Chasing 'Slow Light'

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A critical review of experimental studies of the so-called 'slow light' Arising from 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 for observation of the '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.

I. INTRODUCTION

In the last decade, the topic of 'slow' and 'fast' light - light pulse propagating in a medium with ultralow, superluminal, or even negative group velocity - has gained particular popularity. The keen interest in this topic is not primarily related to the possibility itself of controllably varying the light group velocity in a medium, but instead to the a huge scale of these variations (7 orders of magnitude and more) and to the claimed favorable prospects for the application of 'slow light' in telecommunication and optical computing. As a result, in the late 90s, the 'slow light' has, in fact, turned into a separate trend of physical optics. Several hundreds of publications have been devoted to these problems. They are discussed on special topical meetings and workshops. A 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 mass media. Concurrently with the increased rate of publications on 'slow light' research, the quality of the publications was getting noticeably poorer. The phenomenological simplicity of those manifestations of 'slow light' made it possible to observe similar effects in relatively simple experimental conditions and ascribe them to 'slowing down' and 'stopping' of light without sufficient grounds. In these notes, we critically analyze the publications on 'slow light' and demonstrate inconsistencies in a considerable number of the arguments intended to provide evidence for dramatic changes of the light group velocity.

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II. FROM THE HISTORY OF GROUP VELOCITY OF LIGHT

The problem of slowing down of light in a medium has a long history, dating back to Newton’s ‘Optics’. Early in the last century, attention was again attracted to the problem of the velocity of light in a medium in connection with the as-developed special theory of relativity, which limited (in its second postulate) the speed of transfer of information by the velocity of light in vacuum (c). The propagation of electromagnetic waves in real media was studied in the early 20th century by founders of physical optics. It is worth mentioning A.Sommerfeld and his disciple L. Brillouin, who summarized the results of these studies in a monograph [1]. Later on, the velocity of light in a medium attracted the attention of researchers, mainly, in the cases when it strongly differed from that in vacuum. Forty years ago, a ‘superluminal’ group velocity of light was claimed to be observed in [2]. The studies were performed with the light pulses propagating in a gain medium under conditions of strong nonlinearity related to the gain saturation under the action of the pulse. In this case, the shape of the 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 maximum, the authors of [2] claimed observation of the 9-fold excess of the velocity of light in the medium over that in vacuum. This phenomenon was, in essence, the inverse effect of the light pulse delay in a saturable absorber (see, e.g., [3]) and, therefore, was not of any principal interest. 

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 a medium. In this case, in the standard formula for the light group velocity $V_g$

$$V_g = \frac{c}{n + \omega \frac{dn}{d\omega}} \tag{1}$$

the dispersion term starts to dominate. 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 mechanism are rather limited), but mainly due to 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 [1] is fairly

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1It is noteworthy that neither in this paper, nor in any other subsequent report on superluminal propagation of the light pulse, do the authors claimed to refute the special theory of relativity (see, e.g., review [4]).
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 in practice. As applied to the 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 Eq. (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., [5]), provided that the absorption (gain) of the medium does not strongly change within the spectral width of the pulse (see also the experiment [6]).

Thus, the group velocity in the sense of Eq. (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 self-action of the light pulse, in the process of the 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 the 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 Eq. (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.

III. 'SLOW LIGHT' AND THE GOAL OF THESE NOTES

A real boom of publications devoted to the anomalies in the light group velocity (or to 'slow light' \(^2\)) was associated with realization of the electromagnetically induces transparency (EIT) [7] which has made it possible to combine two, previously exclusive, properties of the medium - a high steepness of dispersion and transparency. The effect is usually observed on the systems with the energy-level diagram schematically shown in Fig. 1 (the

\(^2\)In what follows, for brevity, we will consider 'slow light' to be all the phenomena associated with dramatic changes of the light group velocity due to steep dispersion of the refractive index, i.e., the 'slow light', 'fast light', and the light with 'negative' group velocity.
so-called Λ-scheme). Two electromagnetic fields, \( \omega \) and \( \omega' \), are applied to transitions between two, usually closely spaced, sublevels of the ground state (\( |1\rangle \) and \( |2\rangle \)) and the third common excited level \( |3\rangle \). The excitation of this type is capable of creating coherence between the two lower states. If the frequency \( \omega \) of one (usually stronger) field is fixed, and the frequency \( \omega' \) of the other (probe) field is being scanned, then, in 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. To this dip, in accordance with the Kramers-Kronig relations, should correspond a region of steep dispersion of the refractive index. This steepness may be extremely high due to 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 with the 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 in rather simple experimental conditions, and analysis of the results was made, in our opinion, not critically enough: Any apparent delay of the light pulse in the medium was attributed to its low group velocity. Some obviously erroneous works of this type were criticized in [13–15]. However, the essence of the matter, in our opinion, consists not in the errors committed in certain papers, but rather in the inconsistencies of the provided evidence. As a result, there are presently doubts about the reliability of the conclusions drawn by considerable number of publications on ‘slow light’.

