscillations [19–24, 26] and to a number of papers on the EIT-based 'slow light' [18, 33, 39, 40].

### 5.9 On the intensity spectra

We have already pointed out that the distortion of a smooth light pulse transmitted through a saturable absorber is reduced to a pure shift provided its temporal width exceeds the population relaxation time. A similar requirement reformulated into the language of frequencies is imposed upon the probe pulse of 'slow light' in the effects of EIT or coherent population oscillations, when the pulse spectrum should fit into the narrow transparency window. The difference is that, in the first case, we are dealing not with the spectrum of the optical signal but rather with its *intensity spectrum* (whose amplitude, in particular, at the optical frequency, vanishes). The *intensity spectrum* of the optical pulse can indeed be narrowed by changing its duration, but the optical spectrum of the pulse can be controlled by

changing its duration only if the pulse is transform-limited. This circumstance is often overlooked, and monitoring of the spectral width of an optical pulse is often restricted to monitoring its intensity spectrum (see, e.g., Ref. [18]).

### 5.10 Spatial aspect

When using gaseous nonlinear media with moving elementary carriers of the optical nonlinearity (in particular, the optically pumped atoms), the light-induced anisotropy may come out beyond the beam dimensions, spreading to a greater or lesser degree over the volume occupied by the system. The degree of this spreading evidently depends on the ratio between the relaxation and diffusion parameters of the atomic medium. Specifically, in paraffin-coated ‘vacuum’ cells (with no buffer gas), a narrow light beam a few millimeters in diameter is able to completely orient (or align) the atoms in a cell several cm in size. The light-induced anisotropy (or coherence) may, in this case, be successfully detected by a probe beam passing through any part of the cell. In the cells with buffer gases, this fairly obvious effect has been observed, in various modifications, beginning in 1967 (see, e.g., Refs [41–43]). This is why we cannot agree with the authors of Ref. [44], who newly ‘discover’ this effect and consider it as “significantly expanding the capabilities of the quantum information storage technique.”

## 6. Discussion and concluding remarks

In this article we have considered, in a qualitative way, some simple effects observable in media with nonlinear absorption, which are phenomenologically close to some manifestations of ‘slow light’ but have nothing to do with a narrow spectral dip in the absorption spectrum of the medium, with a steep dispersion of its refractive index, or with ‘slow light’ proper. When considering all these phenomena in the framework of the model of a saturable absorber, we have also touched on a non-degenerate  $\Lambda$ -scheme by moving to the rotating coordinate frame, where the ‘diagonal’ relaxation of populations is replaced by the relaxation of coherence and the effects of *incoherent* nonlinear optics (saturation effects), to which our discussion was originally supposed to be restricted, are transformed into the effects of *coherent* nonlinear optics. This, however, does not change the essence of the matter. In all the cases considered above the retarded response of the medium is a result of the boundedness of its frequency passband. In ‘slow light’ effects, the extreme narrowness of the transparency window gives rise to a similar limitation in the transmission bandwidth. This accounts for the phenomenological similarity of these essentially different effects. The difference is that, in one case, this ‘narrow’ band is localized in the range of optical frequencies, whereas in the other it is in the range of much lower (e.g. zero) frequencies. However, when detecting the *intensity* spectrum of the transmitted light localized at low frequencies, this difference vanishes. To really observe ‘slow light’ in the sense of Eqn (1), one has to necessarily provide the highest frequency stability and spectral narrowness of the light beams used in the experiment.

It seems evident that the nonlinear optical effects considered above are much less exacting to the properties of the nonlinear medium and light beams and can be observed much more easily. These are trivial and rather universal effects of nonlinear optics that should be taken into account by the experimentalist *first of all*. However, in studies on ‘slow light’, these trivial possibilities, as a rule, are not considered at

