

METHODOLOGICAL NOTES

PACS numbers: 42.25.Ja, 42.50.Gy

A fairy tale of stopped light

E B Aleksandrov, V S Zapasskiĭ

DOI: 10.1070/PU2004v047n10ABEH002023

Contents

Abstract. **It is shown that the sensational interpretation of the experiments described in the paper "Storage of light in atomic vapor" by Phillips D F et al. *Phys. Rev. Lett.*, 2001, v. 76, p. 783 is erroneous. The observations made in this work are easily explained in the framework of standard concepts of the light-induced anisotropy of an ensemble of atoms amenable to optical orientation and alignment. The response of the atomic medium detected by Phillips et al. has nothing to do with the authors' claims about 'storage of light', 'dynamic reduction of the group velocity of light', or 'compression of the light pulse'. This paper is an extended version of our critical comment rejected by *Physical Review Letters.***

1. Introduction

The problem of time delay of a light wave is topical for many areas of science and technology. With no special difficulties, optical signals can be delayed with conventional delay lines by time intervals of up to $\sim 10^{-7}$ s. Further progress in this direction is hampered by the necessity to create time-delay lines of huge length. This is why the spectacular experiments [1] which demonstrated the feasibility of the 'storage of light' and the delay of a light pulse by time intervals of around $\sim 10^{-3}$ s in a medium a few centimeters in length immediately attracted the attention of researchers. One of our colleagues who analyzed the offering possibilities of using this unique effect in optical information processing systems appealed to us (as the potential experts in the light storage technique) for advice. The result of our careful examination of paper [1] proved to be rather unexpected. It became evident that the claims of its authors of demonstrating the storage of light in a medium with subsequent light-induced release of the stored energy have nothing to do with real processes occurring in the system under study.

We believed that any criticism of a published paper should be directed to the journal in which the paper had been published, and thus submitted a short comment to *Physical Review Letters*. In that Comment we indicated a serious error made by the authors of Ref. [1], which excluded the possibility of adequately interpreting the experimental results. This Comment was considered by the *PRL* Editorial Board for more than a year. Unfortunately, in all of the five referee reports (beginning with a reply by the authors of Ref. [1] and ending with a reply by the Editor-in-Chief of the American Physical Society), the main (and, actually, the only) thesis of our criticism was not noticed and therefore was not touched upon.

In this paper, which is, in fact, an extended version of that Comment, we briefly describe the experiment in Ref. [1], explain the essence of the error committed by the authors, and show that the pattern of the signals recorded in Ref. [1] contains no novelty and completely agrees with standard concepts of the physics of optical pumping of 50-years' standing.

One of the arguments of our scientific opponents in the discussion with *Physical Review Letters* was that we did not present any mathematical modelling of the effect. We considered this issue as inappropriate because our criticism was directed toward a glaring error related to the fundamentals of optics of anisotropic media. Still, we have fulfilled the wishes of our opponents. In Ref. [2], we have presented a numerical simulation of the effects observed in Ref. [1], have demonstrated that they should necessarily show themselves in virtually all photochromic media, and have exhibited a perfect qualitative and quantitative agreement of the calculations with the experimental data [1] (the results of our simulation are reproduced below in Fig. 2 in comparison with the experimental curve).

2. Description of the experiment

A schematic of the experimental facility employed in Ref. [1] is shown in Fig. 1. Atomic vapor of ^{87}Rb in a zero magnetic

E B Aleksandrov, V S Zapasskiĭ All-Russia Research Center
'S I Vavilov State Optical Institute',
Birzhevaya liniya 12, 199034 St.-Petersburg, Russian Federation
E-mail: zap@vz4943.spb.edu

Received 14 June 2004, revised 8 September 2004
Uspekhi Fizicheskikh Nauk **174** (10) 1105 – 1108 (2004)
Translated by E B Aleksandrov, V S Zapasskiĭ; edited by A Radzig

