Propagation of Ti:sapphire laser pulses along horizontal and slant atmospheric paths

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Radiation extinction and variations of spectral characteristics of femtosecond Ti:sapphire laser pulses are estimated for the case of propagation along horizontal and slant atmospheric paths. In the calculations we took into account the interaction between radiation and atmospheric water vapor.

Introduction

Femtosecond lasers emit radiation with bandwidth comparable to the carrier frequency and reaching several hundreds reciprocal centimeters. The exceptional properties of multimode radiation of stable femtosecond lasers have motivated an interest in them as sources of radiation in various problems connected with the determination of atmospheric parameters.

In this paper we consider propagation of a pulse emitted by a femtosecond Ti:sapphire laser operating in the spectral range 730–980 nm. The cases of horizontal and slant atmospheric paths are considered, and the interaction of laser radiation with atmospheric H_2O is taken into account.

Parameters of laser radiation and characteristics of the atmospheric absorption spectrum

Selective absorption of radiation by molecules of atmospheric gases is among the main processes accompanying propagation of radiation of such spectral composition through the atmosphere.

The spectrum of Ti:sapphire laser radiation falls on the rather strong water vapor absorption bands. Figure 1 shows the atmospheric absorption spectrum synthesized using data from the HITRAN database[1,2] for the surface atmospheric layer and the laser radiation spectrum.

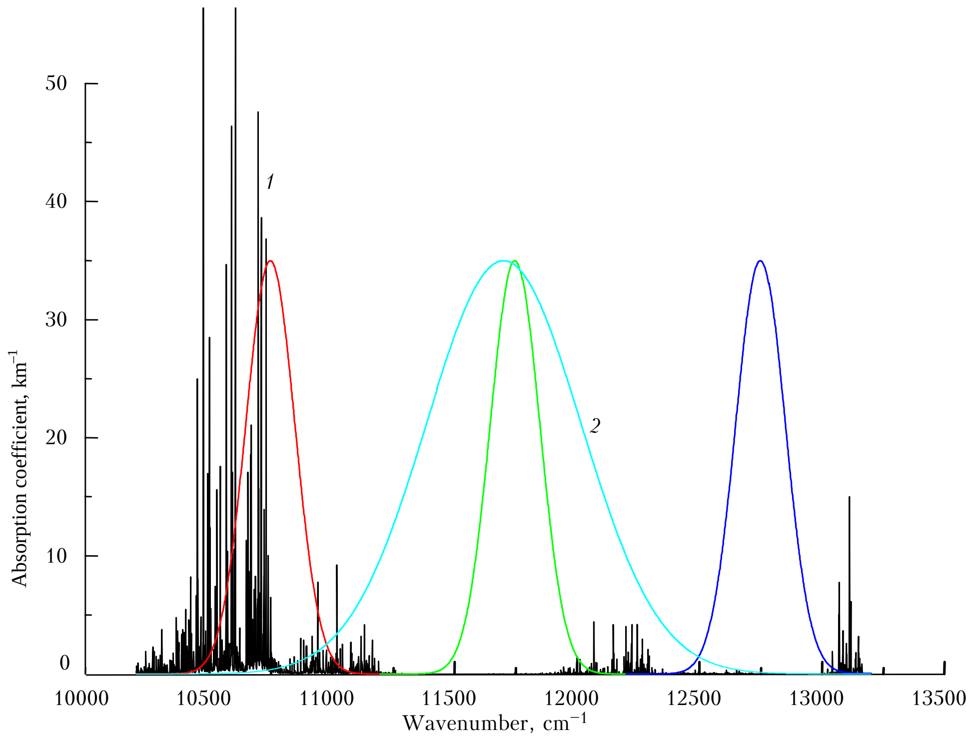

Fig. 1. Atmospheric absorption spectrum (*1*) and envelope of a laser pulse (*2*).

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The molecular absorption coefficients were calculated by the line-by-line method.[3] The temperature, pressure, and concentrations of gases corresponded to the mid-latitude summer model.

About 4000 spectral lines were included in our calculations.

The initial shape of the laser pulse envelope is described by a Gaussian distribution with carrier frequency ν_c. This condition corresponds to the description of the Femtis Ti:sapphire laser with a pulse duration of 50–200 fs and intermode interval determined by the length of the laser cavity.

Calculation of atmospheric transmittance

In our calculations, the atmosphere was modeled as a spherical stratified medium, whose parameters varied according to standard models of the atmosphere.[4]

For low-power femtosecond laser radiation, we can assume that a distinct mode structure is preserved in the laser spectrum. In this case, the transmittance of the atmospheric path for multifrequency radiation with allowance for absorption lines of the gases taken into account that fall within the laser spectrum is given by the following equation[5]:

$$T = \sum_{i=1}^{n} I_i \exp\left\{-\int_0^L \alpha_i[h(l)]\,\mathrm{d}l\right\} \Big/ \sum_{i=1}^{n} I_i \,; \qquad (1)$$

$$h(l) = \sqrt{(R+z_1)^2 + l^2 + 2\,l\,(R+z_1)\sin\theta} - R\,, \qquad (2)$$

where I_i is the radiation intensity in the ith mode; L is the path length; θ is the zenith angle of the path; z_1 is the altitude of the laser source; R is the Earth's radius (R = 6380 km); and $\alpha_i[h(l)]$ is the coefficient of molecular absorption at the altitude h, in km^{-1}.