In these notes, we consider some effects of incoherent nonlinear optics which are phenomenologically similar to the ‘slow light’ effects and should be observed in slow relaxing media with nonlinear absorption, while having nothing to do with ‘slow light’. We attract attention to a number of commonly accepted pieces of evidence for ‘slowing down’ and ‘stopping’ of 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 ‘slow medium’ which are universally observable in resonant media with saturable absorption.

Since the problem of interpretation of experimental observations considered in these notes are of a conceptual nature, and the effects of incoherent nonlinear optics that mimic the ‘slow light’ are well known 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).
IV. THE SUBJECT OF STUDY - A NONLINEAR ABSORBER

The simplest (and chronologically the first discovered) effects of nonlinear optics were related to resonant perturbation of the populations of quantum states (effects of saturation) [16]. For sufficiently long relaxation times, these incoherent nonlinear effects can, in principle, be 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 'state of the art' 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 be revealed 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 with that of the population relaxation. In this case, 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 exist situations when absorption of the medium increases with light intensity. The appropriate nonlinear absorbers are called inverse. For practical applications (mainly in laser techniques), saturable absorbers are used in a diverse array of optical media, like dye solutions, doped crystals and glasses, dielectrics with semiconductor nanocrystals, etc. 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 Cr$^{3+}$ ions to metastable levels, whose long lifetime provides retardation of the optical response of the crystal.

The most perfect model of saturable absorber 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., [17]). As a result, in the field of polarized light, these systems may be considered as polarization saturable absorbers, which differ from the 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 basic subjects of the 'slow light' experiments. We will consider the effects that should necessarily be observed in 'slow' nonlinear absorbers regardless of spectral features of the medium’s dispersion and variation of the light group velocity. All the effects considered below are, in fact, combinations of elementary properties of a saturable absorber.
and do not contain anything essentially new. Still, it is exactly these effects that are frequently considered as manifestations of 'slow light'.

V. ON CAPABILITIES OF SATURABLE ABSORBER

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

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 entrance changes in a step-wise way, the light intensity at the exit, 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 a steady-state populations of the system (Fig. 2).

Experimental dependences of this kind are reported, for instance, in [18], where the probe-pulse shape distortion is ascribed to the effect of steep dispersion of refractive index of the medium in the region of resonance of the electromagnetically induces transparency and electromagnetically induced absorption. These temporal dependences, as being of no interest, usually are not presented in the papers on 'slow light'. We mention this type of response only for completeness sake and for passing to the next, more constructive, item.

2. Frequency-domain response 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 dependencies 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 with the inverse population relaxation time of the absorber (τ). Absolute time delay Δt(ω) of the intensity modulation signal is seen to be the greatest in the region of lowest frequencies, while the relative (i.e., phase) delay ϕ(ω) reaches its maximum at frequencies ω ∼ 1/τ and does not exceed a small fraction of the oscillation period.

In [19,21–24], 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 saturable absorber was shown in [15,25], where one can find a more detailed and grounded criticism of these publications [19–24]. The same perverse interpretation of the effects of delayed photoresponse in a saturable absorber has received further development in the experiments with bacteriorhodopsin molecules in a polymer film [26].
3. The light pulse delay When a light pulse travels through a saturable absorber, the absorption of the medium, in the general case, 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 with the relaxation time $\tau$ or exceeds it, then the distortion of its shape appears to be small, and, in the 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 60s of the last century (see, e.g., [3,27]). In the same category of the effects it can also be attributed the effect (already mentioned above) of apparent increase of the light group velocity in a 'saturable amplifier' [2,28], when, like 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 some ratios of the pulse width $d$ 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 already mentioned papers on hole-burning under conditions of coherent population oscillations, this delay of the light pulse, with no additional justification, was ascribed to 'slow light' (see, e.g., [2,26]).

