SPONTANEOUS SOLITON FORMATION IN THE REGION OF RESONANT ABSORPTION OF MOLECULAR MEDIA

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Received June 21, 1995

Some peculiarities in the spontaneous formation of solitons when high-power optical pulses of an arbitrary shape propagate in resonantly absorbing molecular media are studied. The model of rovibrational band is considered as a resonant transition. The correlation between the results obtained and analogous data for a two-level model of a medium has been studied.

1. INTRODUCTION

The phenomenon of soliton formation can be observed when optical pulses of an arbitrary shape propagate under conditions of nonlinear interaction between the radiation and a medium, when different effects of interaction lead to disintegration of a pulse into a number of stable formations, exhibiting properties of solitons.

The process of soliton formation and properties of solitons essentially depend on the conditions of interaction. Some aspects of this problem for the 3D-nonlinear nonresonant media have been analyzed in Refs. 1 and 2 based on the model using nonlinear Schrödinger equation (NSE). In so doing, various factors, hindering the formation of solitons, including absorption, were considered as perturbations.

Numerical analysis made on the basis of Maxwell-Bloch equations[3] has shown that in resonantly absorbing media the initial stage of soliton formation well fits the NSE model, but at large optical depths the solitons of self-inducted transparency (SIT) are formed,[4] whose properties essentially differ from the NSE solitons. Most interesting is the fact that the initial pulse length can be much greater than the period of medium phase memory, whereas for SIT solitons the inverse relation holds true. In this case the transition from conditions of incoherent interaction between radiation and a medium to coherent one occurs.

Of interest is the analysis of possibility for such a transition and formation of solitons for gaseous media, particularly, in the molecular atmosphere. It is characteristic that pulse length of the majority of lasers used in atmospheric studies corresponds to incoherent interaction.

It should be noted that because of nonlinearity of the problem, the interaction with more than two levels of molecule is possible. It requires to abandon the two-level approximation.

2. STATEMENT OF THE PROBLEM

In this paper we consider the following model of a rovibrational transition. The structure of rotational sublevels is considered to correspond to the model of a rigid rotator. The approximation $J \approx J + 1$ for resonant the transition $J \to J \pm 1$, valid for large enough values of J, is also used. The pulse length is considered to satisfy the relation $\tau_p \ll \tau_{VV'}, \tau_{VV}$, where $\tau_{VV'}$ is the time of intermode relaxation, τ_{VV} is the time of vibrational relaxation inside the resonant vibration mode.

The corresponding problem of propagation is described by the following system of equations:

$$\frac{\partial \varepsilon}{\partial z} = 2\pi i k N \mu P, \tag{1a}$$

$$\frac{\partial P}{\partial \eta} = -\Gamma P - i\kappa\omega_r \varepsilon, \tag{1b}$$

$$\frac{\partial \omega_r}{\partial \eta} = \mathrm{Im}(\varepsilon P^*) - \frac{(\omega_r - \omega_v \theta_J)}{T_r}, \tag{1c}$$

$$\frac{\partial \omega_v}{\partial \eta} = \mathrm{Im}(\varepsilon P^*), \tag{1d}$$

where ε is the complex amplitude of a pulse, P is the complex amplitude of induced polarizability of a medium, ω_r is the difference in population of rotational sublevels between which the resonant transition occurs, ω_v is the difference in population of vibrational levels, θ_J is the function of molecule distribution over rotational sublevels, N is the resonant gas concentration, μ is the dipole moment corresponding to this transition, $\Gamma = 1/T_2 - i\Delta$, $k = \omega/c$, T_2 is the period of medium phase memory, Δ is the detuning from the resonance, T_r is the time of rotational relaxation, $\eta = (t - z/c)$.

Dynamics of populations of the levels involved in the rovibrational transition in the given equations is similar to that presented in Ref. 5.

The initial pulse shape is described as follows:

$$\varepsilon(0, t) = [\sin(\pi t/\tau_p)]^q, \quad t \in [0, \tau_p],$$
$$\varepsilon(0, t) = 0, \quad t \notin [0, \tau_p]$$

and depending on the value of the parameter q it varies from quasi-Gaussian to quasi-rectangular.

The system (1) has been solved numerically. The algorithm used in computations has been discussed in Ref. 6.