In the derivation of Eq. (2), we ignored atmospheric refraction. For a planar stratified medium, the relative change of the path length can be estimated as

$$\delta L / L \approx (n_0 - 1)\tan^2\theta, \qquad (3)$$

where n_0 is the refractive index in the surface atmospheric layer.

The calculated transmittance for different models of the laser spectrum is given in the Table (the position of the central frequency and the spectral width were varied). The difference between these models is illustrated in Fig. 1.

Estimates of variation of laser pulse shape

Linear absorption in the atmosphere is described by the system of equations:

$$\frac{\partial}{\partial l} E = 2\pi i k \sum_{i=1}^{n} N_i\,\mu_i P_i\,; \qquad (4)$$

$$\frac{\partial P_i}{\partial \eta} = -\gamma_i\, P_i + i\delta_i\, \omega^{\mathrm{e}} E\,, \qquad (5)$$

where E is the complex amplitude of the optical pulse; P is the complex amplitude of polarization of the medium; N is the concentration of the resonant gas; $\eta = (t - l/c)$, t is time, c is the speed of light; $\gamma_i = 1/T_{2i} - i\Delta\omega$, T_2 is the phase relaxation time, $\Delta\omega$ is the detuning from resonance; $\delta_i = 2\mu_i/h$, μ_i is the dipole moment of the ith transition; and ω^{e} is the population difference between transition levels.

Using the Fourier transformation, we obtain the final equation in the form

$$E(\eta, z) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} E(0, \nu) \times$$

$$\times \exp \sum_{j=1}^{n} \frac{\tau_j\,[1 + i(\Delta\omega_j\,T_{2j} - \nu\,T_{2j})]}{2\,[1 + (\Delta\omega_j\,T_{2j} - \nu\,T_{2j})^2]} \exp(i\nu\eta)\,\mathrm{d}\nu, \qquad (6)$$

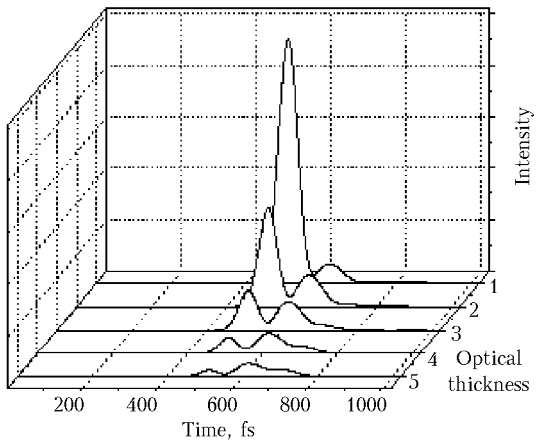
where n is the number of lines taken into account and τ_j is the optical thickness of the atmosphere at the jth absorption line.

Table. Models and calculated results

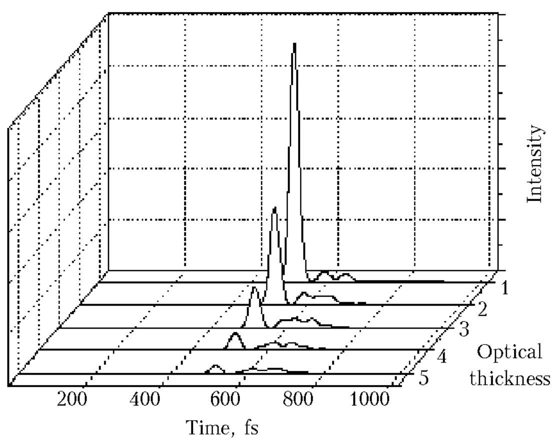
Lasing region, cm^{-1}	Horizontal paths, km		Slant paths					
	1	10	h_1, km^{-1}	h_2, km^{-1}	θ = 0°	θ = 30°	θ = 60°	θ = 80°
10200 – 13200	0.952	0.832	0	10	0.930	0.923	0.897	0.830
			10	20	0.999	1	0.999	0.997
			10	50	1	1	0.999	0.997
			20	50	0.997	0.997	0.997	0.997
10200 – 11200	0.610	0.204	0	10	0.505	0.479	0.377	0.205
			10	20	0.993	0.992	0.998	0.972
			10	50	0.993	0.992	0.987	0.972
			20	50	0.972	0.972	0.972	0.972
11200 – 12200	0.991	0.953	0	10	0.986	0.984	0.976	0.950
			10	20	1	1	1	1
			20	50	1	1	1	1
12200 – 13200	0.990	0.931	0	10	0.981	0.978	0.966	0.926
			10	20	1	1	1	1
			10	50	1	1	1	1
			20	50	1	1	1	1

N o t e . h_1 and h_2 are altitudes; θ is the zenith angle of the path. The intermode interval was set equal to 0.01 cm^{-1}.

The transformation of a laser pulse as it propagates in a gaseous medium, calculated with allowance for the 400 strongest absorption lines, is depicted in Fig. 2.



a



b

Fig. 2. Change in the shape of a laser pulse as it propagates through a gaseous medium. The initial pulse durations were 200 (*a*) and 50 fs (*b*).

Conclusions

It has been shown that if a narrower femtosecond laser spectrum is used in the calculations, varying the position of the central frequency causes the transmittance to vary where the difference in the transmittance values can reach 25% (for a 1-km long horizontal path).

As a short laser pulse with initial shape described by a Gaussian distribution propagates through the atmosphere, it undergoes a transformation. The speed and character of this process depend, in particular, on the initial duration of the pulse.

Extinction of femtosecond laser radiation is much stronger when the pulse propagates along horizontal paths.

Acknowledgments

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