Ecologically safe regimes of generation and maintenance of artificial ionized regions in the stratosphere by microwave radiation

A. A. Matveyev[1] and V. P. Silakov[2]
[1]High-Voltage Research Center of the All-Russian Electrotechnical Institute, 143500, Istra-2, Moscow Region, Russia
[2]M. V. Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences, Miusskaya Square, 4, Moscow 125047, Russia
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A mathematical model of the artificial ionized region created in the atmosphere in the intersection zone of two beams of powerful coherent TE microwaves is presented. The model is based on the solution of the nonstationary system of Maxwell equations and kinetic Boltzmann equation for electrons, as well as on a vast ramified kinetic scheme of plasma chemical processes in humid air. In the framework of such a model, it is possible to calculate, in a correct and self-consistent way, the electrodynamic and kinetic characteristics of the artificial ionized regions (AIR) created in air at various altitudes. The calculations conducted for the stratosphere had revealed the possibility of realization at great altitudes (~55 km) of the regimes of the AIR prolonged maintenance that simultaneously have the following advantages: they require the minimum energy expenditures, ensure good radio-reflecting properties of the plasma structure and do not lead even to local degradation of the ozone layer. Modeling of the kinetic and photochemical processes proceeding at the post-discharge stage had shown that the destructive action of the NO_x molecules produced in the discharge on the stratospheric ozone is substantially limited by their diffusive transport beyond the AIR boundaries. Production of excess active hydrogen radicals HO_x in the discharge does not exert any essential influence on ozone due to fast proceeding of the reactions of their mutual binding. [S1063-651X(96)06509-9]

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I. INTRODUCTION

The rapid advancement of the techniques of the generation of powerful microwave radiation has given rise to new ideas connected with handling a number of urgent problems in energetics, radio communication, quantum electronics, plasma chemistry, etc.. Among them is the idea of creating artificial ionized regions (AIRs) in the terrestrial atmosphere for the purpose of retransmitting radio waves over long distances [1]. The results of concrete examination of this proposal were presented in [2]. According to the project, the AIR should be created and maintained at an altitude of 30–60 km in the intersection area of the pulsed-recurring beams of electromagnetic waves in high frequency (hf) or microwave range generated by ground antennas. However, Askaryan *et al.* [3] had raised a warning, based on the results of laboratory modeling, that the AIR may turn out to be an intense source of nitrogen oxides, giving rise to a local degradation of the ozone layer. According to [4,5], the high yield of nitrogen oxides obtained by Askaryan *et al.* is connected with the fact that conditions of the laboratory experiment in [3] differ essentially from the proposed conditions of the discharge ignition in the stratosphere in gas density, the value of a specific energy deposit, etc.. Kinetic calculations performed in [4,5] had enabled the authors of these works to come to a conclusion about ecological admissibility of the regimes of exciting and maintaining the AIR in the stratosphere that were proposed and discussed in [2].

However, as it was shown later [6–8], description of the discharge was carried out in [4,5] in the framework of incomplete kinetic schemes. In particular, dominant channels of oxygen atoms formation

$$N_2(Y)+O_2\rightarrow N_2(X)+O+O,$$

$$Y=A\ ^3\Sigma_u^+,\ B\ ^3\Pi_g,\ W\ ^3\Delta_u,\ B'\ ^3\Sigma_u^-,\ a'\ ^1\Sigma_u^-,$$

$$a\ ^1\Pi_g,\ w\ ^1\Delta_u,\ C\ ^3\Pi_u,\ E\ ^3\Sigma_g^+,\ a''\ ^1\Sigma_g^+,$$

were not taken into account. The work [5] had ignored even processes of dissociation of the N_2 and O_2 molecules by direct electron impact. This led to significant understating of the calculated concentration of nitrogen oxides forming in the reactions

$$N(Y)+O_2(X)\rightarrow NO+O,\quad Y={}^4S,{}^2D,{}^2P,$$

$$N_2(A\ ^3\Sigma_u^+)+O\rightarrow NO+N(^2D),$$

$$N_2(A\ ^3\Sigma_u^+)+O_2\rightarrow N_2O+O.$$

Moreover, in the model by Milikh the role of the only considered source of the N and O atoms—reactions of dissociative recombination of electrons with the N_2^+ and O_2^+ ions—is essentially overestimated, since the model neglects fast processes of complex ions formation.

The indicated drawbacks of the works [4,5] call into question the general conclusion on a weak influence of the artificial plasma mirrors on the stratospheric ozone made therein. Thus the solution of the question on the existence of the ecologically safe regimes of prolonged maintenance of such mirrors by electromagnetic radiation requires a complete and self-consistent consideration of nonequilibrium plasma chemical processes in the discharge. The stated requirement had been taken into account in our previous paper [9]. The search of the conditions of realizing the AIRs had been conducted there in the framework of the ramified ki-

netic scheme of nonequilibrium discharge in air (see [10]). In doing so, the maintenance of the artificial plasma structures was conditioned by pulse-recurring exposure to intersecting microwave beams. It had been shown that the realization of a steady plasma mirror with good reflecting characteristics, at the least energy expenditures of microwave radiation sources and the minimum degradation of the ozone component of air resulting from nitrogen oxides production in the discharge area is possible only at great altitudes of 50–60 km.

In spite of the results of the work [9], the question on the possibility of a prolonged maintenance of ecologically safe plasma mirrors even at great altitudes can not be treated as ultimately solved. Indeed, the presence of a noticeable admixture of water molecules in air may lead, according to estimates, to production of a great amount of the active radicals HO_x in the discharge. These radicals constitute a threat to the ozone component of air (see [11]), since they are able to destroy ozone, for instance, in the catalytic cycle

$$OH+O_3\rightarrow HO_2+O_2; \quad HO_2+O\rightarrow OH+O_2.$$

In this work the additional destroying influence of water admixtures on the stratospheric ozone according to the described scenario is taken into account in the framework of a reasonably complete kinetic scheme of nonequilibrium discharge in humid air (see below). In doing so, much attention is given to the correctness of modeling the nonstationary process of plasma interaction with the electromagnetic field of overlapping wave packets of the microwave beams. Besides, numerical modeling of the postdischarge kinetics of the gas is patterned so that it is possible to follow rather accurately the diffusive evolution of the ozone-destroying components, NO_x and HO_x.

II. THE BASIC EQUATIONS AND CONDITIONS DETERMINING THE SPATIOTEMPORAL STRUCTURE OF THE AIR

In this section we give (according to [2]) brief characteristics of the AIR structure, state the basic requirements to its maintenance regime, and present a derivation of the equations necessary for a correct numerical modeling of the AIR dynamics.

Plasma in the intersection area of two beams of coherent TE waves has a layered structure conditioned by interference phenomena. The layers are parallel to the bisector of the angle between the beams' axes and to the vector of the electric field strength. The distance between adjacent layers is equal to $\delta l_{(X)}=\lambda/(2\sin[\theta/2])$, where λ is the wavelength of the radiation generating the AIR and θ is the angle between the beams' axes. Depending on the concrete regime, rise of electronic concentration in the layers is limited either by kinetic processes of electron losses or by the phenomenon of the electric field decreasing in the area occupied by plasma.