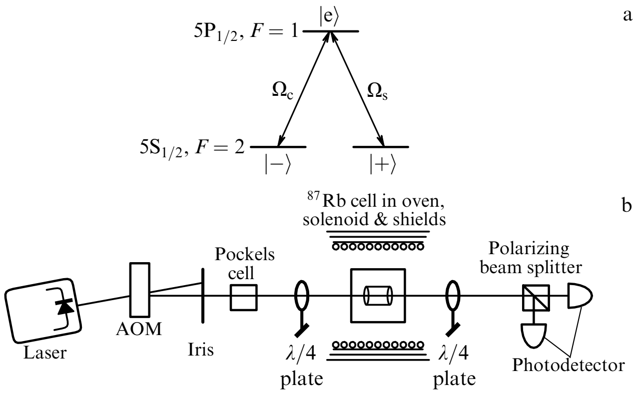

Figure 1. (a) Simplified Λ-type configuration of ^{87}Rb atomic states resonantly coupled to a control (Ω_c) field and a signal (Ω_s) field. Symbols $|-\rangle$ and $|+\rangle$ mark the ground state levels $F = 2$, $m = 0$ and $m = +2$, respectively, while the symbol $|e\rangle$ stands for an excited $F = 1$, $m = 1$ level. (b) Schematic of the experimental facility (AOM — acousto-optic modulator). The figure is borrowed from Ref. [1].

field was excited by a laser beam tuned to the resonance $5\,^2S_{1/2}, F = 2 \to 5\,^2P_{1/2}, F' = 1$ transition. The authors considered the exciting laser beam (generally, elliptically polarized) as a coherent superposition of two circularly polarized beams, namely, a strong 'control' beam with σ_+ polarization, and a weaker σ_--polarized 'signal' beam which was turned on for just a few dozen microseconds. After passing through the cell with the Rb vapor, the light was again split into two circularly polarized components (σ_+ and σ_-) which were detected by separate photodetectors. It is important that these two beams were assumed to be independent, i.e., the σ_+ component at the exit from the medium was always ascribed to the 'control' beam (with σ_+ polarization at the entrance), and the σ_- component at the exit was always ascribed to the 'signal' beam (with σ_- polarization at the entrance). This approach contains a simple (and fatal!) error which makes the authors' interpretation of the experiment [1] inadequate.

We will analyze the experimental examinations of Ref. [1] in the most general form, based on the simplest physical considerations, in order to represent the experimental situation of work [1] in the most transparent fashion. We will not discuss the theoretical treatment presented in Ref. [1], first of all, because we do not consider it appropriate to simulate the situation with the simplest three-level Λ-type configuration, whereas the spectral transition under study comprises 16 levels, with 11 of them being directly involved in the formation of the dynamics of the system perturbation via radiative and collisional relaxation processes. In addition, the approximate computing methods used in Ref. [1] are inappropriate for such high power densities of light fields connecting 8 energy levels of the atomic system. And, what is most important, even the most sophisticated methods of theoretical treatment do not relieve the authors of the necessity to take into account the basic laws of optics of anisotropic media, which we will deal with.

3. The essence of the error

In relation to the aforesaid, the authors of Ref. [1] actually studied a response of the atomic system to a pulsed polarization modulation of the pump. The admixture of an orthogonally polarized component to the circularly polarized 'control' beam converted the light acting upon the medium (during the 'signal' pulse length) from circularly polarized to elliptically polarized (in the experiment, the polarization modulation was provided by a Pockels cell). In the fundamentally nonlinear experiment we are dealing with, the medium excited by an elliptically polarized beam with a distinguished direction in the plane of the wave front loses its axial symmetry (which was originally provided by the absence of an external magnetic field and by circular polarization of the pump), circularly polarized waves cease to be normal modes of the medium, and the authors' approach, which implied mutual independence of circularly polarized waves in the medium, becomes invalid. Now, the circularly polarized 'control' beam propagating in the medium will be subjected to elliptic birefringence and dichroism (the latter being most important). Its polarization state will vary while it propagates through the medium, and the 'control' beam (initially σ_+-polarized) will be elliptically polarized at the exit of the medium. Being decomposed by the beamsplitter into basis circular polarizations, it will contribute to the signal of the second detector which, according to the authors, is capable of detecting only the σ_--polarized 'signal' beam. The same is valid for the 'signal' beam, which will also be detected both in the control and signal channels. This is succinctly the essence of the error committed in Ref. [1].

