SOME SPECIFIC FEATURES OF SHORT OPTICAL PULSES PROPAGATING IN A RESONANTLY ABSORBING ATMOSPHERE. II. SLANT PATHS

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An analysis is presented of some specific features of short optical pulses propagating along the slant paths in a resonantly absorbing medium. Results are obtained for the model of an inhomogeneous, vertically stratified medium in the geometrical optics approximation. It has been shown that the inertia of response of the resonant medium has an appreciable effect on the propagation process so that both the pulse shape and the energy parameters of the beam depend on the direction of propagation.

INTRODUCTION

Some specific features of deformation and attenuation of short optical pulses with various shape when such pulses propagate in a resonantly absorbing gaseous atmosphere along slant paths are discused.

The atmosphere is modeled as inhomogeneous vertically stratified medium, the parameters of which are varied according to standard statistical models of the atmosphere. The thickness of the atmospheric layer is about 10 km. As the resonantly absorbing component of the medium, we consider water vapor. The variations in shape, width, central frequency of the absorptions line, and water vapor concentration as functions of altitude are taken info account in calculations. In addition, the resonant part of the refractive index of the medium undergoes similar variations caused by a resonantly absorbing gas. The nonresonant component of the refractive index is calculated according the formula

$$n_0(h) = 1 + 58.2\cdot10^{-6}(1 + 7.52\cdot10^{-3}\cdot\lambda^{-2})p(h)/T(h), \qquad (1)$$

where λ is the radiation wavelength in microns, $p(h)$ is the air pressure in torr, and $T(h)$ is the temperature in degrees Kelvin.

The analysis of the transformation of the pulse parameters during the propagation of the beams is based on the Maxwell—Bloch equations for quasiplane wave in the approximation assuming both geometric optics and small area of the pulse. In this case propagating through the ith layer of the inhomogeneous stratified medium is described by the system of equations

$$\left[\cos\theta_i \frac{\partial}{\partial h} + \frac{n_{0i}}{c}\left(1 - \frac{h}{\omega}\frac{\partial K_i}{\partial t}\right)\frac{\partial}{\partial t}\right]\varepsilon_c = 2\pi ik \times$$

$$\times \int_{-\infty}^{\infty} P_c(\Delta')g(\Delta - \Delta')\mathrm{d}\Delta', \qquad (2.1)$$

$$\psi_i = \psi_{i-1} + \omega t - K_i\cdot h\ , \qquad (2.2)$$

$$\left[n_{0,\,i-1} + n_{r,\,i-1}(t)\right]\cdot\sin\theta_{i-1}(t) = \left[n_{0,\,i} + n_{ri}(t)\right]\cdot\sin\theta_i(t), \qquad (2.3)$$

and

$$\mu(h)\frac{\partial P_c}{\partial t} = -\gamma P_k + i\varepsilon_c. \qquad (2.4)$$

Here the rediation field is represented in the form $E = \mathrm{Re}\left[\varepsilon_c e^{i\psi}\right]$, where $\varepsilon_c = \varepsilon_0 e^{i\varphi}$ is the complex, slowly varying amplitude, ψ is the rapidly varying phase of the optical wave, θ_i is the angle of the direction of propagation of the wave through the ith layer with the normal to its boundary, h is the coordinate along the normal, n_{ri} is the resonant part of the refractive index of the layer, which is proportional to the ratio of the imaginary part of the right side of Eq. (2.1.) and the optical field intensity ε_c,

$$\gamma = 1 - i\cdot(\Delta - \dot{K}_i\cdot h)\cdot T_2(h),\ K_i = n_{0i}k/\cos\theta_i\ ,$$

$\mu = T_2(h)/\tau_p$, τ_p is the pulse duration, T_2 is the phase memory time of the medium, $k = \omega/c$, and Δ is the detuning of the incident radiation from resonance.

The system of equations (2) must be completed by the corresponding initial conditions and the conditions prescribed on the layer boundaries. It should be noted that relations (2.2) and (2.3), which reflect the essence of the model, follow from these boundary conditions.

SOME SPECIFIC FEATURES OF RESONANT REFRACTION DURING THE PROPAGATION OF SHORT OPTICAL PULSES

By the term 'resonant refraction' we understand a change in the direction of beam propagation caused by the resonantly interacting component of the medium.