all. As was already mentioned, many papers do not contain highly important information about spectral widths of the light beams. The experiments are frequently performed with phase-correlated light beams with a well defined difference frequency but with poorly defined optical frequencies and, hence, with a fundamentally uncertain position of the ‘transparency window’. The effects of the slowing down and storage of light are frequently demonstrated using the ‘degenerate’  $\Lambda$ -scheme, which perfectly models the polarization saturable absorber and is unsuitable for demonstrating specific properties of the EIT effect (at least for totally coherent beams). A delay of the light pulse in the medium (in different experimental arrangements) is always ascribed to a change in its group velocity related to a steep dispersion of the refractive index. The group velocity is always calculated by dividing the length of the medium by the delay time of the pulse maximum. It is evident that the quantity with the dimensions of velocity obtained in this way may have nothing in common with the group velocity of light in the medium. This universal practice of measuring the light group velocity in some cases becomes obviously self-exposing. In particular, in Ref. [26], a sluggishness of the photoresponse (in the range of seconds) of bacteriorhodopsin molecules in a polymer film is ascribed to the spectral hole-burning effect under conditions of coherent population oscillations, and the group velocity measured in the standard way is found to be  $0.091 \text{ mm s}^{-1}$ . There is no question that ‘group velocity’ records of this kind can be set up ad infinitum. An even more striking example is the experiment [45], in which was detected a retarded holographic reconstruction of a writing light beam in a photorefractive crystal. In this study, the group velocity calculated in the same universal way was as low as  $0.025 \text{ cm s}^{-1}$  (with the shape and amplitude of the pulse at the output of the crystal modified drastically). Of course, this effect (as well as holography proper) may be referred to as ‘slow’ or ‘stopped’ light, but is there any sense in these terminological manipulations? The authors frequently ignore the fact that the standard formula for the light group velocity (1) is applicable only to a *linear, optically transparent* medium and cannot be applied to a *nonlinear absorber*, where the speed of motion of the pulse peak cannot be identified with the *group velocity of light*. At the same time, studies on ‘slow light’ frequently do not pay sufficient attention to the experimental facts that contradict the canonical model of the effect. Among them may be mentioned, in particular, the dependence of the ‘released’ pulse shape on the pump beam intensity [34], the admissible nonadiabaticity of the switching of the pump beam [44], and the ideal agreement of the results of experiments on ‘slow light’ under conditions of ‘coherent population oscillations’ with the prediction of the trivial model of the saturable absorber (see Refs [15, 25]).

In our opinion, to observe the ‘slow light’ effect, in the sense assigned to it by the authors of this term [7], it is not enough to demonstrate a delay in the light pulse maximum in the medium, a phase delay of the amplitude modulation of the probe light, or a polarization memory of a photochromic medium. Specificity of this effect allows one fairly easily to distinguish it from standard manifestations of the properties of a nonlinear absorber. We stress once again that the difference between the pulse distortion in the saturable absorber (including the polarization schemes considered above) and dispersion-related pulse retardation is of a *physical* nature and cannot be attributed to terminological discrepancies (as our opponents sometimes claim). The



dispersive basis of the group velocity variation in 'slow light' effects is known to be revealed not only in specific features of their spectral behavior but also in a dramatic *spatial compression* of the light pulse in the medium. This popular image is frequently used in publications on 'slow light' (see, e.g., Refs [30, 37]), whereas real compression was demonstrated only in classical experiments with ultracold atoms [46], as well as in recent experiments with photonic crystal waveguide structures [47]. Unfortunately, the difficulties of experimental observation of this compression usually do not allow one to use it for the diagnostics of 'slow light' effects. The pulse delay exceeding the pulse width may serve as implicit evidence of the spatial compression of the pulse. In this case, the spatial size of the light pulse cannot exceed the size of the medium. It is implied, of course, that the changes in the pulse shape are negligibly small. Pulse delays considerably exceeding their width have indeed been observed in Refs [10, 11], in which the conditions for observation of the EIT effect were satisfied and the interpretation of the results raises no questions.

As for the prospects of applying 'slow light' in atomic vapor for the buffering and processing of optical signals, these hopes seem to be substantially deflated by the narrow frequency band inherent in this effect [48]. Perhaps more interesting in this respect are experiments on light slowing down in optical fibers under conditions of stimulated Raman or Brillouin scattering [49].

In these notes we did not pursue the goal of giving a comprehensive review of publications on 'slow light' and, of course, a great number of papers devoted to these problems remained beyond the scope of our discussion. Still, the above analysis allows us to definitely state that a considerable number of claims of having observed 'slow light' are erroneous or, at best, groundless. The situation is aggravated by the fact that even the most evident physical errors in these papers systematically remain 'unnoticed' and the relevant publications do not find critical evaluation in the literature, holding their high citation rate. It is noteworthy also that all the papers involved in this trend, regardless of their scientific novelty or degree of reliability, are published in the most prestigious journals and automatically acquire a high rating, whereas attempts to express, in the same journals, some doubts about the correctness of these 'achievements' meet strong institutional resistance. This state of affairs, in our opinion, damages both the prestige of science and the recognition of genuine achievements in this trend of physical optics.

