EFFECT OF SPATIAL VARIATIONS OF A RELAXATION MATRIX ON TRANSMITTANCE OF THE MOLECULAR ATMOSPHERE

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The resonant transmittance of media is analyzed for the case in which the relaxation matrix of the medium (determining, in particular, the width and the central frequency of absorption line) varies along a propagation path. Conditions are found under which spatial variations of the relaxation matrix cause a dependence of the transmittance of the medium on the radiation propagation direction, for example, as it changes to opposite one. Applied importance of this effect is briefly discussed.

INTRODUCTION

The relaxation matrix, characterizing the broadening of a line corresponding to a resonant transition and line frequency shift, typically varies along the propagation path in the atmosphere. This raises the question about the manner in which such variations influence the absorption of a propagating radiation.

Obviously, spatial variations of the relaxation matrix primarily cause changes of the local absorption coefficient, so that atmospheric transmittance along both vertical and slant paths differs from that along the horizontal paths. Estimates of pressure–induced shifts of absorption lines may be found in Refs. 1 and 2, while Ref. 3 estimates the changes in atmospheric transmittance along a horizontal path vs. its altitude.

However, in this case finer effects may take place. For example, numerical simulation of optical pulsed radiation propagation through the atmosphere has demonstrated that atmospheric transmittance along a slant path may significantly change for opposite propagation direction.[4]

The present paper studies the conditions under which the dependence of the transmittance of a medium on the propagation direction will be caused by the spatial variations of the relaxation matrix of the medium.

SETTING UP THE PROBLEM

We used a two–layer model of an inhomogeneous gaseous medium with the parameters typical of gaseous mixtures under normal atmospheric conditions. It has been found expedient to use this model due to the fact that, because of its simplicity, the possibility exists not only to establish the effect, but also to analyze the relative contributions of different factors to it.

The corresponding propagation problem was described by a system of modified Maxwell–Bloch equations (MMBE) for a quasi–plane wave, which has the following form for the jth layer of the medium:

$$\left[\cos\theta_j \frac{\partial}{\partial z} + \frac{n_0}{c}\frac{\partial}{\partial t}\right] E = 2\pi\, i\, k\, N_j\, \mu\, P\ , \qquad (1a)$$

$$\frac{\partial P}{\partial t} = -\,\gamma_j\, P + i\, w\, E\ , \qquad (1b)$$

$$\frac{\partial w}{\partial t} = -\,\mathrm{Im}(E\, P^*) - \frac{w - w^e}{T_1}\ , \qquad (1c)$$

$$\psi_j = \psi_{j-1} + \omega\, t - K_j\, z\ , \qquad (1d)$$

$$[n_{0,\,j-1} + n_{\mathrm{r},\,j-1}]\,\sin\theta_{j-1} = [n_{0j} + n_{\mathrm{r}j}]\,\sin\theta_j\ , \qquad (1e)$$

where E is the complex amplitude of a pulse, ψ_j is its phase, P is the complex amplitude of polarization of the medium, θ_j is the angle between the wave propagation direction and the normal to the interface between the layers, z is the running coordinate along this normal, n_0 is the nonresonance part of the refractive index of the medium, N_j is the number density of resonance molecules, $\gamma_j = 1/T_{2j} - i\,(\Delta_j - z\partial K_j/\partial t)$, $K_j = kn_0/\cos\theta_j$, T_{2j} is the phase memory time of the medium, Δ_j is the detuning of the pulse frequency from resonance, $k = \omega/c$, μ is the dipole moment of transition, T_1 is the population relaxation time, w is the level population difference of resonant transition (w^e is its equilibrium value), and $n_{\mathrm{r}j}$ is the resonance part of the refractive index of the medium.

The last equation in system (1) is a generalization of Snell's law for media with resonant constituent. MMBE differs from the standard system of equations[5] in that it considers the inhomogeneities of the medium.

The initial pulse shape is described by the function

$$E(0,\, t) = [\sin(\pi\, t\, /\, \tau_{\mathrm{p}})]^q, \quad t \in [0,\, \tau_{\mathrm{p}}]\ ,$$
$$E(0,\, t) = 0, \quad t \notin [0,\, \tau_{\mathrm{p}}]\ .$$

Initial pulse shape varied from quasi–rectangular to quasi–Gaussian depending on the value of the parameter q.

RESULTS

1. Normal propagation

Calculations for normal incidence of optical radiation on a medium have shown that spatial variations in the parameter of nonlinearity of interaction (Rabi frequency or saturation intensity) cause the dependence of transmittance on propagation direction. In the atmosphere, spatial variations in the nonlinearity parameters may be caused by pressure–induced shift of the absorption line as well as by line width changes.

Figure 1 shows the results of calculation of the ratio of energies of two identical quasi–Gaussian pulses after passage of a two–layer medium in the forward (W_+) and backward (W_-) directions. Our calculations were carried out for spatially uniform distribution of resonantly absorbing gas concentration. However, the frequency of resonant transition changed from layer to layer. Figure 2 shows the calculational results for the case in which the collisional width of the absorption line γ undergoes analogous variations.