To retain the reflecting capability of plasma during the interval between the pulses, electron concentration should not decrease essentially (during this interval the concentration may decrease no more than twice). If, according to [12], to consider plasma decay to be governed by recombination, we get an equation for the recurrence frequency

$$F\approx k_r n_{e(\max)}(x=0), \tag{1}$$

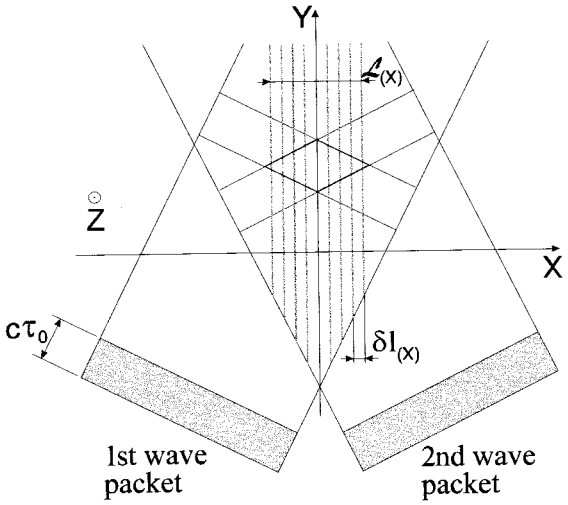

FIG. 1. The AIR structure in the case of short maintaining microwave pulses.

where k_r is an effective rate constant of electron-ion recombination, $n_{e(\max)}(x=0)$ is the maximum value of electron concentration on the bisector of the angle between the axes of the beams (X axis is perpendicular to the bisector and lies in the plane passing through the axes). Recombination decay of electron concentration must be replenished by ionization during the pulse, so

$$\nu_i(E(x=0))\tau_0\approx \ln 2 \tag{2}$$

(here τ_0 is the pulse duration, ν_i is electron-impact ionization frequency).

We shall restrict our consideration to the case of short maintaining pulses, when the length of the electromagnetic wave packet satisfies an inequality

$$c\tau_0 \ll 2R_0 \tan\frac{\theta}{2} \tag{3}$$

(R_0 is the radius of microwave beams in the region of their intersection). In this case the area of interference overlapping of two wave packets has a rhombic shape (Fig. 1), and the transverse size of the ionization area, $\mathcal{L}_{(X)}=c\tau_0/\sin(\theta/2)$, is much less than the transverse size of the beams' intersection area $L_{(X)}=2R_0/\cos(\theta/2)$. The interference zone of the electromagnetic pulses is propagating along the Y axis with a phase velocity

$$v_y=\frac{c}{\cos(\theta/2)}. \tag{4}$$

The duration of the joint action of wave packets at the point with the x coordinate is equal to

$$\tau(x)=\tau_0\left[1-\frac{2\sin(\theta/2)}{c\tau_0}|x|\right].$$

Note that the usage of short pulses requires high values of ionization frequency and, correspondingly, high values of the field amplitude in the beams E_a. However, in this case there is a possibility of breakdown in a single beam before its

intersection with another beam. To avoid this, the ionization frequency averaged over the period between pulses should not exceed the frequency of the three-particle attachment of thermal electrons to oxygen molecules:

$$\nu_i(E_a)\tau_0 F \leqslant \nu_a^{(3)}. \tag{5}$$

Another possibility of a free passage of radiation to the beams' intersection area is connected with a condition ensuring a sufficiently fast removal of electrons arising in a caustic of a single beam, by stratospheric wind (i.e., with the condition: $2R_0\nu_i(E_a) \ll v_h$; v_h is a horizontal component of the stratospheric wind speed). But it is necessary to take into account that in the beams' intersection zone the time of electron concentration rising from the background value to the maximum one should be much shorter than $2R_0/v_{(\mathrm{tr})}$. However, an analysis has shown a bad compatibility of the last requirement with the condition of a quick removal of electrons by the wind (indeed, due to a large length of the caustic, absorption and refraction of waves in each beam tell on the development of the discharge in the AIR even at low concentration of electrons arising in the caustic [13]). Hence, in what follows we suppose that regimes of the AIR maintenance satisfy condition (5).

Taking into account a relationship

$$\nu_i(E(0))\tau_0 F \approx k_r \overline{n_e}(0) + \nu_a^{(3)},$$

where $\overline{n_e}$ is electron concentration averaged over the period, condition (5) may be rewritten in the form

$$\frac{\nu_i(E_a)}{\nu_i(E(0))} < \frac{\nu_a^{(3)}}{k_r \overline{n_e}(0) + \nu_a^{(3)}}.$$

From the obtained relationship, an inequality follows:

$$\frac{\nu_i(E_a)}{\nu_i(2E_a)} < \frac{\nu_a^{(3)}}{k_r \overline{n_e}(0) + \nu_a^{(3)}},$$

that, at given levels of electron concentration, imposes an upper limit on the amplitude of electric fields in a microwave beam.

We are now coming to the derivation of the equations determining the AIR dynamics. The process of the interaction of the crossed TE beams with the plasma structure of the AIR is described by Maxwell's equations

$$\mathrm{rot}\mathbf{H} = \frac{4\pi}{c}\,\hat{\sigma}\mathbf{E} + \frac{1}{c}\frac{\partial}{\partial t}(\hat{\varepsilon}\mathbf{E}), \tag{6}$$

$$\mathrm{rot}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}, \tag{7}$$

and by the equation for electron concentration

$$\frac{\partial n_e}{\partial t} = J_e. \tag{8}$$

Here J_e is a symbol for electron source, $\hat{\sigma}$ and $\hat{\varepsilon}$ are operators of conductivity and dielectric permissivity of plasma, generally speaking, nonlocal in time. However, we shall consider below only such regimes of the AIR maintenance that the length of the wave packets is much greater than the wavelength of the electromagnetic radiation. Then the frequency spectrum of the electromagnetic field in the beams conditioned by a limitation of the wave packets is concentrated in a rather narrow region, so the operators $\hat{\sigma}$ and $\hat{\epsilon}$ may be approximately replaced by scalar coefficients corresponding to the main (carrier) frequency ω

$$\hat{\varepsilon}\mathbf{E} \to \varepsilon\mathbf{E} = \left(1 - \frac{n_e}{n_c}\right)\mathbf{E}, \quad \hat{\sigma}\mathbf{E} \to \sigma\mathbf{E} = \frac{\nu n_e}{4\pi n_c}\,\mathbf{E},$$

where $n_c = m(\omega^2 + \nu^2)/(4\pi e^2)$ is the critical concentration of electrons, ν is the electron-neutrals collisions frequency.

With the TE geometry, nonzero components of the electromagnetic field are the quantities $E_z \equiv E$, H_x and H_y. Then the field equations (6),(7) take the form

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = \frac{4\pi}{c}\,\sigma E + \frac{1}{c}\frac{\partial}{\partial t}(\varepsilon E), \tag{9}$$

$$\frac{\partial H_x}{\partial t} = -c\,\frac{\partial E}{\partial y}, \tag{10}$$

$$\frac{\partial H_y}{\partial t} = c\,\frac{\partial E}{\partial x}. \tag{11}$$

Since we are interested in solutions corresponding to the propagation of the area of the wave packets intersection along the Y axis with a constant velocity v_y (4), their dependency on the parameters y and t should be determined by a combination $y - v_y t$ that is tantamount, with the value of the y coordinate held fixed, to executing a replacement $\partial/\partial y \to -(1/v_y)/(\partial/\partial t)$ in Eqs. (9)–(11). Note that in the case being considered [when the inequality (3) takes place] it is possible to abstract from the effects connected with the limitation of the beams' radius. So, after the indicated replacement in Eqs. (9)–(11), we get a set of equations determining the evolution of the electromagnetic field in some fixed line $y = \mathrm{const}$

$$\frac{\partial}{\partial t}\left[\left(\sin^2(\theta/2) - \frac{n_e}{n_c}\right)E\right] = c\,\frac{\partial H_y}{\partial x} - 4\pi\sigma E, \tag{12}$$

$$\frac{\partial H_y}{\partial t} = c\,\frac{\partial E}{\partial x}, \tag{13}$$

$$H_x = E\,\cos\frac{\theta}{2}.$$

According to the physical sense, obtained field equations are destined for describing opposing propagation (along the line $y = \mathrm{const}$) of two quasipackets of waves with phase velocities of $v_x^{(1)} = c/\sin(\theta/2)$ and $v_x^{(2)} = -c/\sin(\theta/2)$. It is obvious that till the moment of the quasipackets entering the area occupied by plasma their amplitudes are constant and equal to E_a. Hence, the initial distribution of the field along the line $y = \mathrm{const}$ may be represented by relationships

$$E(t=0,x)=E_a\varphi\left((x+x_0)\sin\frac{\theta}{2}\right)\exp\left[-\frac{i\omega}{c}(x+x_0)\sin\frac{\theta}{2}\right]$$
$$+E_a\varphi\left((x-x_0)\sin\frac{\theta}{2}\right)\exp\left[\frac{i\omega}{c}(x-x_0)\sin\frac{\theta}{2}\right], \quad (14)$$

$$H_y(t=0,x)=-E_a\sin\frac{\theta}{2}\varphi\left((x+x_0)\sin\frac{\theta}{2}\right)$$
$$\times\exp\left[-\frac{i\omega}{c}(x+x_0)\sin\frac{\theta}{2}\right]$$
$$+E_a\sin\frac{\theta}{2}\varphi\left((x-x_0)\sin\frac{\theta}{2}\right)$$
$$\times\exp\left[\frac{i\omega}{c}(x-x_0)\sin\frac{\theta}{2}\right]. \quad (15)$$