4. Authors' interpretation of the observations

Consider in more detail the dynamics of the 'signal' beam intensity observed by the authors of Ref. [1]. Figure 2 shows one of the experimental time dependences of the 'signal' beam intensity, demonstrating the delay and stoppage of the light. The upper part of the figure displays the time dependences of the control and signal beam intensities at the entrance to the cell (dashed and dotted curves, respectively), while the lower (noisy) curve shows the behavior of the signal beam intensity at the detector. The initial state of the medium is formed by a

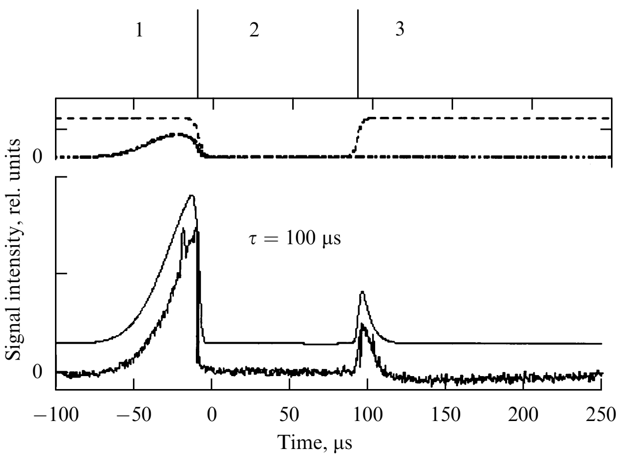

Figure 2. Demonstration of the light storage effect in the cell with ^{87}Rb vapor. The 'storage' time is 100 μs (a fragment of a figure from Ref. [1]). The upper part of the figure shows the time dependence of the 'control' (dashed line) and 'signal' (dotted line) beam intensities. The lower part of the figure displays the time dependence of the 'signal' beam intensity at the exit from the cell. The curve slightly shifted up with respect to the noisy experimental curve is the result of mathematical modelling [2] of the experiment [1].

long preliminary action of the 'control' beam. The presented time dependences comprise three regions (denoted by numbers 1, 2, and 3). In the authors' opinion, the experimentally examined behavior of the 'signal' beam at the exit from the medium demonstrates new physics deserving to be published in *PRL*.

In region 1 (before the dark interval), the medium is affected by both the 'control' and 'signal' beams, with the 'signal' beam, as can be easily seen, being strongly delayed (when the signal pulse at the entrance has already ended, at the exit it is only approaching its maximum). According to the authors' estimate, this delay is about 30 μs, which corresponds to a signal pulse group velocity of approximately 1 km s^{-1}.

Region 2 is the dark interval, when neither 'control' nor 'signal' beams are on (switching the beam on and off is performed *adiabatically*). The authors emphasize the fact (nontrivial, in their opinion) that during the dark interval no output signal is detected in the σ_- channel; they write, "Note that no output signal was observed as long as the control field was off". According to the authors, this fact demonstrates that the 'signal' beam propagating in the Rb vapor with extremely low velocity is completely stopped, when the light at the entrance to the cell is turned off.

In region 3, the 'control' σ_+-beam is turned on again, and, as the authors believe, the tail of the 'signal' pulse, which during the dark interval was stored in the medium in a spatially compressed state, is released and detected. By varying the duration of the dark interval (up to 0.5 ms), the authors varied the 'storage' time of the light in the medium.

This is how the experimental evidence of Ref. [1] looks in the authors' interpretation with no allowance made for the time-dependent anisotropy of the medium. If the latter is taken into account, most of the authors' statements lose their sense (in particular, the notion of the light propagation velocity is applicable only to normal modes of the medium), and the entire picture of the observations appears to be totally deprived of any novelty or nontriviality.

