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COHERENT EFFECTS IN ULTRASHORT PULSE PROPAGATION THROUGH OPTICALLY THICK THREE-LEVEL MEDIUM

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Propagation of a weak ultrashort pulse through an optically thick inhomogeneously broadened three-level medium of V-configuration driven by a self-induced transparency pulse on the coupled transition is investigated theoretically. The weak coherent pulse experiences a greatly enhanced transparency. The new transparency effect is discussed in details and the results are in a good agreement with recent experimental observations.

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The pioneering work of McCall and Hahn on self-induced induced transparency (SIT) [1] was followed by a number of theoretical and experimental works on pulse propagation through the systems of two-level atoms. The most exciting feature of this phenomenon is that above a critical power threshold a short coherent pulse can propagate with anomalously small energy loss while at resonance with a two-level system of absorbers. Recently a variety of new coherent nonlinear quantum optical phenomena have been found, in which a secondary optical pulse cooperates with or even controls a primary pulse, such as electromagnetically induced transparency (EIT) [2], simulton propagation [3], Raman solitons [4], efficient upper state excitation by counterintuitive pulse sequencing [5].

In most cases the pulses are to be injected into a medium of atoms that are well approximated as three-level Λ-system. Major part of the effects are closely related to the phenomenon of EIT, which arises due to an excitation of a superposition wave function, often termed as a population trapped or dark state [6]. In the bare atomic basis, this wave function has no component of the upper state and therefore, once prepared, is immune to any kind of decay which affects only the upper state. This kind of transparency is of little importance in a V-type system, if for no other reason than the trapped state for a V-type medium requires all the atoms to be in the superposition of two upper states, $|a\rangle$ and $|c\rangle$. It is evidently not the case of practical use, because normally all the atoms are initially prepared in the lower state $|b\rangle$. In this Letter we come back to the classical SIT effect, and basing on it show how a new type of transparency originates in a three-level configuration of V-type.

This Letter has been initiated by recent experiments [7] on the simultaneous propagation of two pulses through an inhomogeneously broadened V-type absorbing medium (the plasma of a positive glow-discharge neon column), see Fig.1a. One of the pulses (driving pulse) with a shape close to that of a SIT soliton, and with a small detuning from the exact resonance propagated at the resonant wavelength $\lambda = 614.3$ nm. Simultaneously, the other pulse (probe pulse) was launched into the absorbing medium at the resonant

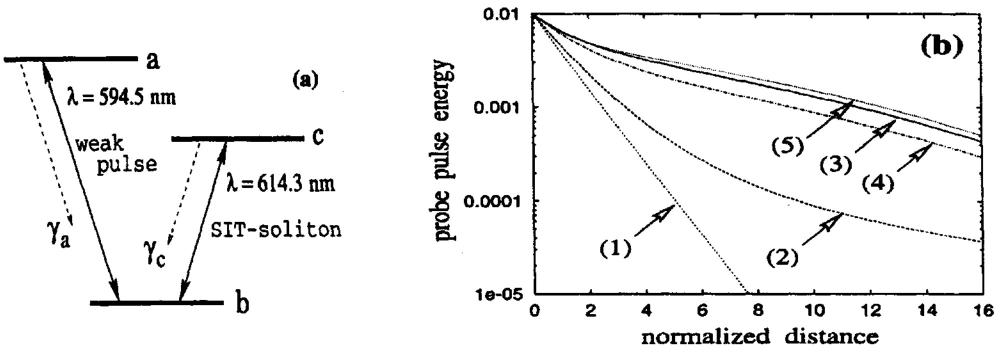

Fig.1. (a) Schematic level diagram of the absorbing medium in [7]. Population decay rates (indicated with unidirectional arrows) are $\gamma_a = \gamma_c = 19$ ns. Relaxations of all polarizations, ρ_{ab}, ρ_{cb} and ρ_{ac}, are 11 ns, inhomogeneous spectral width (FWHM) is 1400 MHz. (b) Energy versus propagation distance: *1* – Beer's law; *2* – weak pulse in a two-level medium. Weak pulse in a V-type medium, driven by a SIT soliton: *3* – peaks of the pulses coincides at the entrance; *4* (and *5*) – weak pulse has a delay (advance) of 0.5 ns. For all figures: the both pulses are sech-shaped; weak pulse (SIT pulse) duration is 0.5 ns (1 ns) and initial detuning is 290 MHz (750 MHz). Distance is normalized to the linear absorption coefficient on $|a\rangle - |b\rangle$ transition, κ_{ab} (the linear absorption coefficient on $|c\rangle - |b\rangle$ transition is $\kappa_{cb} = 2.14\,\kappa_{ab}$)

wavelength $\lambda = 594.5$ nm, and passed it attenuating by only a factor of 8. When the same probe pulse propagated independently it was absorbed so strongly that the experimentalists were unable to detect the pulse at all at the output of the cell. Note, that in the experiments the optical thickness $\kappa_{ab}L$ at $\lambda = 594.5$ nm was equal to 15, so that a weak cw radiation had to be attenuated by a factor of exp(-15).