Let us now consider the specific features of the refraction of the short optical pulses at the boundaries between the layers of the inhomogeneous, stratified, resonantly absorbing atmosphere. For simplicity let the

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pulse have a step–like shape and the absorption line be homogeneously broadened. It then follows from Eqs. (2.3) and (2.4) together with the initial conditions and the fact that for the atmosphere, as a rule, $n_{oi} \gg n_{ri}$ that

$$\frac{\sin\theta_i}{\sin\theta_{i-1}} = \frac{n_{0,\,i-1}}{n_{0i}} + \frac{1}{n_{0i}}\left[n_{\text{ex},\,i-1} - \frac{n_{0,\,i-1}}{n_{0i}}\,n_{\text{ex},\,i}\right]\times$$

$$\times\left\{1 - e^{-(t-t_0)/T_2}\left[\cos[\Delta(t-t_0)] + \sin[\Delta(t-t_0)]/\Delta T_2\right]\right\}, \quad (3)$$

where t_0 is the time of arrival of the pulse at the boundary between the layers, $n_{\text{ex},\,i}$ is the value of the resonant part of the refractive index of the medium in the ith layer exposed to the monochromatic radiation.

Since for the model atmosphere $n_{0,\,i-1}/n_{0i} - 1 \ll 1$, it follows from Eq. (3) that changes of the refraction angle caused by the resonantly absorbing gas are symmetric with respect to the detuning of the incident radiation from resonance and change sign for the backward propagation. In addition, the refraction angle undergoes temporal variations at the start of interaction for $t \lesssim T_2$ as a result of the time delay of the response of the resonant system.

With further propagation of the wave through the homogeneous layer, the refraction angle changes as a function of time, resulting in a time–dependent angular divergence of the beam. However, because of the small value of the resonant refraction,[2] we may continue to consider the optical wave to be quasiplanar, and the most important consequence of this phenomenon is phase modulation of the wave according to Eq. (2.2). The resulting pulse frequency shift can be great in this case since $K_i{\cdot}h \gg 1$.

RESULTS OF NUMERICAL COMPUTATIONS

The analysis of system of equations (2) was performed numerically. The same approximation technique was used as in Ref. (3).

The optical pulse was modeled as a plane coherent wave whose shape upon entrance into the medium has the form

$$\varepsilon_c(0,\,t) = \begin{cases} [\sin(\pi t/\tau_p)]^q, & t\in[0,\,\tau_p]\ , \\ 0, & t > \tau_p\ . \end{cases}$$

Depending on the parameter q, the pulse shape varies from quasi–rectangular to quasi–Gaussian.

Results of the numerical calculations of $\varepsilon = \text{Re}\varepsilon_c$ with $\lambda = 1.315$ μm for the summer atmospheric models at mid–latitudes at incidence angle $\theta = 40°$ are presented below.

Figures 1 and 2 depict the deformation of the shape of the transmitted pulse as a function of direction of propagation and the parameters q and Δ. It can be seen that the deformation is determined mainly by the direction of propagation: noticeable stochasticity of the pulse shape occurs for downward propagation and disappears for upward propagation. Figures 1 and 2 also show that the energy of the transmitted pulse is a function of the direction of propagation (see also Table I). The above indicated dependence is due to the deviation of the carrier frequency under conditions of resonant refraction. In addition, in one case the pulse frequency shifts mainly toward the line center, and in the other for the reverse direction of propagation it shifts toward the wing of the absorption line.

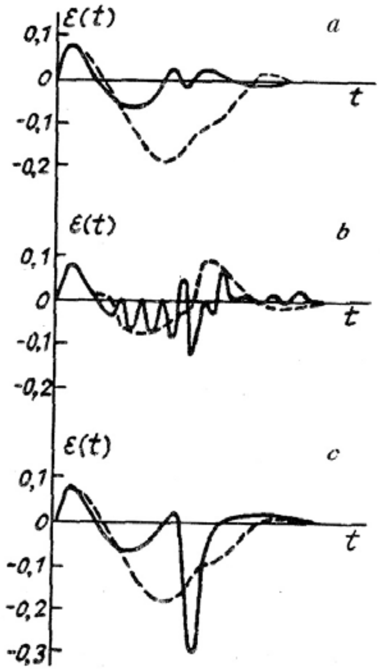

FIG. 1. Dependence of the optical pulse shape on the direction of propagation: the solid curve plots the results for downward propagation and the dashed curve – for the upward propagation for $q = 1$, $\tau_p = 30$ cm, *and* $\Delta = 0.1$ *(a)*, 0 *(b)*, *and* -0.1 *(c)* cm^{-1}.