4. Dynamics of polarization response Under the action of a resonant polarized light, the polarization saturable absorber, mentioned above, becomes dichroic. In accordance with the general laws of symmetry (Neumann’s principle), the type of the 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 zero magnetic field, amenable both to orientation and alignment (this fact was recently demonstrated once again in [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 exit of the medium follow these changes with a certain time delay controlled by the characteristic time of the absorber (for more detail, see [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 phase shifting the polarization components in a single beam with the aid of polarization modulators like, e.g., a Pockels cell). Polarization dynamics of the pulse at the exit of the medium can be also 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 exit of a saturable (bleachable) absorber for some ratios between the pulse width $\delta$ and relaxation time $\tau$. As is seen from the figure, the distortion of the pulse shape at the exit (as for the case of pure intensity modulation, see item 3) decreases with increasing pulse width, gradually approaching pure shift. For the bleachable polarization absorber, this shift is positive (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 item 3, the observed delay of the polarization component, as one can see by comparing Figs. 4 and 6, may be fairly large. Additionally, in this case the delays, although not apparent, is nevertheless real in the sense that the signal at the exit can be observed after completion of the input signal (due to permanent presence of the initial 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 Eq. (1). However, in the works on 'slow light', the delay of this kind is usually ascribed to the group velocity reduction (see, e.g., [30,31]). Note also that the above scheme with admixing of the orthogonal polarization component and its separation at the exit (Fig. 5) makes it possible to monitor the polarization dynamics of the light at the exit of the absorber, but does not allow one, by any means, to probe the medium by this polarization component no matter how weak the probe. This 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 for the waves that are not normal cannot be introduced [32].

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 $(t^{-1})$, controlled by the sum of the dark and light-induced relaxation processes, grows in a linear way (see, e.g., [16]), whereas the delay time of the pulse or of the light intensity oscillations (at sufficiently low frequencies, see item 2), correspondingly decrease hyperbolically. For this reason, the dependence presented in Fig. 7 demonstrate standard properties of a saturable absorber and cannot be used to confirm the 'slow light' model, as this is made in [33].

6. **'Storage' of the light-induced anisotropy** The real delay of the polarization pulse at the exit 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 was already pointed out above, 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 existed at the moment of switching the light off. It means that the light beam will continue 'readout' of the anisotropy of the medium induced by the polarization pulse, and at the exit 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., [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 Λ-scheme is used (see., e.g., [30,31,35–37]; for more detail see [13,14]).

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 in 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 where, like 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, paradoxical and which is widely exploited in the '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 (P-P), but, being unable to bleach the medium, will experience strong absorption and appears to be strongly attenuated at the exit. However, if we measure transmission of the probe light in the presence of the pump, we will find that the system is transparent. Therefore, in this experimental arrangement, bleaching of the medium in one polarization makes it bleached for an arbitrarily weak beam of orthogonal polarization. Paradoxicality of this result is that 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 the laws of polarization optics.

Of course, there is no riddle here. On the one hand, this is a simple combination of nonlinear absorption with an effect due to the interference of polarized rays. If we trace the amplitudes of the two fields (it 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 polarization plane of the acting field. Due to 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 its component) passes through the medium with no attenuation. Keep in mind that 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). Anurthermore, it will eventually be correct to say that this is the EIT effect or what this effect turned into in the degenerate Λ-scheme. However, whereas for unequal frequencies of the beams in the non-degenerate Λ-scheme, with the measuring time being 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 truly able to probe it. However for equal frequencies this approach is unphysical. For this reason, in the degenerate polarization Λ–scheme, the notions of the 'probe' and 'pump' beams are improper. These reasoning refers to all the papers on 'slow light' that used the popular degenerate configuration described in [30].

8. Saturable absorber in the rotating frame

We have already mentioned that optically pumped atoms in zero magnetic field may serve as an adequate model of the saturable absorber. In these case the absorption saturation of the system corresponds, depending on the light polarization, to either orientation, alignment, or combination thereof. 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., [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, 'dark' polariton, etc. (see, e.g., [38]). The EIT effect is most frequently implemented in a 3-level Λ-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 bean is applied to one of the arms of the Λ-scheme (with the unpopulated low level) and to the other arm, a weak probe beam. 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⟩ and |2⟩. “Exactly” means to within the width of this transition, which determines spectral width of the 'transparency window’ and may be extremely small. From the narrowness of this 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 that the group velocity (due to the normal spectral dependence of the dispersion), is extremely low.
The 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, the fact of observation of the EIT resonance upon scanning of the frequency difference between the beams (i.e., the fact that the resonance is observed in the low-frequency domain of the transition $|1\rangle - |2\rangle$) 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 a small width for 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 loses its meaning. At the same time, this circumstance is, in our opinion, highly important for interpretation of the 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 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].