Our model for numerical calculations is based on the simultaneous solution of two Maxwell equations for the driving and the probe fields in the form of plane waves and the density matrix equations for a three-level absorber of V-type. It incorporates all the decay processes and the inhomogeneous broadening, the values of which are taken from the experiment [7] (see figure captions for details).

Fig.1b displays the changes in energy with propagation distance. The abrupt absorption of a weak continuous wave radiation represents the familiar Beer's law of exponential energy decay, see curve *1*. Curve *2* shows how a short pulse attenuates during propagation in a two-level subsystem $|a\rangle - |b\rangle$, when the driving pulse is switched off. A strong deviation from the Beer's law arises from the fact that the pulse is short and has a spectral width ("input" in Fig.3b), which is comparable to the width of the inhomogeneously broadened line (absorption spectrum in Fig. 3b). The additional transparency is due to a less absorption of the pulse spectral wings. This effect known as ***abnormal classical absorption*** was described by Crisp in Ref. [8].

Curves *3*, *4* and *5* in Fig.1b correspond to the propagation of the probe pulse when a drive pulse in the form of a SIT soliton is simultaneously launched into the medium on the adjacent transition. For the curve *3* the two pulse peaks coincide at the entrance of the medium, for the curve *5* the probe pulse experiences an advance equal to 0.5 ns, and for the curve *4* – a delay of the same magnitude. Transparency enhancement takes place for all three cases, and the most favorable conditions are established when the probe pulse goes ahead of the SIT soliton. One can see the increasing in transparency by an order of magnitude in comparison with the case of independent pulse propagation [compare curves *2* and *3*].

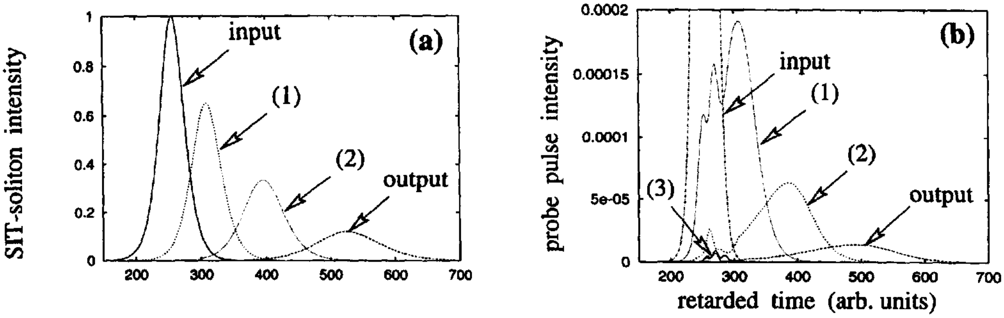

Fig.2. (a) SIT soliton shape for different propagation distances $\kappa_{ab} L$: (*1*) 5; (*2*) 10; (output) 15. (b) The same for a weak pulse. Curve *3* shows the pulse shape at $\kappa_{ab} L = 15$ in a two-level configuration

Temporal shapes of the two pulses for four different propagation distances are plotted in Fig.2. SIT soliton propagates through the medium demonstrating the familiar features of SIT effect. As a result of relaxation of the atomic polarization between $|a\rangle$ and $|b\rangle$ states as well as the decay of $|a\rangle$ state, it gradually decreases in amplitude with the corresponding increasing in duration in order to keep its area equal to 2π. On the other hand, the probe pulse shows an unusual behavior, clearly splitting into two portions. One of which propagates with the velocity of light (without retardation in Fig.2b), and attenuates essentially in the same manner as if the pulse propagated in the absence of a SIT soliton (compare the left part of the "output" with curve *3*). The other, more larger, portion is trapped by the SIT soliton and experiences a large delay. It is this part of the probe pulse that provides the transparency enhancement.