Here the function $\varphi(x)$ describes the initial distribution of the field amplitude in quasipackets [in the case of severely rectangle pulse of the amplitude $\varphi(x)=\vartheta(x+[1/2]c\tau_0)\vartheta(-x+[1/2]c\tau_0)$], x_0 is an arbitrary constant defining the position of the quasipackets at the initial moment of time.

As estimates show, in the considered case of short pulses maintaining the AIR, the dynamics of electron concentration during the discharge [Eq. (8)] is completely determined by the ionization process

$$\frac{\partial n_e}{\partial t}=J_e\approx\nu_i n_e. \quad (16)$$

On the other hand, decay of electron concentration in the period between pulses is conditioned by the processes of electron-ion recombination and electron attachment to oxygen molecules. At great enough heights, (ambipolar) diffusion of charged particles may be of essential importance. In neglection of electron detachment from negative ions due to collisions with the atoms N and O as well as with excited particles (the case of low energy deposit into the gas), the equation for an electronic component in the periods between the maintenance pulses has the form

$$\frac{\partial n_e}{\partial t}=D_{\rm am}\frac{\partial^2 n_e}{\partial x^2}-\nu_a^{(3)}n_e-k_r n_+ n_e, \quad (17)$$

where $D_{\rm am}$ is the coefficient of ambipolar diffusion, n_+ is the concentration of positive ions. In the opposite case of high energy deposit, when electron attachment is compensated by detachment and decay of electron concentration, has a pure recombination character [12], we get

$$\frac{\partial n_e}{\partial t}=D_{\rm am}\frac{\partial^2 n_e}{\partial x^2}-k_r n_e^2. \quad (18)$$

It should be noted that the equation for electron concentration must also include a convective term conditioned by electron removal by stratospheric wind. However, for definiteness, we shall restrict our consideration to the case when the horizontal component of the stratospheric wind speed is directed along plasma layers. This case is the most profitable one for the purpose of obtaining the greatest electron concentration in the AIR, but at the same time it represents the greatest threat from the viewpoint of nitrogen oxides production.

III. OPTIMIZATION OF THE AIR MAINTENANCE REGIMES AS REGARDS ENERGY EXPENDITURES AND NITROGEN OXIDES PRODUCTION

One of the main requirements to the AIR is a minimization of the energy expenditures necessary for its maintenance. In the work [2] a minimization of energy expenditures was conducted for a single maintaining pulse per unit cross section of the microwave beam. However, of greater practical interest is a consideration of the total mean power in a single beam

$$W\approx\frac{cE_a^2}{8\pi}\pi R_0^2 F\tau_0.$$

According to [2] $R_0\approx 0.6\lambda h/(D_a\cos\varphi)$, where h is the altitude, D_a is the diameter of the ground antenna, φ is the angle between the beam's axis and the vertical. Taking into account the relationships (1) and (2), and using an approximate expression for the quantity $n_{e(\max)}$

$$n_{e(\max)}\approx 0.4 n_c\sin^2\left(\frac{\theta}{2}\right), \quad (19)$$

obtained in [2] for the conditions of electrodynamic saturation of electron concentration in the AIR, we get the following analytical expression for the total mean power in the beam:

$$W\approx 9\times 10^{-3}$$
$$\times\pi(\ln 2)\frac{mc^3}{e^2}\left[\frac{\sin(\theta/2)}{D_a\cos\varphi}\right]^2\frac{k_r\kappa^2}{k_i(\kappa)}Nh^2\left[\frac{\omega^2+\nu^2}{\omega\nu}\right]^2, \quad (20)$$

where

$$\kappa=\frac{2E_a}{N[2(1+\omega^2/\nu^2)]^{1/2}}, \quad k_i(\kappa)=\nu_i/N,$$

N is the density of neutral particles.

The minimization of the quantity W was conducted with respect to the parameter h at fixed values of the parameters ω and $2E_a/E_c$ (E_c is the critical breakdown amplitude of the electric field strength) defining the structure of the AIR. If to use the relationship (20), then, on the assumption that $k_r=\text{const}$ and $d(\ln\nu)/d(\ln h)\gg 1$, we get the condition of the minimum energy expenditures

$$\omega\approx\sqrt{3}\,\nu. \quad (21)$$

This condition is confirmed with reasonable accuracy by the results obtained on the basis of a more rigorous self-consistent calculation of the AIR structure. A comparison of condition (21) with the results of energy expenditures minimization derived in [2] for a single pulse and unit cross sec-

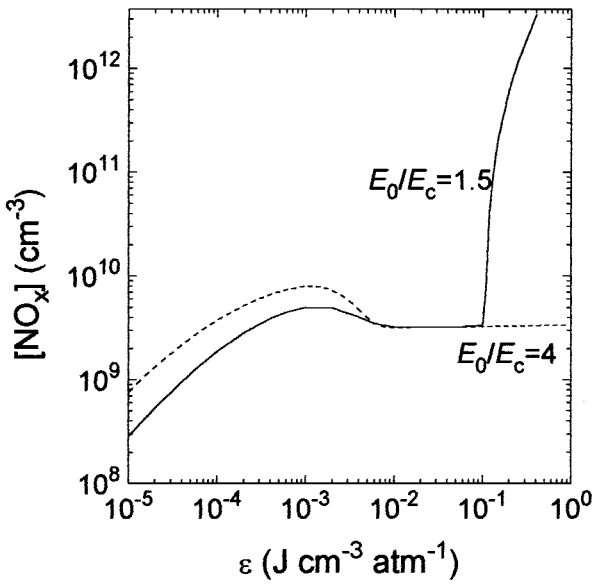

FIG. 2. The dependence of the NO_x molecules concentration on the specific energy deposit into the gas. $h=55$ km ($N=1.19\times10^{16}$ cm^{-3}, $T=264$ K), $\lambda=60$ cm.

tion of the microwave beam shows that the change in setting up the optimization problem had led to an increase of the optimal altitude of the AIR ignition by approximately 5 km.

In view of the threat to the ozone layer of the terrestrial atmosphere, which may arise from the prolonged maintenance of the AIR in the stratosphere [3,7,8], of actual interest are only those regimes of interaction of crossed beams of electromagnetic waves with plasma, in which the production of nitrogen oxides is comparable with their concentration under natural conditions. The possibility of the existence of such regimes is suggested by the characteristic dependencies of the $[NO_x]$ concentration on the specific energy deposit in the discharge plasma ε. Figure 2 shows the computed dependence $[NO_x](\epsilon)$ for a single-pulse regime, the altitude $h=55$ km, the wavelength $\lambda=60$ cm, and various values of the electric field amplitude. Calculations were performed on the basis of the kinetic scheme of a discharge in nitrogen-oxygen mixtures [10], with kinetic coefficients of electrons being determined by averaging rates of electron-neutral reactions over electronic energy distribution (the distribution function was found from a numerical solution of Boltzmann equation for electrons interacting with monochromatic microwave).