5. Correcting errors

In region 1, the medium, preliminarily oriented by the intense 'control' beam, is subjected to a pulsed action by the elliptically polarized light, which leads to a partial alignment of the atomic system. Since the duration of the 'signal' pulse is comparable with the characteristic time of atomic alignment, the degree of alignment follows the ellipticity pulse acting upon the medium with some delay. A similar behavior is displayed by the fraction of the 'control' beam detected in the signal channel (σ_-). This delay, evidently, has nothing in common with the claims about a huge reduction (by a factor of 300,000!) of the light group velocity. The growth of the signal in region 1 reflects the process of accumulation of ground-state atomic spin alignment rather than the shape of the leading edge of the 'signal' pulse, and the delay of this pulse is related to *dynamics of anisotropy of the medium*, rather than to the low group velocity of light.

In region 2 (dark interval), the spin alignment accumulated in the medium relaxes with a characteristic time on the order of 1 ms. Contrary to the authors' claims, no energy is stored in the medium, and there are no grounds to be surprised that no output signal is observed as long as the input light is off.

In region 3, the 'control' σ_+-polarized beam (turned on again) keeps detecting the residual elliptic anisotropy of the medium (partly relaxed during the dark interval). This anisotropy is revealed, as before, in the nonorthogonality of circular polarizations in the medium and in the branching of a fraction of the 'control' beam into the signal channel. The authors erroneously take the signal in the σ_--channel for the tail of the 'signal' pulse switched off fairly long ago. Notice, however, that the similarity between the kinetics of this tail and of the observed σ_--signal has an incidental nature: the kinetics of the alignment decay may differ arbitrarily from the kinetics of the 'signal' pulse having passed long before, because the former is determined by the intensity of the 'control' beam which, together with relaxation processes, destroys the spin alignment of the system.

Thus, if we take into account the alignment of the atomic system in the field of the elliptically polarized pump, ignored by the authors, all the observations in work [1] become trivial.

6. What is really 'stored' in the atomic system?

It is true that the 'control' beam (turned on after the dark interval) in a certain sense *reads out* the information about the relative phase and energy of the passed 'signal' beam. This information is stored in the magnitude and direction of the alignment and controls (via polarization of the emerging light) the phase and amplitude of the wave projected into the signal channel. However, first, the authors are not interested in the phase of the signal wave and, second, the accumulated anisotropy can hardly be regarded as 'stored light' whose physical meaning is unambiguously explained by the authors: "A pulse of light which is several kilometers long in free space is compressed to a length of a few centimeters and then converted into spin excitations in a vapor of Rb atoms. After a controllable time, the process is reversed and the atomic coherence is converted back into a light pulse". In our opinion, the experiment described in Ref. [1] is so ordinary and simple that it leaves no room for such speculations. Note also, in addition to all aforesaid, that the atomic coherence in the absence of any magnetic field (as was the case in the experiment staged in Ref. [1]) carries no energy, and the spin 'coherence' stored in the medium is reduced to a spatially uniform anisotropy of the medium.

The absurdity of the authors' interpretation can be made absolutely evident using an imaginary modification of their experiment [1], with the atomic vapor replaced by an optically nonlinear medium whose light-induced anisotropy does not relax in time at all. Suppose a plate of such a material is irradiated by a linearly polarized light pulse of arbitrary duration. This light can be evidently considered as a coherent superposition of a σ_+-polarized 'control' beam and a σ_--polarized 'signal' beam. After the irradiation, the plate becomes linearly anisotropic. Let it become, for example, a quarter-wave plate. Now, after a 'dark interval' of arbitrary length, we can irradiate the plate by a 'control' circularly polarized beam and obtain the 'signal' beam of circular polarization but opposite handedness (absent at the entrance!) at the exit. This is exactly what the authors of Ref. [1] call 'storage of light' and 'release of light' under the action of a 'control' beam. In the authors' terminology, any quarter-wave plate 'stores' a circularly polarized light which may be 'released', for instance, by illuminating it with a circularly polarized light of opposite handedness.

