Capture of Solitons in Layered Phaseonium

W.P. Beeker, D.N. Deriga, K.J. Boller
University of Twente, the Netherlands
w.p.beeker@alumnus.utwente.nl

Abstract

We predict that injecting a sequence of several 2π soliton pulses into a medium of three-level-atoms can lead to staggered layers in which the atoms are left in a phaseonium-type of ground state superposition.

The nonlinear propagation of resonant optical pulses through strongly absorbing media receives continuous interest since decades. Different types of pulses based on Self Induced Transparency (SIT) [1] or on Electro- magnetically Induced Transparency (EIT) [2] can interplay in media with a V-type [5] or a Λ-type [3] three-level scheme. Of special interest is the coherent excitation of two long-living ground states in Λ systems to store optical information in the medium. Such coherence within the ground state population has been termed phaseonium [4] and plays a center role for storage and retrieval of pulses. For example, making use of the EIT effect with a stronger coupling laser it has been demonstrated that phase and amplitude information of a weak probe pulse may be stored and retrieved within the lifetime of the ground state coherence [6]. It has been suggested to manipulate stronger (SIT soliton) probe pulses as well [7] or to clone a probe soliton into the coupling laser transition [8]. However, all these schemes involve the creation of only a single spatial region of phaseonium in the medium.
Here we theoretically describe a novel way of sequentially writing a series of layers of phaseonium into a medium, by injecting a series of SIT probe pulses, the first of which has been stopped by a coupling laser pulse. The spatial properties of the medium thus created may be of interest as temporary optical components (such as gratings) that can be written and erased by light.

Our considerations are based on a medium with a 3 level system as shown in fig.1, which is irradiated with a resonant probe laser field connecting the states 1 and 3, and a resonant coupling laser connecting states 2 and 3. For the theoretical description we numerically solve the Maxwell-Bloch equations in the slowly varying envelope approximation and one spatial dimension of light propagation (z). To study only the basic dynamics we have assumed that the atoms are at rest, such that Doppler broadening and collisional damping can be neglected. Also, we consider only interactions with SIT pulses much shorter than the spontaneous emission lifetime of the upper state.

Before we come to our main observation we describe how to coherently prepare the medium in a specific spatial distribution. Initially the system is considered to be purely in ground state 1. Next an SIT pulse with a field area of 2π and *sech*-shape is injected at the absorbing probe transition (1-3) which leads to propagation as a soliton. After a certain distance of propagation, a second weaker pulse [8] is launched on the non-absorbing coupling transition (2-3). As the SIT probe pulse propagates with its soliton speed slower than c, it is overtaken by the coupling pulse which travels at the speed of light on the empty transition.

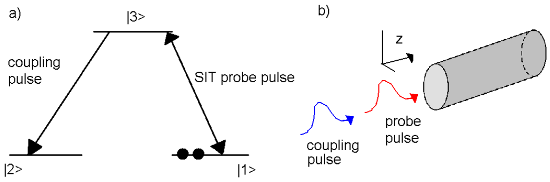

Fig.1a: A 2π SIT pulse is applied on the populated transition and a following coupling pulse is applied on the empty transition. Fig.1b represents the medium entirely in ground state 1 before the two pulses enter.

When the pulses meet in the medium, the coupling beam causes the probe soliton to be absorbed. At the same time the coupling pulse is amplified and leaves the medium. Fig. 2 shows that at a certain depth of the medium a coherent superposition of the ground states is created. Closer inspection of the spatial distribution of ground state coherence and population in fig. 2 reveals that a coherent double-layer with opposite signs is formed, between which the population is swapped entirely to the other ground state 2.

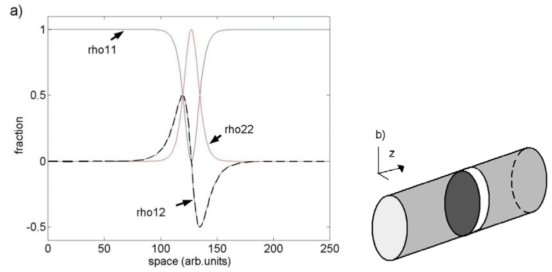

Fig.2a: Ground state coherence (ρ_{12}) and the population (ρ_{11} and ρ_{22}) along the propagation coordinate after an SIT pulse has been overtaken by a coupling pulse. Two regions attain the maximum possible coherence (0.5 and -0.5) between which the population is swapped to the other ground state. Fig.2b depicts the layer of swapped ground state population separating a double-layer of phaseonium at a certain depth of the medium.

Fig.2 further shows that in the region where the SIT soliton was absorbed the ground state coherence reaches its maximum possible value, and may thus be termed phaseonium. This also expresses that after the absorption of the SIT pulse is completed no population is left in the upper state. As a result the medium can stay in this state as long as ms. [6].
The optical output from the described process has been previously investigated [8] and named cloning of the probe soliton into the coupling transition. However, what has not been studied there is what effects the left-behind phaseonium and population layers would have on the propagation of subsequent pulses.

For an investigation of such novel scenarios we applied a second *sech*-pulse with 2π area on the probe transition, which was eventually followed by a third 2π probe pulse. Initially both pulses travel through the medium as standard SIT solitons. However, upon crossing the region with the stored coherence, the second SIT probe pulse is captured by the medium and a pulse generated on the coupling transition leaves the medium. In this interaction, the formerly written coherence layers are found shifted and deformed in space and a new layer is staggered next to them. Simultaneously a double layer of swapped ground state population is formed. We noticed that this occurs independent of the optical phase of the captured soliton. Fig.3a shows the spatial distribution of coherence and population, after also the third SIT soliton has been captured. It can be seen that now the medium contains two layers of double-peaked phaseonium separated by three regions of swapped ground state population. The latter is depicted in Fig.3b as three slices in the medium. We have noted that the caption of additional pulses leads to a chirped grating type of distribution.

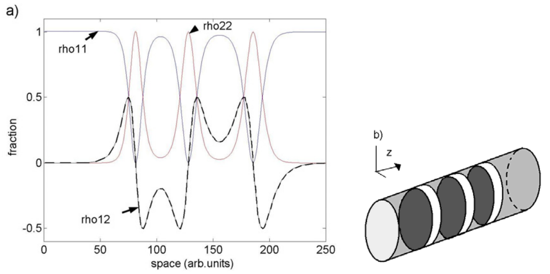

Fig.3a: Spatial state of the medium after two additional SIT probe pulses are captured by the medium as left behind in fig.1. Fig.3b: The staggered layers of swapped population embedded in layers of phaseonium is depicted as slices in the medium.

Conclusion

We have shown that after a 2π SIT soliton pulse is captured in a Λ-type medium by a coupling pulse there remains a double-layer of phaseonium around a single layer of swapped ground state population in the medium. After such preparation the medium is capable to capture additional SIT probe pulses, without using a coupling laser pulse. Each of the captured probe pulses leaves an additional layer of swapped ground state population and coherence behind. Each soliton capturing event shifts the layered structure stepwise along the former propagation direction. Our calculations indicate that such staggering of layers of phaseonium and swapped ground state can be repeated by injecting additional SIT probe pulses. The entire layer structure can be erased by injecting a coupling laser beam. We thank Edip Can for helpful discussions.

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