In the case of low energy deposit the production of the NO_x compounds in air results from the reactions of atomic nitrogen formed by electron-impact dissociation of the N_2 molecules, with oxygen [10]

$$N(^4S)+O_2\underset{k_1}{\rightarrow}NO+O,$$

$$k_1=4.5\times10^{-12}\times\exp(-3220/T)\ \frac{cm^3}{s}, \tag{22}$$

$$N(^2D)+O_2\underset{k_2}{\rightarrow}NO+O,\quad k_2=7.5\times10^{-12}\left(\frac{T}{300}\right)^{0.5}\frac{cm^3}{s}, \tag{23}$$

$$N(^2P)+O_2\underset{k_3}{\rightarrow}NO+O,\quad k_3=2.6\times10^{-12}\ \frac{cm^3}{s}. \tag{24}$$

Here T is the gas temperature in K. From the data presented it follows that the characteristic time of the reactions (23), (24) is much longer than that of the reaction (22). In energy deposit range $10^3\leqslant\varepsilon\leqslant10^{-1}$ J cm^{-3} atm^{-1} the NO production in reactions (22)–(24) is limited by the processes of odd nitrogen binding [10]

$$N(^4S)+NO\underset{k_4}{\rightarrow}N_2+O,\quad k_4=1.05\times10^{-12}\times T^{0.5}\ \frac{cm^3}{s}. \tag{25}$$

According to Slovetskii [14] dissociation of vibrationally unexcited N_2 molecules by electron impact at neutral particles density $N\gg10^{15}$ cm^{-3} gives rise to atoms $N(^1S)$ and $N(^2D,^2P)$ in approximately equal amounts. So, on completion of reactions (23) and (24), concentrations of the particles N and NO are about the same. An analysis of the set of reactions (22) and (25) shows, in this case the final concentration of nitrogen oxide is

$$[NO]_f=\frac{k_1}{k_4}[O_2].$$

The NO_x concentration rise takes place only at $\varepsilon>0.1$ J cm^{-3} atm^{-1} due to the activation of the reaction

$$N_2(A\,^3\Sigma_u^+)+O\rightarrow NO+N(^2D).$$

At even greater energy deposit the NO_x production cost decrease is conditioned also by gas heating and the reactions

$$N_2(X,v\geqslant12)+O\rightarrow NO+N.$$

However, in the regimes of gas irradiation interesting for us, the discharge parameters are such that the role of these latter channels in the process of nitrogen oxides production may be neglected.

Note also that the concentration $[NO_x]$ decreases as the electric field amplitude rises, with the energy deposit value being fixed (Fig. 2). This is conditioned by increasing the energy cost of production of the N and O atoms as well as electronically excited N_2 molecules.

From the data presented it follows that the AIR yields the least quantity of nitrogen oxides, if during the longest possible residence time of the gas particle in the discharge τ_m (the case of the horizontal component of the wind speed v_h being directed along plasma layers) the specific energy deposit in plasma ε_m does not exceed the value of 0.05-0.1 J cm^{-3} atm^{-1}.

In the framework of the effective field approximation the highest possible energy deposit in the discharge is determined by an equation

$$\varepsilon_m\approx\frac{N_L}{N}\frac{2R_0}{v_h}F\int_0^{\tau_0}0.5\sigma E^2dt$$

$$\approx\frac{1.2\times10^{-2}}{\pi}\frac{mcN_L}{e^2}\frac{h\,\sin^4(\theta/2)}{v_hD_a\cos\varphi}\frac{k_r\kappa^2}{k_i(\kappa)}\frac{(\omega^2+\nu^2)^2}{\omega\nu}.$$

In view of condition (21) the quantity ε_m is approximately proportional to ω^2. So the inequality $\varepsilon_m \leqslant 0.1$ J cm^{-3} atm^{-1}, under the condition of the optimal total energy expenditure, corresponds to an upper constraint on the value of the maintaining radiation frequency. In particular, at $2E_a/E_c=4$, $\theta=60°$, the antenna diameter of $D_a=100$ m, and the stratospheric wind speed of $v_h \approx 40$ m/s [15], we obtain: $\omega \leqslant 4\pi\times10^9$ s^{-1}, that, according to condition (21), corresponds to the altitude $h \geqslant 45$ km. Selection of the value of the $2E_a/E_c$ parameter had been dictated in this case by the condition of the absence of breakdown in a single beam (5).

IV. RESULTS OF MODELING THE AIR DYNAMICS AND ITS RADIO-REFLECTING PROPERTIES

For a number of the AIR maintenance regimes satisfying the optimization conditions obtained in the preceding section, a numerical modeling of the dynamics of the AIR structure formation had been carried out. In doing so, it was assumed that at the initial moment of time there was a small background concentration of electrons: $n_e(t=0, x)=n_{e0}\sim1$ cm^{-3}.

For each pulse, the process of interaction of two intersecting microwave packets with the AIR plasma structure was first modeled on the basis of Eqs. (12), (13), (16). Thereupon electron concentration decay during the interpulse spacing was calculated with the use of Eqs. (17) or (18). This procedure was repeated to the point of steady state.

Equations (12), (13) with the initial conditions (14), (15) were solved using the finite-difference time-domain (FDTD) method [16] with the Halpern-Thefethen second-order absorbing boundary conditions [17]. Grid step along the X axis δx was taken from the condition: $\lambda/(\delta x \sin[\theta/2])=40$. In order to decrease the effect of numerical dispersion of the method, forward and reverse fronts of the pulses were assumed to have a width $\sim\lambda/2$.

When determining ionization frequency ν_i entering Eq. (16), it is necessary to take into account that under conditions of short microwave pulses acting on the gas, the ratio of their duration τ_0 to the characteristic time between electron-neutral collisions is equal to 10–100, so the use of the method of expanding electron distribution function $f(\varepsilon,\theta,t)$ in terms of temporal harmonics [18,19] for the solution of the Boltzmann equation may lead to crude errors (here ε and θ are electron energy and the angle between its velocity and the electric field direction). Thus the calculation of kinetic coefficients of electrons should be conducted on the basis of the explicitly nonstationary Boltzmann equation. In the approximation of the two-term expansion of the function $f(\epsilon,\theta,t)$ over spherical harmonics, this equation reduces to the following system of equations:

$$\left(\frac{m\varepsilon}{2}\right)^{1/2}\frac{\partial f_0}{\partial t}=\frac{\partial}{\partial\varepsilon}\left[\frac{eE}{3}\,\varepsilon f_1+\sum_{j=\mathrm{N_2,O_2}}\frac{2m}{M_j}\,n_j\sigma_j^{\mathrm{tr}}(\varepsilon)\varepsilon^2\times\left(f_0+kT\,\frac{\partial f_0}{\partial\varepsilon}\right)\right]+I_{\mathrm{inel}}[f_0], \tag{26}$$

$$\left(\frac{m\varepsilon}{2}\right)^{1/2}\frac{\partial f_1}{\partial t}=eE\varepsilon\,\frac{\partial f_0}{\partial\varepsilon}-\varepsilon f_1\sum_{j=\mathrm{N_2,O_2}}n_j\sigma_j^{\mathrm{tr}}(\varepsilon), \tag{27}$$

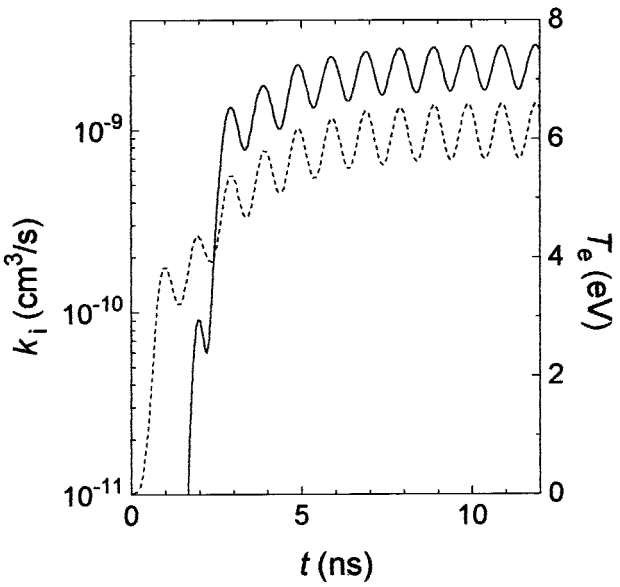

FIG. 3. Temporal dependency of the effective rate constant of ionization (solid line) and effective electron temperature (dashed line) at turning on oscillating electric field with amplitude of $E_0=140$ V/cm and frequency of $\omega=\pi\times10^9$ s^{-1} at the moment $t=0$. Density of neutral particles $N=1.19\times10^{16}$ cm^{-3}.

where $f_0(t,\varepsilon)$ and $f_1(t,\varepsilon)$ are symmetric and antisymmetric components of electron distribution function; n_j, M_j, and $\sigma_j^{\mathrm{tr}}(\varepsilon)$ are concentration, molecular mass, and transport cross section of electron scattering for the jth component of the gas; I_{inel} is the integral of inelastic collisions written with consideration for the processes of excitation of rotational, vibrational, and electronic degrees of freedom of the N_2 and O_2 molecules, ionization, and attachment.