As shown in Fig.2a, the SIT pulse repeatedly reproduces itself while propagating through the medium. The theory of classic SIT effect teaches us that a leading front of a SIT soliton transfers the population from a lower state to an upper state, and then the second half of the pulse coherently replaces the excited atoms in their original position. This energy exchange takes a finite interval of time providing a significant pulse delay. The temporal evolution of polarization undergoes a cycle, developing an absorptive portion at the leading edge, and the identical gain portion at the trailing edge. Moreover, polarization of *each* frequency group of inhomogeneously broadened line oscillates *in phase* with that of any other frequency group, providing a complete transparency for the SIT soliton. The mechanism of "phase locking" in two-level medium turns on only for a sufficiently strong pulse with area more than π.

Now, comparing all stages of reshaping displayed in the both plots of Fig.2, one can see that the probe pulse also experiences a delay, associated with the absorption of the leading edge and the subsequent reradiation energy at the trailing edge, just as for a SIT soliton. Basing on this similarity we conclude, and this is the key point of the Letter, that the polarizations of all frequency atomic groups within the inhomogeneously broadened line are "locked" together, i.e. oscillate in phase. This differs dramatically from the conventional interaction picture of a weak pulse with a two-level system. Since the dipoles have different detunings from a center of an atomic line, they oscillate at different frequencies and cannot interfere constructively, such that the net atomic polarization, obtained as a summation over all frequency groups, quickly vanishes. In a three-level configuration a SIT-pulse on the adjacent transition provides an additional "phase locking" mechanism between all dipoles on $|a\rangle - |b\rangle$ transition, allowing a weak pulse to propagate without absorption. So, in some sense, we are dealing with the extension of SIT effect for weak coherent pulses.

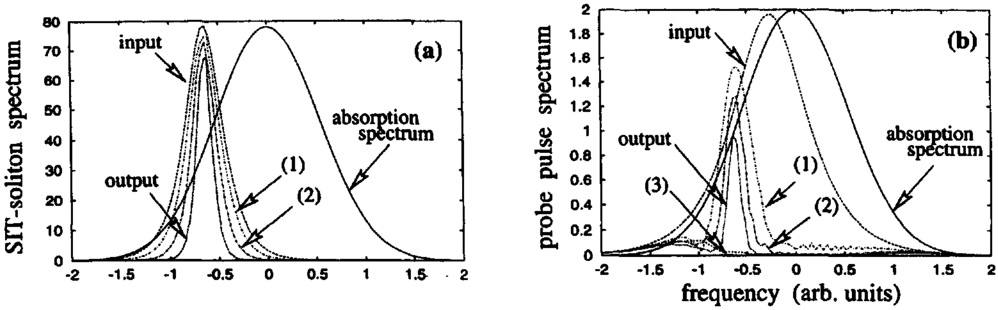

Fig.3. The same as in Fig.2 for spectra of the pulses

Spectral measurements in the experiment [7] revealed a new effect, associated with the shift of the probe pulse spectrum towards the carrier frequency of the SIT pulse. Fig.3a displays how initially detuned SIT pulse keeps its carrier frequency and shape unchanged, while its spectral width gradually decreases with distance. This fact is due to unique correspondence between a temporal shape and its Fourier transform, such that a spreading in time domain corresponds to contraction in frequency domain. A probe pulse spectrum also does not have any striking features, if its propagation is not accompanied by a SIT pulse. The absorbing medium burns a hole in the probe spectrum, such that only far off-resonant frequency components can survive (curve *3* in Fig.3b).

In the presence of a SIT soliton the evolution of the probe pulse spectrum becomes more complicated and manifests two pronounced tendencies: (i) the pulling of spectral peak towards the carrier frequency of the SIT pulse, in accordance with the experimental observations; (ii) the amplification of those frequency components, which are arranged about the center of the SIT pulse spectrum. The surprising thing is that the whole region of frequencies exhibits a real amplification and grows within the place, where the spectral components vanish without the SIT pulse (compare to curve *3*). Of course, this fact does not contradict with conservation of energy, and the net pulse energy gradually decreases with propagation, as shown in Fig. 1b. The amplification of some spectral components is due to the SIT pulse, which induces a nonlinear frequency conversion involving the transfer of energy from some spectral regions to another.

In conclusion, we have demonstrated a new type of transparency for a weak coherent pulse, induced by a SIT soliton, propagating on the adjacent transition of a three-level system. The SIT pulse induces the correlations between the dipoles oscillating with different frequencies. It is these correlations that underlies the physics of the new transparency effect. The impressive rearrangement of the probe pulse spectrum and the frequency pulling effect accompany the new phenomenon.

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