0235-6880/95/12 975-02 $02.00

3. RESULTS

As computations have shown, the process of spontaneous formation of solitons can be observed in the molecular media too, but it starts at much lower intensity of radiation propagating as compared to a two-level model of resonant transition. Energy losses, accompanying the initial stage of soliton formation, also are much smaller (see Fig. 1 and similar data in Ref. 3).

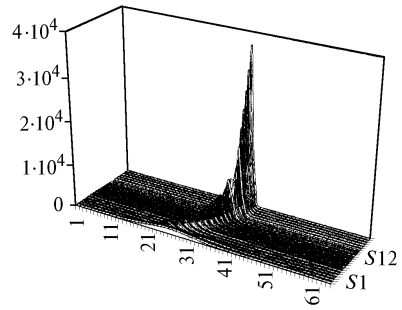

FIG. 1. Pulse intensity as a function of time and distance covered. Computation was done at $S = 4\pi$, $T_2/\tau_p = 0.5$, $q = 4$, $\Delta = 0$ *(S is the initial pulse cross section).*

It should be noted that variations of the initial pulse length have much weaker influence on the number of solitons formed as compared to the two-level model. With pulse length being of the order of the rotational relaxation time, the number of SIT solitons formed, N_s, was, as a rule, $N_s = S/2\pi - 1$, where S is the initial pulse length. In other words, the number of SIP solitons formed is less by one soliton than in the case of purely coherent interaction when $\tau_p \ll T_r$.

All the above-mentioned peculiar features are most likely due to the fast depletion of the vibrational level of resonant transition, since during the interaction with optical pulse the radiationless transitions to the lower vibrational level are absent because of a negligibly small rate of vibrational relaxation (the difference between vibrational and rotational relaxation times may reach orders of magnitude[5]).

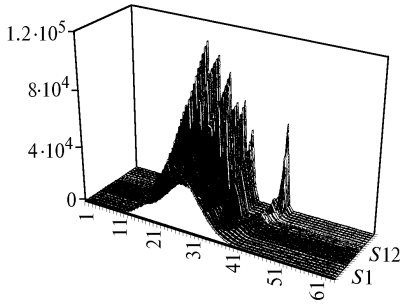

FIG. 2. The same as in Fig. 1 but at $S = 24\pi$, $T_2/\tau_p = 1$, $q = 4$, *and* $\Delta T_2 = 1$.

The fact turned to be a characteristic feature of the model that in a number of cases the last pulse had much smaller speed of propagation (Figs. 2 and 3). If the energy of the initial pulse is sufficient, this pulse converts into 2π-soliton (Fig. 2), otherwise, its dissipation in a medium takes place (Fig. 3). For the two-level model of resonant transition,[3] similar results were not observed.

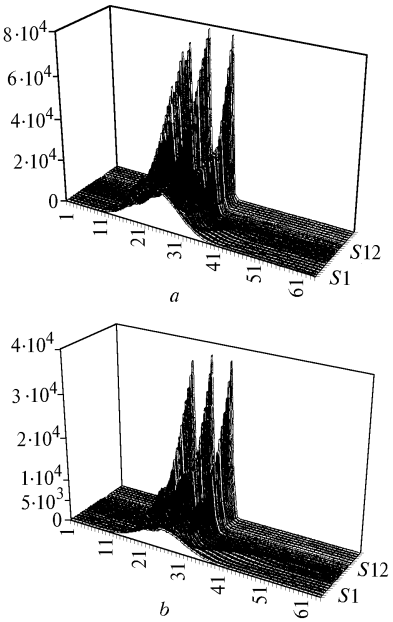

FIG. 3. The same as in Figs. 1 and 2 but at $S = 8.2\pi$, $q = 4$ *with* $T_2/\tau_p = 1$, $\Delta = 0$ *(a) and* $T_2/\tau_p = 0.5$, $\Delta T_2 = 1$ *(b).*

4. CONCLUSION

Our computations have shown that the process of spontaneous formation of solitons in molecular media is qualitatively similar to analogous process in two-level media. The peculiar feature of interaction with a molecular medium is in the fact that in a number of cases the difference is observed in speeds of propagation of solitons formed.

The quantitative differences are the reduced threshold of soliton formation and the drop in energy losses, accompanying this process, in molecular media as compared to a two-level medium. This is due to the difference in a relaxation processes.

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