Equations (26), (27) have to be solved in each node of the calculational grid along the X axis that requires impressive expenditures of computer time. However, a numerical analysis of the character of the establishment of the electronic kinetic coefficient $k_i=\nu_i/N$ in a single spatial point at turning on or changing oscillating field of various amplitude (see, for example, Figs. 3 and 4) had shown that the dynamics of changing the ionization rate constant k_i averaged over the period of field oscillations may be described with a high degree of accuracy almost in the whole temporal range by an equation of the relaxation type

$$\frac{\partial\overline{k_i}}{\partial t}=\frac{\alpha(\overline{k_i})^{1/2}}{1+\beta\overline{k_i}}(\overline{k_{\mathrm{eq}}}-\overline{k_i}), \tag{28}$$

where $\overline{k_{\mathrm{eq}}}$ is the established mean rate constant of ionization, the quantities α, β, and k_{eq} are, at given values of the parameters N and ω, functions of the field amplitude E_0. An exception is only the case when at the initial moment of time electrons are cold (i.e., $T_e\sim T$). In this case relationship (28) begins to hold after some time delay τ_d necessary for strong heating of electrons (when $T_e/T\gg1$) and formation of the ''tail'' of the distribution function $f_0(t,\varepsilon)$.

At $N\sim10^{16}$ cm^{-3}, $E_0/E_c=2$–4 the value of the τ_d amounts to ~1 ns. Note that at the points such that $|x|>c\tau_d/(2\sin[\theta/2])$ the indicated delay of turning on the

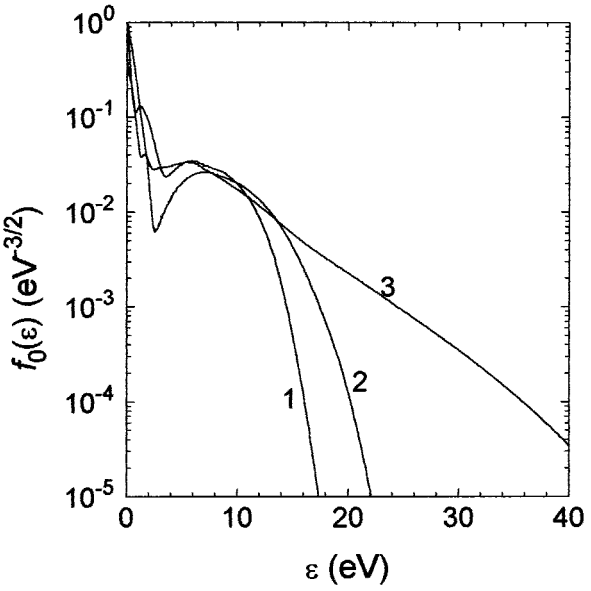

FIG. 4. Electron energy distribution function at the moments of time $t_1=1.6$ ns, $t_2=2.26$ ns, $t_3=6.25$ ns after turning on oscillating electric field. Conditions are the same as in Fig. 3.

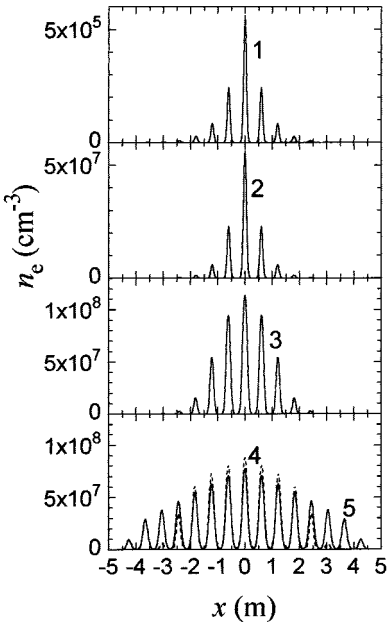

FIG. 5. Profiles of electron concentration in the AIR after passage of n microwave pulses ($n_1=25$, $n_2=35$, $n_3=45$, $n_4=70$, $n_5=200$). The discharge parameters: $\omega=\pi\times10^9$ s^{-1}, $2E_a=143$ V/cm, $\tau_0=25$ ns, $F^{-1}=7.2$ ms, $h=55$ km, $R_0=200$ m, $\theta=60°$.

ionization processes occurs in that period of time when overlapping of both wave packets in the specified point has not happened yet. At the same time a noticeable ionization is possible only as a result of an interference of the wave packets. Hence, the delay effect may exert any noticeable influence on the plasma dynamics only in the region $|x|<c\tau_d/(2\sin[\theta/2])$. On the other hand, in this region the duration of the joint action of the wave packets $\tau(x)\approx\tau_0\gg\tau_d$. Besides, the characteristic time of establishing the quasistationary frequency of ionization also essentially exceeds the quantity τ_d. So hereinafter the delay effect is not taken into account, and Eq. (28) is assumed to be valid in the whole calculational time interval.

Hence, Eq. (28) with the initial condition $\overline{k_i}\ (t=0)=0$ closes the set of Eqs. (12), (13), (16) describing an interaction of two intersecting wave packets with the AIR plasma structure. Solution of Eqs. (16), (18) with the pretabulated functions $\alpha(E_0)$, $\beta(E_0)$, and $k_{\rm eq}\ (E_0)$ had been conducted with the use of the fourth-order Runge-Kutta method.

Figures 5 and 6 present results of calculations for the following values of the wave discharge parameters: the altitude $h=55$ km ($N=1.19\times10^{16}$ cm^{-3}, $T=261$ K), $2E_a=143$ V/cm ($2E_a/E_c\approx4$), $\omega=\pi\times10^9$ s^{-1}, $\tau_0=25$ ns, $F^{-1}=7.2$ ms, $\theta=60°$. Figure 5 shows the profiles of electronic concentration at various moments of time. At the initial stage of the discharge the peripheral plasma layers are growing essentially slower than the central ones, since at the periphery the duration of the joint action of the wave packets is comparable with or even less than the characteristic time of the ionization frequency relaxation. At $t\sim0.3$ s concentration of electrons in the central layer of the AIR reaches a saturation. Later, as adjacent layers grow, the amplitude of the electric field in the AIR center falls down, which leads to some decrease of electronic concentration in the central layers. Finally, peripheral layers of the AIR reach saturation at $t>1.4$ s. Comparison of the calculations carried out for recombination and recombination-attachment mechanisms of electron concentration decay between pulses had revealed only slight differences.

The process of the interaction of crossed microwave beams with the AIR in the saturation state is represented graphically in Fig. 6, where spatial distributions of the quantities E_0 and k_i are shown for a number of time moments. When the wave packets enter the region occupied by plasma [Fig. 6(a)], electromagnetic waves begin to absorb and reflect, giving rise to oscillations on the profile of the field amplitude E_0. A characteristic interference structure is formed in the beams' intersection area [Figs. 6(b)–6(d)], with the maximum value of the field amplitude being substantially less than $2E_a$ due to partial absorption of waves in plasma. Once the wave packets have passed the AIR, their field amplitude amounts to ~50 V/cm that indicates 50% absorption of radiation by the AIR plasma. Forward and reverse fronts of the spatial distribution of the field amplitude in each quasipacket have become noticeably blurred [Figs. 6(c)–6(f)] due to reflection effects.