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' for EIT effects or coherent population oscillations, when the pulse spectrum should fit into the narrow transparency window. The difference is that, in the first case, we deal not with the spectrum of optical signal but rather with its intensity spectrum (whose amplitude, in particular, at optical frequency vanishes). The intensity spectrum of the optical pulse can be narrowed indeed by changing its duration, but the optical spectrum of the pulse can be varied by changing its duration only if the pulse is transform-limited. This circumstance is often overlooked, and the spectral width of an optical pulse is implied to be entirely controlled by the pulse duration (see, e.g., [18]).

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 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 the paraffin-coated 'vacuum' cells (with no buffer gas), a narrow light beam, a few millimeter 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 was observed, in various modifications, beginning from 1967 (see, e.g., [41–43]). This is why we cannot agree with the authors of [44] who consider this effect as "significantly expanding the capabilities of the quantum information storage technique".

**VI. DISCUSSION AND CONCLUDING REMARKS**

In these notes, we have considered, in a qualitative way, some simple effects observable in the media with nonlinear absorption, which are phenomenologically close to some manifestations of 'slow light', but have nothing to do either with a narrow spectral dip in the absorption spectrum of the medium, or with a steep dispersion of its refractive index, or with the 'slow light' proper. When considering all these phenomena in the framework of the model of saturable absorber, we have also touched on a non-degenerate Λ-scheme by passing to the rotating coordinate frame, when 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. However, this does not change the essence of the matter.

In all the cases considered above, the retarded response of the medium is a result of boundedness of its frequency passband. In the 'slow light' effects, the extreme narrowness of transparency window gives rise to 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, 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 with ultralow group velocity in the sense of Eq. (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 effects considered above are much less exacting to the properties of the nonlinear medium and light beams and can be observed much easier. These are trivial and rather universal effects of nonlinear optics that should be taken into account by the experimentalist first and foremost. However, in the studies on 'slow light', these trivial possibilities, as a rule, are not considered at all. In fact, 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 slowing down and storage of light are frequently demonstrated using the 'degenerate' Λ-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 of 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 [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 was found to be 0.091 mm/s. There is no question that the achievement of this kind can be set up ad infinitum. An even more striking example is the experiment [45], in which a retarded holographic reconstruction of the writing light beam in a photorefractive crystal was detected. In this study, the group velocity calculated in the same universal way was as low as 0.025 cm/s (with the shape and amplitude of the pulse at the exit of the crystal modified drastically). Of course, this effect (as well as the 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, when the speed of motion of the pulse peak cannot be identified with the group velocity of light. At the same time, the studies on 'slow light' frequently do not pay sufficient attention to the experimental facts that contradict canonical models 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 switching of the pump beam [44], and an ideal agreement of the results of the experiments on 'slow light' under conditions of 'coherent population oscillations' with the prediction of the trivial model of saturable absorber (see, [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 of the light pulse maximum in the medium, or phase delay of the amplitude modulation of the probe light, or polarization memory of a photochromic medium. Furthermore, specificity of this effect allows one fairly easily to distinguish it from standard manifestations of properties of a nonlinear
absorber. Stress once again that the difference between the pulse distortion in the saturable absorber (including the polarization scheme considered above) and dispersion-related pulse retardation is of physical nature and cannot be attributed to terminological discrepancies (as sometimes claim our opponents). The dispersive basis of the group velocity variation in the '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., [30,37]), whereas, real compression was demonstrated only in the 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 diagnostics of the 'slow light' effects. As an implicit evidence of the spatial compression of the pulse may serve the pulse delay exceeding the pulse width. 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. The pulse delays considerably exceeding their width has been indeed observed in [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 application of '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 the experiments on the light slowing down in optical fibers under conditions of stimulated Raman or Brillouin scattering [49].