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## References

- Brillouin L *Wave Propagation and Group Velocity* (New York: Academic Press, 1960)
- Basov N G et al. *Zh. Eksp. Teor. Fiz.* **50** 23 (1966) [*Sov. Phys. JETP* **23** 14 (1966)]
- Selden A C *Br. J. Appl. Phys.* **18** 743 (1967)
- Milonni P W *J. Phys. B: At. Mol. Opt. Phys.* **35** R31 (2002)
- Crisp M D *Phys. Rev. A* **4** 2104 (1971)
- Chu S, Wong S *Phys. Rev. Lett.* **48** 738 (1982)
- Harris S E *Phys. Today* **50** (7) 36 (1997)
- Harris S E, Field J E, Kasapi A *Phys. Rev. A* **46** R29 (1992)
- Min Xiao et al. *Phys. Rev. Lett.* **74** 666 (1995)
- Kasapi A et al. *Phys. Rev. Lett.* **74** 2447 (1995)
- Hau L V et al. *Nature* **397** 594 (1999)
- Liu Ch et al. *Nature* **409** 490 (2001)
- Aleksandrov E B, Zapasskii V S *Usp. Fiz. Nauk* **174** 1105 (2004) [*Phys. Usp.* **47** 1033 (2004)]
- Kozlov G G, Aleksandrov E B, Zapasskii V S *Opt. Spektrosk.* **97** 969 (2004) [*Opt. Spectrosc.* **97** 909 (2004)]
- Zapasskii V S, Kozlov G G *Opt. Spektrosk.* **100** 447 (2006) [*Opt. Spectrosc.* **100** 419 (2006)]; Zapasskii V S, Kozlov G G, physics/0509181
- Allen L, Eberly J H *Optical Resonance and Two-Level Atoms* (New York: Wiley, 1975) Ch. 6 [Translated into Russian (Moscow: Mir, 1978) Ch. 6]
- Happer W *Rev. Mod. Phys.* **44** 169 (1972)
- Akulshin A M et al. *Phys. Rev. A* **67** 011801(R) (2003)
- Hillman L W et al. *Opt. Commun.* **45** 416 (1983)
- Malcuit M S et al. *J. Opt. Soc. Am. B* **1** 73 (1984)
- Bigelow M S, Lepeshkin N N, Boyd R W *Phys. Rev. Lett.* **90** 113903 (2003)
- Bigelow M S, Lepeshkin N N, Boyd R W *Science* **301** 200 (2003)
- Baldit E et al. *Phys. Rev. Lett.* **95** 143601 (2005); ccsc-00004377 (2005)
- Zhang Yun-Dong et al. *Chinese Phys. Lett.* **21** 87 (2004)
- Selden A C, physics/0512149
- Wu P, Rao D V G L N *Phys. Rev. Lett.* **95** 253601 (2005)
- Selden A C *J. Phys. D: Appl. Phys.* **3** 1935 (1970)
- Icsevci A, Lamb W E (Jr.) *Phys. Rev.* **185** 517 (1969)
- Gao H, Rosenberry M, Batelaan H *Phys. Rev. A* **67** 053807 (2003)
- Phillips D F et al. *Phys. Rev. Lett.* **86** 783 (2001)
- Kozuma M et al. *Phys. Rev. A* **66** 031801 (2002)
- Born M, Wolf E *Principles of Optics* (Oxford: Pergamon Press, 1969) [Translated into Russian (Moscow: Nauka, 1970)]
- Kash M M et al. *Phys. Rev. Lett.* **82** 5229 (1999)
- Lezama A et al., physics/0506199
- Gao H et al. *J. Phys. B: At. Mol. Opt. Phys.* **38** 1857 (2005)
- Mair A et al. *Phys. Rev. A* **65** 031802 (2002)
- Lukin M D *Rev. Mod. Phys.* **75** 457 (2003)
- Scully M O, Zubairy M S *Quantum Optics* (Cambridge: Cambridge Univ. Press, 1997) Ch. 7 [Translated into Russian (Moscow: Fizmatlit, 2003) Ch. 7]
- Schmidt O et al. *Phys. Rev. A* **53** R27 (1996)
- Turukhin A V et al. *Phys. Rev. Lett.* **88** 023602 (2002)
- Novikov L N *Opt. Spektrosk.* **23** 498 (1967)
- Nakayama S, Series G W, Gawlik W *Opt. Commun.* **34** 389 (1980)
- Agap'ev D et al. *Pis'ma Zh. Tekh. Fiz.* **10** 774 (1984)
- Zibrov S et al. *Phys. Rev. Lett.* **88** 103601 (2002)
- Podivilov E et al. *Phys. Rev. Lett.* **91** 083902 (2003)
- Dutton Z et al. *Europhys. News* **35** 33 (2004)
- Gersen H et al. *Phys. Rev. Lett.* **94** 073903 (2005)
- Matsko A, Strekalov D, Maleki L *Opt. Express* **13** 2210 (2005)
- Gauthier D *Phys. World* **18** (12) 30 (2005)