We now turn to an analysis of the radio-reflecting properties of the AIR. Assume that a low-intensity plane electromagnetic wave with a frequency of ω_1 is incident upon the plasma structure at an angle of θ_1. It is supposed that coherence length of the waves being reflected is much longer than the AIR sizes, so reflection from plasma layers bears a coherent character. Complex amplitude of the wave being reflected is described at $\lambda_1\ll R_0$ by an equation (see [2])

$$\frac{\partial^2 E_1}{\partial x^2}+k_1^2\left[\sin^2\theta_1-\frac{n_e}{n_{c1}}\left(1+\frac{i\nu_1}{\omega_1}\right)\right]E_1=0, \qquad (29)$$

with boundary conditions

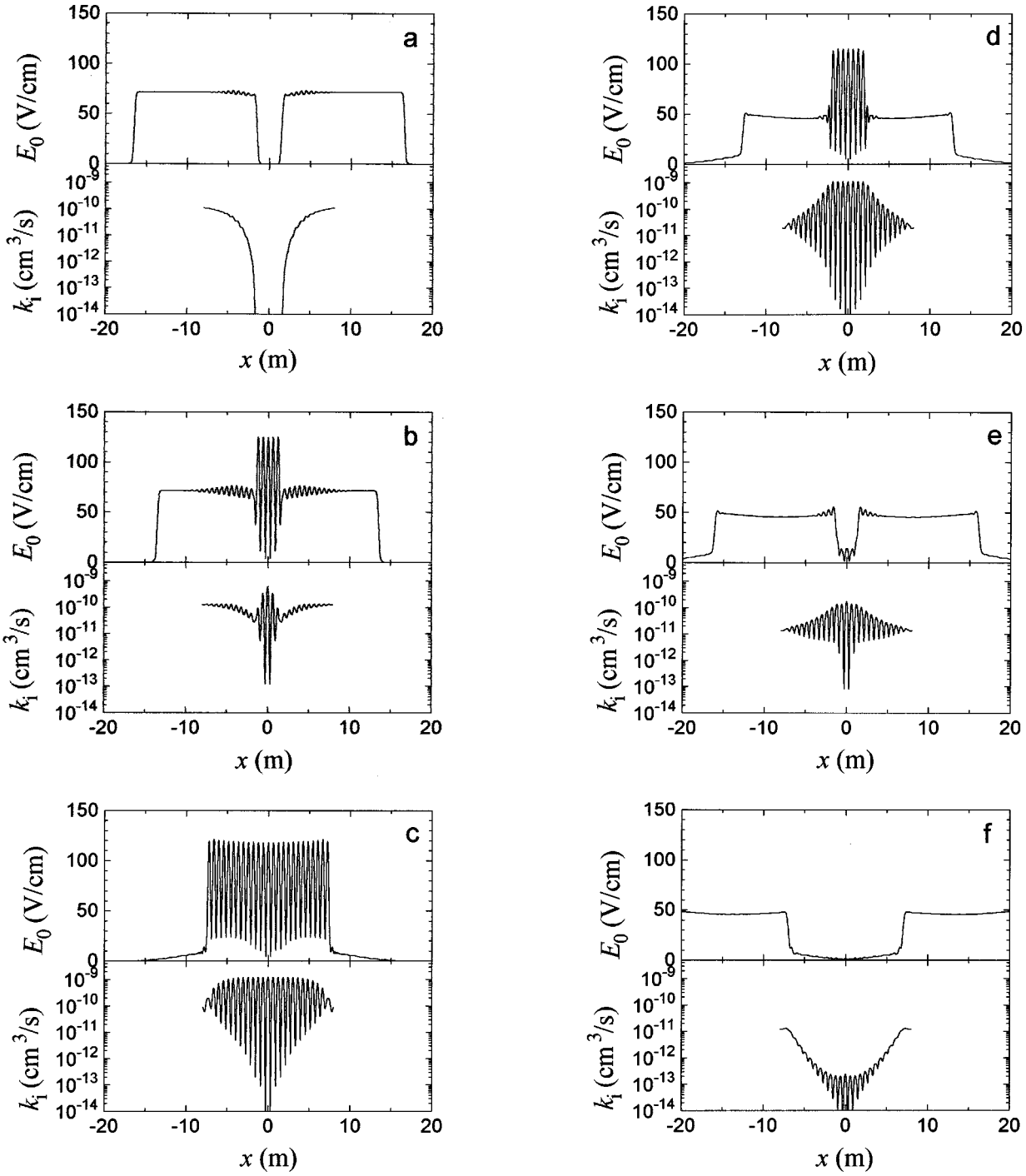

FIG. 6. Spatial distributions of the quantities E_0 and $\overline{k_i}$ at interaction of the microwave beams with the AIR in steady state. Time moments: t_a=11 ns, t_b=16 ns, t_c=26 ns, t_d=35 ns, t_e=40.5 ns, t_f=50 ns (the origin of time measure was selected arbitrarily).

$$\left[\frac{\partial E_1}{\partial x}-ik_1\sin\theta_1 E_1\right]_{x=-L}=-2ik_1E_r\sin\theta_1\exp(ik_1L\ \sin\ \theta_1),$$

$$\left[\frac{\partial E_1}{\partial x}+ik_1\sin\theta_1 E_1\right]_{x=L}=0,$$

where E_r is the amplitude of the incident wave. Equation (29) immediately follows from Eqs. (12) and (13) on the assumption that the quantities E and H_y are harmonic functions of time.

Since reflection from the AIR occurs mainly in the intervals between the pulses of maintaining radiation, the frequency of electron-neutral collisions ν_1 appearing in Eq. (29) should correspond to thermal electrons. This frequency is much lower than that for an electron in the field of a strong electromagnetic wave. According to [2] it may be approximated by an expression

$$\nu_1\approx 1.84\times 10^{-8}N\left(\frac{T}{1000}\right)^{5/6}\quad \mathrm{s}^{-1}.$$

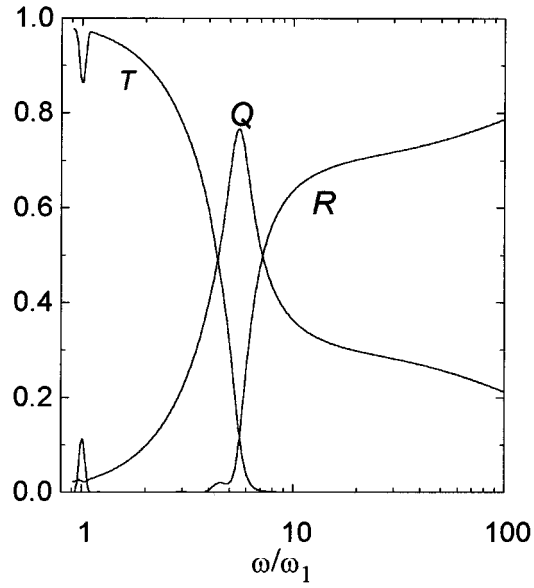

FIG. 7. Frequency dependence of the coefficients of reflection, transmission, and absorption of radiation incident upon the AIR at an angle of $\theta_i = 30°$.

The solution of Eq. (29) was performed with the use of the finite-difference method [20]. Obtained frequency dependencies of coefficients of reflection, transmission, and absorption (R, T, and Q, correspondingly) for the AIR maintenance regime being considered (Figs. 5, 6) are shown in Fig. 7. As is seen from the figure, the region of incident radiation frequencies where a substantial reflection from the AIR is observed, consists of two parts. Continous spectrum of reflection corresponds to frequencies $\omega_1 \leqslant 0.25\omega$ (i.e., $\lambda_1 \geqslant 2.5$ m). Besides, owing to interference of waves reflected from different layers of the AIR, there is a line spectrum defined by the condition

$$\frac{\omega}{\omega_1} = \frac{\sin\theta_1}{n\ \sin(\theta/2)}, \quad n = 1,2,\ldots\ . \tag{30}$$

Actually, however, a line spectrum usually consists of no more than several lines, because the coefficient of reflection from a single layer declines rapidly at high values of the frequency ω_1.