In these notes we did not pursue the goal to give 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 on observation of 'slow light' are erroneous or, at best, groundless. The situation is aggravated by the fact that even the most evident physical errors of these papers systematically remain 'unnoticed', and the relevant publications do not find critical evaluation in the literature, holding their high citation level. It is noteworthy also that all the papers involved into this trend, regardless of their scientific novelty and degree of reliability, are published in the most prestigious journals and automatically acquire a high rating, whereas the attempts to express, in the same journals, some doubts about correctness of these 'achievements' meet a strong corporative resistance. This state of affairs, in our opinion, brings damage both to the prestige of science and to recognition of genuine achievements of this trend of physical optics.
FIG. 1. A model for the three-level energy diagram for observation of the electromagnetically induced transparency effect (Λ-scheme).
FIG. 2. Schematic depiction of time dependence of the light intensity at the exit of a usual (b) and inverse (c) saturable absorber for a step-wise change of the intensity at the entrance (a).
FIG. 3. Typical frequency variations of the amplitude $|K(\omega)|$, phase $\varphi(\omega)$, and time delay $\Delta t(\omega)$ of intensity oscillations of the light beam passed through a saturable (bleachable) absorber.
FIG. 4. Normalized Gaussian pulses $I(t) \sim \exp\left(-\frac{t}{\delta}\right)^2$ propagating through a usual (a) and inverse (b) saturable absorber for different ratios of the pulse width $\delta$ and the relaxation time of the absorber $\tau$: $\delta/\tau = 1$ (1), 2 (2) and 4 (3). Solid lines - pulses at the entrance, dashed lines - pulses at the exit [15].
FIG. 5. The pump-probe configuration, popular in the 'slow light' experiments with coherent orthogonally polarized beams from a single source (‘degenerate’ Λ-scheme). - pump (coupling) beam, - probe beam, SA - saturable absorber, BS - polarization beamsplitter, PD - photodetector.
FIG. 6. The shape of the ‘probe’ pulse (in the arrangement shown in Fig. 5) at the entrance (1) and at the exit (2 - 4) of the medium for different ratios of the pulse width $\delta$ and relaxation time of the absorber $\tau$: $\tau = \delta/2(2), \delta(3), \text{and } 2\delta(4)$ [15].
FIG. 7. Standard dependence of the pulse (or intensity oscillation) delay time at the exit of a nonlinear absorber and of the absorption relaxation rate on light intensity.
FIG. 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 entrance, dashed line - intensity of the pump beam at the entrance.
[1] L. Brillouin "Wave Propagation and Group Velocity", Academic Press Inc., New York (1960).

[2] N. G. Basov, R. V. Ambartsumyan, V. S. Zuev, P. G. Kryukov, and V. L. Letokhov, Zh. Eks. Teor. Fiz., 50, 23 (1966).

[3] A. C. Selden, Brit. J. Appl. Phys., 18, 743 (1967).

[4] P. W. Milonni, J. Phys. B: At. Mol. Opt. Phys., 35, 31 (2002).

[5] M. D. Crisp, Phys. Rev., A 4, 2104 (1971).

[6] S. Chu and S. Wong, Phys. Rev. Lett., 48, 738 (1982).

[7] S. E. Harris, Phys. Today, 50, 36 (1997).

[8] S. E. Harris, J. E. Field, and A. Kasapi, Phys. Rev., A 46, R29 (1992).

[9] Min Xiao, Yong-qing Li, Shao-zheng Jin, and Julio Gea-Banacloche, Phys. Rev. Lett., 74, 666 (1995).

[10] A. Kasapi, Maneesh Jain, G. Y. Yin, and S. E. Harris, Phys. Rev. Lett., 74, 2447 (1995).

[11] L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, Nature, 397, 594 (1999).

[12] Ch. Liu, Z. Dutton, C. N. Behroozi, and L. W. Hau, Nature, 409, 490 (2001).

[13] E. B. Aleksandrov and V. S. Zapasskii Physics: Uspekhi, 47, 133 (2004)

[14] G. G. Kozlov, E. B. Aleksandrov, and V. S. Zapasskii, Opt. Spectrosc., 97, 909 (2004).

[15] V. S. Zapasskii and G. G. Kozlov, Opt. Spectrosc., 100, 000 (2006); V. S. Zapasskii and G. G. Kozlov, LANL, arXiv:physics/0509181, v1, 22 Sept. 2005.

[16] L. Allen and J. H. Eberly, Optical Resonance and Two-Level Systems, John Wiley, Chichester, 1975, Ch. 6.

[17] W. Happer, Rev. Mod. Phys., 44, 169 (1972).