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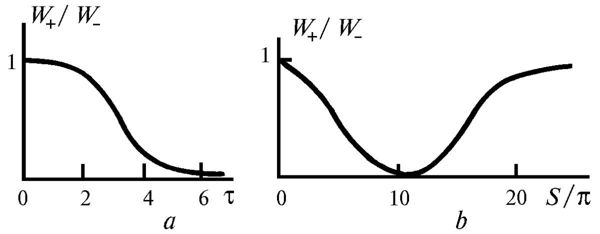

FIG.1. Ratio W_+/W_- vs. optical depths of the layers of a medium $\tau_1 = \tau_2 = \tau$ and pulse area S. Calculations were conducted at $\theta = 0$ with $\Delta_1 = 1/T_2$, $\Delta_2 = 0$, $T_2/\tau_p = 0.03$, and $S = 12\pi$ (a); $\tau = 5$ (b).

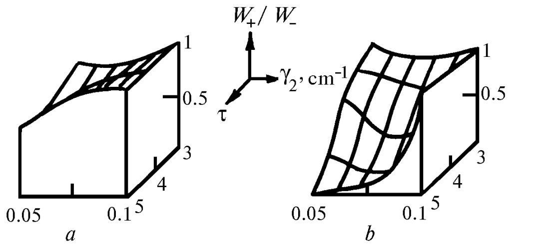

FIG. 2. Ratio W_+/W_- vs. optical depths of the layers of a medium $\tau_1 = \tau_2 = \tau$ and absorption line half–widths γ_1 and γ_2. Calculations were conducted at $\theta = 0$ with $\Delta_1 = \Delta_2 = 0$, $\gamma_1 = 0.1$ cm^{-1}, $T_2/\tau_p = 0.3$, and $S = 2\pi$ (a); $T_2/\tau_p = 0.03$ and $S = 12\pi$ (b).

2. Slant propagation

Nonstationary refraction in the spectral region of abnormal dispersion of a medium provides an additional factor that causes the dependence of the transmittance of a stratified inhomogeneous medium on the propagation direction in the case of slant incidence of radiation on this medium.

Nonstationary refraction takes place in an inhomogeneous resonant medium when the pulse duration is comparable to the phase memory time of the medium. Such refraction is caused by temporal variations of n_r (for a detailed description of the mechanism, see Ref. 4). One of the reasons causing the spatial inhomogeneity of n_r is the absorption line shift due to, e.g., the variations in the air pressure along the propagation path.

We estimated such dependences for a two–layer gaseous medium, in which its molecular number density remained constant, while its resonance frequency changed (see Fig. 3*a*). Apparently, as the radiation intensity increases, the dependence of the transmittance of the medium on the propagation direction becomes stronger due to the effects described in the previous section.

Of special interest is the case in which both molecular number density and resonant transition frequency of a resonantly absorbing gas undergo spatial variations. As this takes place, a situation may arise in which the change of absorption due to spatial variations of the molecular number density will be either partially or completely compensated by variations of the transition frequency. In this case, the local absorption coefficient would remain constant, as for the homogeneous propagation path, which it is not. Apparently, such an inhomogeneity cannot be detected in the general case of linear stationary interaction. As calculations indicate (see Fig. 3*b*), the effects described above result in $W_+/W_- \neq 1$. This points to the fact that the medium is inhomogeneous.

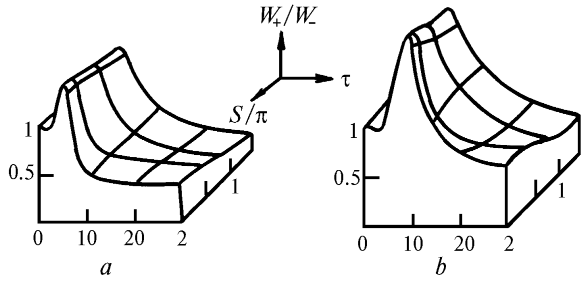

FIG. 3. Ratio W_+/W_- vs. optical depths of the layers of a medium and pulse area S. Calculations were conducted at $\theta = 40°$ for $\Delta_1 = 1/T_2$ and $\Delta_2 = 0$; $\tau_1 = \tau_2 = \tau$ (a); $\tau_1 = \tau_2$ and $\tau_2 = \tau/2$ (b).

CONCLUSIONS

The above results show that for optical pulsed radiation propagation through inhomogeneous resonant media, such as the atmosphere, the total transmittance may depend on the propagation direction. One reason for such a dependence is spatial variations of the relaxation matrix of a medium.

Apparently, this effect may introduce additional systematic error into a solution of the inverse problem of optical sounding of the atmosphere. However, as shown above, the same effect may yield additional data on the parameters of an inhomogeneous resonant medium, more comprehensive than those retrieved from stationary linear interaction.

Note also that the above results give an insight into the general patterns of transmission of optical pulses through the inhomogeneous molecular atmosphere, since the total atmospheric transmission may be calculated sequentially for the two–layer models with corresponding adjustment of their parameters.

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