The effect of interference strengthening the reflection of electromagnetic waves from plasma structure in the intersection area of two coherent microwave beams had been observed experimentally by Kuo *et al.* [21,22]. The authors of these works indicate also that the effect should be enhanced as the number of layers increases.

This fact is confirmed by the results of numerical modeling of the radio-reflecting properties of multilayer AIRs performed by us in the paper [9]. It was demonstrated that, with a number of plasma layers $\sim 10^3$, the coefficient of reflection from the AIR at frequencies satisfying the interference condition (30) may exceed the value of 0.8, whereas the upper boundary of the continous spectrum is close to $10^{-2}\omega$.

It should be noted, however, that the distribution of electronic concentration in the multilayer AIR was set in [9] in a non-self-consistent way. In this work attempts were made to obtain, on the basis of the model described above, plasma formation with the number of layers of the order of 10^2 by increasing the duration of maintaining pulses and [according to condition (2)] decreasing the field amplitude in the beams. In so doing, the following situation was observed. As in the example considered earlier, growing of several central layers first takes place (see Fig. 5). Formation of peripheral layers proceeds already under the action of the field essentially weakened by central layers. As a result, the time of peripheral layers formation turns out to be substantially greater than the time of gas removal by the stratospheric wind from the domain of microwaves action, at reasonable values of the wind speed and beam radius. Increasing the field amplitude in the beams does not give any gain because of self-regulation of the discharge (rise of the quantity E_0 leads to an increase of electron concentration in the central layers that in its turn results in strengthening absorption of the maintaining radiation). Thus creation of multilayer AIRs is rather questionable in the framework of the approach being considered and constitute a separate problem.

V. CHEMICAL CONSEQUENCES OF PROLONGED MAINTENANCE OF THE AIR IN THE STRATOSPHERE

A selection of the AIR maintenance regimes with the minimum production of nitrogen oxides was made by us in Sec. III on the basis of the general character of the dependence of nitrogen oxides' production cost on the specific energy deposit in the discharge. For a more detailed analysis of the chemical consequences of creating the AIR in the stratosphere under selected optimal regimes, kinetic modeling of plasmachemical processes accompanying generation and maintenance of plasma during the residence time of the specified volume of gas in the AIR ($\tau_m \approx 2R_0/v_h$), as well as of the subsequent chemical relaxation of the gaseous mixture formed in the discharge was carried out. In doing so, diffusive transport of admixture molecules beyond the AIR along the X axis was also taken into account.

The kinetic scheme used in computations includes a vast set of reactions with a participation of the following components of the gas: $N_2(X\ ^1\Sigma_g^+)$, $N_2(A\ ^3\Sigma_u^+)$, $N_2(B\ ^3\Pi_g, W\ ^3\Delta_u, B'\ ^3\Sigma_u^-)$, $N_2(a'\ ^1\Sigma_u^-, a\ ^1\Pi_g, w\ ^1\Delta_u)$, $N_2(C\ ^3\Pi_u, E\ ^3\Sigma_g^+, a''\ ^1\Sigma_g^+)$, $O_2(X\ ^3\Sigma_g^-)$, $O_2(a\ ^1\Delta_g)$, $O_2(b\ ^1\Sigma_g^+)$, $O_2(c\ ^1\Sigma_u^-, C\ ^3\Delta_u, A\ ^3\Sigma_u^+)$, $N(^4S)$, $N(^2D)$, $N(^2P)$, $O(^3P)$, $O(^1D)$, $O(^1S)$, O_3, NO, NO_2, N_2O, H_2O, H, H_2, OH, HO_2, H_2O_2. Data on rate constants of reactions were taken for the most part from the works [10,23]. In addition to purely chemical processes, the processes of photodissociation of the molecules O_2, O_3, NO_2 and N_2O under the action of solar radiation [15,24] were also considered. The kinetic scheme does not include reactions with a participance of the particles NO_3, N_2O_4, N_2O_5, HNO_2, HNO_3 and so on, since at the altitudes being considered ($h \geqslant 45$ km) the particles indicated are subject to very fast photodissociation [15].

According to Sec. III we consider only the cases of a low specific energy deposit into the gas: $\varepsilon \leqslant 0.05$ J cm^{-3} atm^{-1}. Then even under a supposition that all absorbed energy transforms into heat (not any chemical processes), the maximum increase of gas temperature in the isobaric approximation amounts to 40 K. Test kinetic calculations had shown

that this quantity actually does not exceed 15 K. So the plasmachemical model used herein does not take into account gas heating. Correspondingly the processes of thermal decomposition of ozone, nitrogen oxides production, etc. are not considered.

Besides, a study of ion kinetics had shown that, under conditions corresponding to the altitude of 55 km, the basic ionic components of the AIR plasma during the discharge are O_2^+, O_2^+, NO^+, and O^-, O_2^-. Only at the postdischarge stage, when a major part of charged particles has disappeared due to recombination, the main role belongs to complex ions: $NO^+ \cdot O_2$, $NO^+ \cdot (H_2O)_n$, $H^+ \cdot (H_2O)_n$, and NO_3^-, CO_3^-. As zero-dimensional kinetic calculations had shown, ion-molecular reactions give just a small contribution to chemical transformations of air components, since, with values of electric field amplitude characteristic for the regimes being considered, the main part of the energy absorbed by the discharge plasma goes into excitation of electronic degrees of freedom, including dissociation. So, hereinafter we neglect the contribution of ion-molecular reactions and consider only interactions of neutral particles.

To obtain correct initial conditions for modeling the influence of the AIR on stratospheric air, kinetic calculations of photochemical processes in the undisturbed stratosphere had been performed first. In doing so, concentrations of admixture components of the gas that are not in a purely photochemical equilibrium (that is, their distribution in the stratosphere is substantially conditioned by transport processes)—NO_x, N_2O and H_2O were set according to [15,23]. The calculation had been performed to the point of reaching total equilibrium. Obtained equilibrium concentrations of the gas components were used then as initial conditions when modeling the AIR kinetics. Note that variation of the values of these concentrations from the data [15,23] with regard for day averaging does not exceed 15%.

The influence of the AIR on the kinetics of air mixture is conditioned by exciting plasma chemical processes with a participation of electrons. In the case of a low specific energy deposit into the gas being of interest, we shall restrict our consideration to the processes of electronic excitation and dissociation of the particles N_2 and O_2 (see the kinetic scheme [10]). Besides, dissociation of water molecules are taken into account, with the total cross section of this process being taken from the work [25]. Because of a great number of pulses direct simulation of the pulsed-recurring regime requires a great amount of computer time. Thus, as in [26], we used a ''smoothed'' model in which rates of processes initiated by electron impact are averaged over the period between pulses

$$J_{\alpha j} \equiv k_{\alpha j} n_e n_j \rightarrow \langle k_{\alpha j} n_e \rangle n_j = n_j F \int_t^{t+1/F} k_{\alpha j}(t',x) n_e(t',x) dt',$$

where $k_{\alpha j}$ is the rate constant of the αth reaction of electron with a neutral particle of the jth sort. The validity of this model was tested by comparing the results obtained with its use, with the results of direct numerical simulation of discharges characterized by a relatively small number of pulses (up to 50) and various initial conditions. When integrating the rates of proceeding of inelastic processes with a participation of electron over the interpulse spacing, corresponding

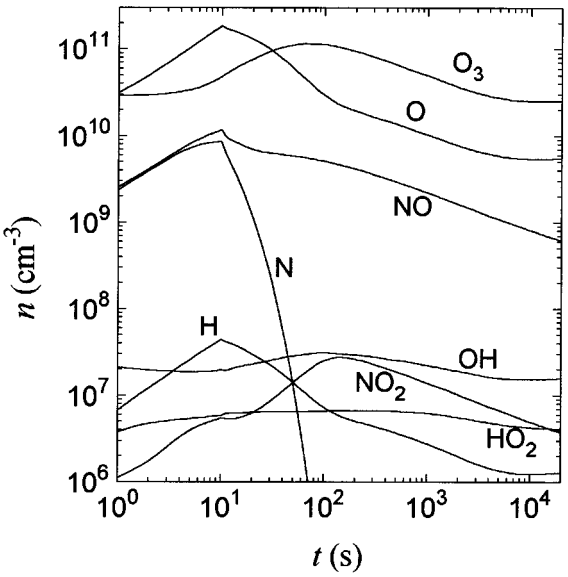

FIG. 8. Temporal dependencies of the concentration of gas components at the center of the AIR ($x=0$).

rate constants were determined on the basis of the solution of the nonstationary Boltzmann equation, with temporal dependencies of the electric field strength and electron concentration in each node of the calculational grid along the X axis being taken from the solution of the problem on interaction of intersected microwave beams with the AIR plasma (Sec. IV).