[18] A. M. Akulshin, A. Cimmino, A. I. Sidorov, P. Hannaford, and G. I. Opat, Phys. Rev., A 67, 011801(R) (2003).

[19] L. W. Hillman, R. W. Boyd, J. Krasinski, and C. R. Stroud, Jr., Opt. Commun., 45, 416 (1983).

[20] M. Malcuit, R. W. Boyd, L. W. Hillman, J. Krasinski, and C. R. Stroud, Jr. J. Opt., Soc. Am. B 1, 73 (1984).

[21] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, Phys. Rev. Lett. 90, 113903 (2003).
[22] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, Science, 301, 200 (2003).

[23] E. Baldit, K. Bencheikh, P. Monnier, A. Levenson, and V. Rouget, Phys. Rev. Lett., 95, 143601 (2005); LANL, arXiv: csd-00004377, 2005.

[24] Yun-Dong Zhang et al., Chinese Phys. Lett., 21, 87 (2004).

[25] A.C. Selden, ArXiv: physics/0512149 v1, 16 Dec. 2005.

[26] P. Wu and D. V. G. L. N. Rao, Phys. Rev. Lett. 95, 253601 (2005).

[27] A. C. Selden, J. Phys. D: Appl. Phys., 3, 1935 (1970).

[28] A. Icsevor and W. E. Lamb, Jr., Phys. Rev., 185, 517 (1969).

[29] H. Gao, M. Rosenberry, and H. Batelaan, Phys. Rev., A 67, 053807 (2003).

[30] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Phys. Rev. Lett., 86, 783 (2001).

[31] M. Kozuma, D. Akamatsu, L. Deng, E. W. Hagley, M. G. Payne, Phys. Rev., A66, 031801 (2002).

[32] M. Born and E. Wolf, *Principles of Optics*, Pergamon Press, 1993.

[33] M. M. Kash, V. A. Sautenkov, A. S. Zibrov, L. Hollberg, G. R. Welch, M. D. Lukin, Yu. Rostovtsev, E. S. Fry, and M. O. Scully, Phys. Rev. Lett., 82, 5229 (1999).

[34] A. Lezama, A. M. Akulshin, A. I. Sidorov, and P. Hannaford, LANL, arXiv: physics/0506199, 2005.

[35] H. Gao, M. Rosenberry, J. Wang, and H. Batelan, J. Phys. B: At. Mol. Opt. Phys., 38, 1857 (2005).

[36] A. Mair, J. Hager, D. F. Phillips, R. L. Walsworth, and M. D. Lukin, Phys. Rev., A, 65, 031802(R) (2002).

[37] M. D. Lukin, Rev. Mod. Phys., 75, 457 (2003).

[38] M. O. Scully and M. S. Zubairy, *Quantum Optics*, Cambridge University Press, 1997. Ch. 7.

[39] O. Schmidt, R. Wynands, Z. Hussein, and D. Meschede, Phys. Rev., A 53, R27 (1996).

[40] A. V. Turukhin, V. S. Sudarshanam, M. S. Shaahrian, Phys. Rev. Lett., 88, 023602 (2002).

[41] L. N. Novikov, Opt. Spektrosk., 23, 498 (1967).

[42] S. Nakayama, G. W. Series, and W. Gawlik, Opt. Comm., 34, 389 (1980).
[43] B. D. Agapiev, M. B. Gorny, N. A. Dovator, R. A. Zhitnikov, and B. G. Matisov, Pis’ma Zh. Tekh. Fiz., 10, 774 (1984).

[44] A. S. Zibrov, A. B. Matsko, O. Kocharovskaya, Y. V. Rostovtsev, G. R. Welch, and O. Scully, Phys. Rev. Lett., RL 88, 103601 (2002).

[45] E. Podivilov and B. Sturman, Phys. Rev. Lett., 91, 083902 (2003).

[46] Z. Dutton, N. S. Ginsberg, Ch. Slowe, and L. V. Hau, Europhys. News, 35, 33 (2004).

[47] H. Hersen, T. J. Karle, R. J. P. Engrirn, W. Bogaerts, J. P. Korterik, N. F. van Hulst, T. F. Krauss, and I. Kuipers, Phys. Rev. Lett., 94, 073903 (2005).

[48] A.B.Matsko, D.V.Strekalov, L. Maleki, Opt. Express, 13, 2210 (2005).

[49] D. Gauthier, Physics World, 18, 30 (2005).