7. Conclusions

In the course of our polemics with *Physical Review Letters*, our scientific opponents claimed that we do not understand the role of coherence of the two acting fields in the (degenerate) Λ-type diagram and reduce a complicated process to Kastler-type optical pumping. We want to specially emphasize that any particular mechanism of the alignment is of no importance for our reasoning (this is also demonstrated by the calculations performed in Ref. [2]). What really matters is the indisputable fact that the 'signal' pulse renders the (originally circularly anisotropic) system elliptically anisotropic (this is the key point of our criticism, which, for some reason, was not touched on by any of our opponents). In Ref. [2], we have shown that the effects observed in Ref. [1] may be universally observed in virtually any photochromic medium.

One more argument against publication of our Comment was that the criticized paper [1] had given birth to numerous subsequent publications, and we had to consider all of them. Without arguing the correctness of this claim, note that, indeed, we did not intend to solve such a general problem, and, what is more, we did not address our criticism to this research field as a whole and did not mean to belittle its real achievements. At the same time, the public excitement that has arisen around the effect of electromagnetically induced transparency and so-called 'dark' states is, in our opinion, not quite justified. The effect of electromagnetically induced transparency has been known for more than 40 years [3]. The fact that the group velocity of light may significantly differ from the velocity of light in a vacuum has also been known for about a century [4]. There have been many observations on the reshaping of the pulse propagating through a nonlinear medium. These phenomena were also considered as indications of variations, in a wide range, in the velocity of light (in one sense or another). In one of the first papers of this kind [5], the velocity of the light pulse propagating in an inverted medium was reported to exceed the velocity of light in a vacuum by a factor of 6 – 9. A detailed theoretical analysis of numerous situations of this kind was performed by Vainshtein [6] (see also references in Chapter 10 of Ref. [7]). Note that in all the cited publications, the authors stress that the observed effects do not violate the causality principle (which restricts only the speed of transmission of information).

As for the possibility of stopping and storing light in a medium, these phenomena (in various modifications) are also known as, e.g., the photon echo, the storage of light in resonators, or the effects of static and dynamic holography (to say nothing about some incoherent ways of light storage in photo- and thermoluminescence, phosphorescence, etc.). The light-induced anisotropy can also be regarded as a sort of stored light or, at least, as a facsimile of the light that created this anisotropy. We want to stress once again that our objections refer to the adequacy of description of the observations rather than to problems of terminology.

In summary, the interpretation of the results obtained in work [1] contains obvious errors, and the reported experimental findings (quite correct on their own) do not provide any evidence of the 'storage' or 'release' of light. This paper, in our opinion, not only misleads the reader but also raises serious doubts about other publications that refer to paper [1] as to a basic publication of this line of inquiry. That is why we consider adequate assessment of this paper, which has a very high citation index and even enthusiastic reception in the mass media, to be important. The correctness of our position was additionally confirmed by positive responses to our publication on the Internet [8].

References

1. Phillips D F et al. "Storage of light in atomic vapor" *Phys. Rev. Lett.* **86** 783 (2001)
2. Kozlov G G, Zapasskii V S, Aleksandrov E B *Opt. Spektrosk.* **97** 964 (2004)
3. Bell W E, Bloom A L *Phys. Rev. Lett.* **6** 280 (1961)
4. Brillouin L *Wave Propagation and Group Velocity* (New York: Academic Press, 1960)
5. Basov N G et al. *Dokl. Akad. Nauk SSSR* **165** 58 (1976)
6. Vainshtein L A *Usp. Fiz. Nauk* **118** 339 (1976) [*Sov. Phys. Usp.* **19** 189 (1976)]
7. Chiao R Y (Ed.) *Amazing Light*: *A Volume Dedicated to Charles Hard Townes on His 80th Birthday* (New York: Springer-Verlag, 1996)
8. Alexandrov E B, Zapasskii V S, quant-ph/0304192