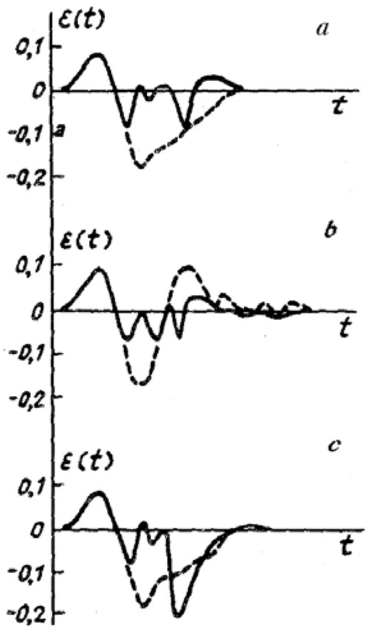

FIG. 2. Dependence of the optical pulse shape on the direction of propagation: the solid curve plots the results for downward propagation and the dashed curve – for upward propagation for $q = 4$, $\tau_p = 30$ cm, *and* $\Delta = 0.1$ *(a)*, 0 *(b)*, *and* -0.1 *(c)* cm^{-1}.

TABLE I. The transmitted optical pulse energy scaled to its initial value during propagation of the beam through the resonantly absorbing atmosphere.

Direction of propagation	Δ, cm^{-1}			τ_p, cm	q
	0.1	−0.1	0		
Upward	0.0796	0.0760	0.0317	30	4
	0.0609	0.0561	0.0094	30	1
	0.5949	0.5966	0.5935	3	1
	0.0191	0.0148	$3.62\cdot10^{-5}$	100	1
Downward	0.0164	0.0411	0.0227	30	4
	0.0083	0.0284	0.0130	30	1
	0.5856	0.5911	0.5863	3	1
	0.0139	0.0098	$4.15\cdot10^{-5}$	100	1

It should be noted that the representation of Eq. (2) in the form of a Fourier integral makes it impossible to take into account the fact that the frequency shift due to resonant refraction and in this case the pulse energy is independent of the direction of propagation.[4]

The asymmetric character of the changes of sign of the detuning as well as a dependence of the pulse parameters on the direction of propagation for null detuning are associated with the absorption lineshift in the band center due to air pressure. Numerical calculations performed neglecting this factor confirm this conclusion.

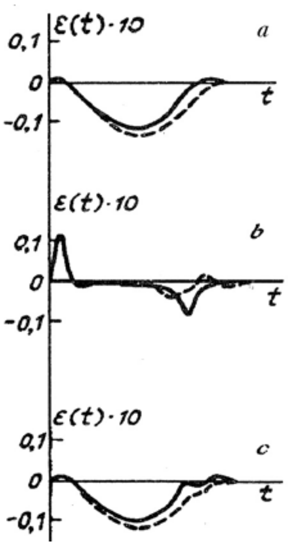

FIG. 3. Deformation of pulse shape in a resonantly absorbing atmosphere: the solid curve shows downward propagation and the dashed curve – upward propagation for $q = 1$, $\tau_p = 100$ cm, *and* $\Delta = 0.1$ *(a),* 0 *(b), and* −0.1 *(c)* cm^{-1}.

As was mentioned in Ref. 3, nonstationary pulse deformations in beams under conditions of resonant absorption along horizontal paths are significant for $\mu \sim 1$. Figures 3 and 4 and Table I show the same conclusion is valid for slant paths, in which the resonant refraction is added to the resonant absorption. In addition, if the duration of the pulse decreases to such an extent that $\mu \gg 1$, the dependence of the shape and energy parameters of the pulse on the detuning and, therefore, on the lineshift in the band center due to air pressure disappear (see also Ref. 4).

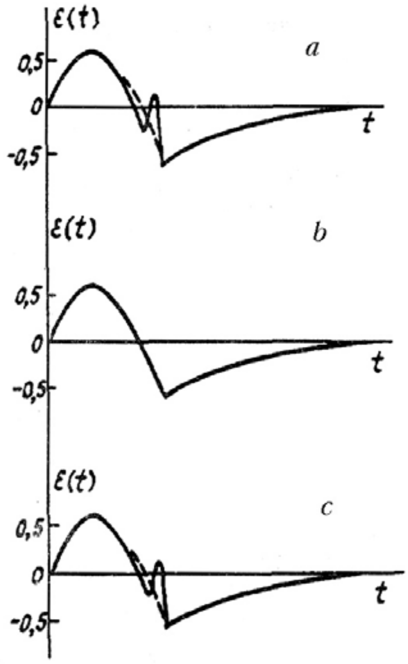

FIG. 4. Deformation of pulse shape in a resonantly absorbing atmosphere: the solid curve shows downward propagation and the dashed curve — upward propagation for $q = 1$ $\tau_p = 3$ cm, *and* $\Delta = 0.1$ *(a),* 0 *(b), and* −0.1 *(c)* cm^{-1}.

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