Diffusion coefficients of a number of admixture components of the gas were taken from the handbook [27]. Where the necessary information was absent, diffusion coefficients were determined from data for other particles according to scaling relationship: $D \sim \mu^{-1/2}$, where μ is the reduced mass of diffusing particles and particles of the buffer gas.

The results of the kinetic modeling for the AIR maintenance regime at the altitude of 55 km described earlier are represented in Figs. 8 and 9. The main chemical products accumulating during the discharge time ($\tau_m \approx 2R_0/v_h \approx 10$ s) are atoms O, N, H, and nitrogen oxide NO. Note that accumulation of the radicals OH also produced in the discharge as a result of water molecules dissociation does not take place owing to fast proceeding of their reaction with oxygen atoms

$$OH + O \rightarrow H + O_2.$$

By the time of the completion of the discharge the peaks in the spatial distribution of the discharge products conditioned by layered structure of the AIR are practically completely smoothed due to diffusion of particles into interlayer areas.

At the postdischarge stage in a time of about 50 s conversion of atomic oxygen into ozone and of atomic nitrogen into NO oxide occurs, and photochemical equilibrium in the O_x and NO_x is established. Subsequent destruction of the produced ozone in a catalytic cycle of reactions [10]

$$NO + O_3 \underset{k_5}{\rightarrow} NO_2 + O_2,$$

$$k_5 = 4.3 \times 10^{-12} \exp(-1560/T) \ \text{cm}^3/\text{s}, \qquad (31)$$

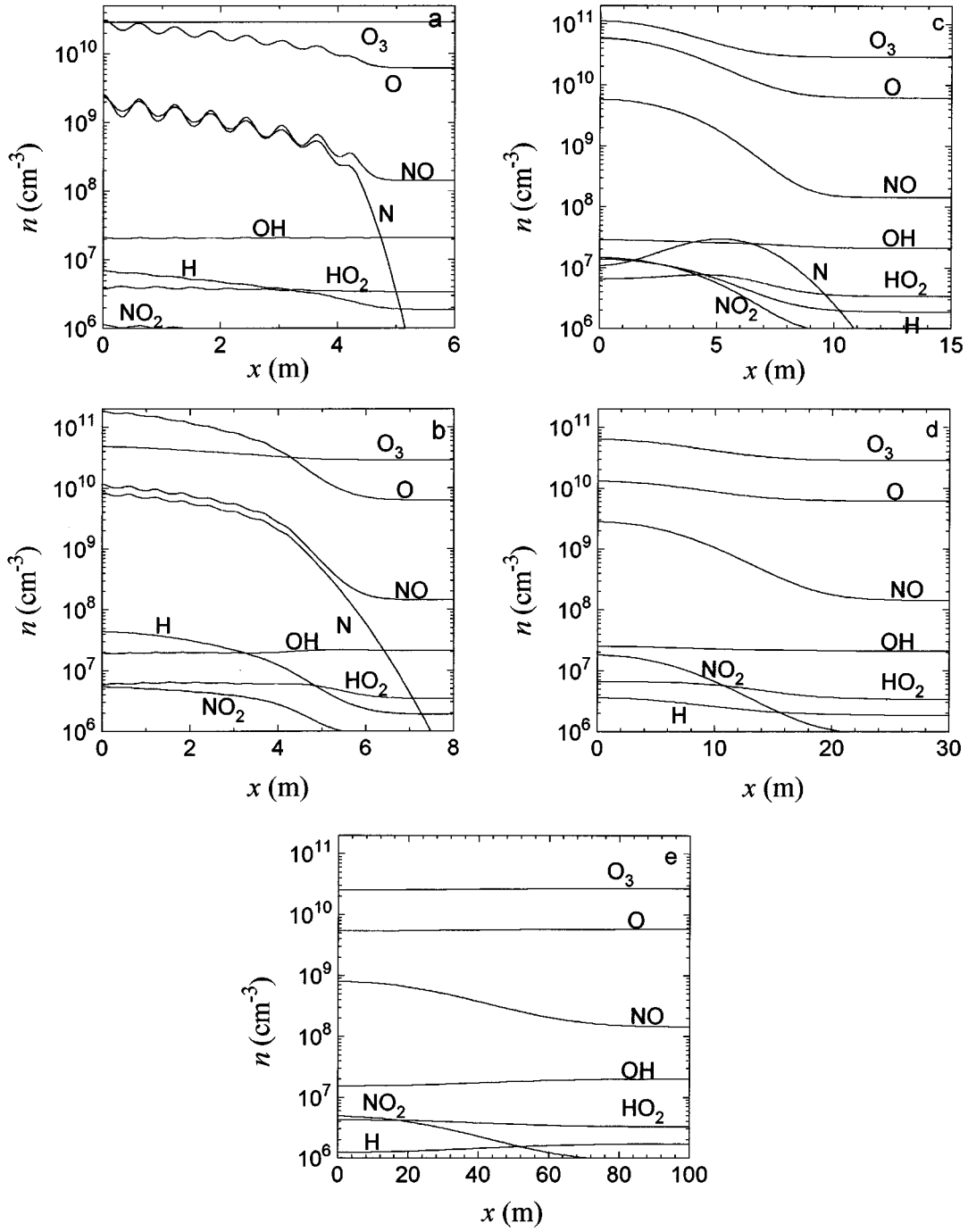

FIG. 9. Spatial distributions of the concentrations of gas components at the moments of time: $t_a=1$ s, $t_b=10$ s, $t_c=52$ s, $t_d=550$ s, $t_e=10^4$ s.

$$\mathrm{NO_2+O}\underset{k_6}{\rightarrow}\mathrm{NO+O_2}, \quad k_6=1.13\times10^{-11}(T/1000)^{0.18}\ \mathrm{cm^3/s}, \tag{32}$$

is proceeding on the background of the process of expansion of the region with an elevated content of the molecules O_x and NO_x. So during the characteristic time of the O_x decay in reactions (31) and (32)

$$\tau_{\mathrm{NO}_x}\approx\frac{[\mathrm{O_3}]+[\mathrm{O}]}{k_5[\mathrm{NO}][\mathrm{O_3}]+k_6[\mathrm{NO_2}][\mathrm{O}]}\approx1\ \text{hour},$$

the concentration of the NO_x particles decreases due to diffusion from the value of 1.2×10^{10} cm^{-3} to the value of $\sim1.2\times10^{9}$ cm^{-3}. Thus a consideration of the process of diffusive transport leads to lowering nitrogen oxides concentration by the order of magnitude and thereby essentially reduces their destroying effect on the stratospheric ozone.

Integrating the spatial distribution of the NO_x concentration, we get that the total yield of the NO_x, taking into account after-glow reactions, amounts to 1.1×10^{19} particles per pulse, or 9×10^{15} particles per 1 J of absorbed energy of microwave beams. The ratio between the NO_x production and electron production is approximately equal to 0.22.

As is seen from Figs. 8 and 9, production of the HO_x radicals in the discharge conditioned by water molecules dissociation in collisions with electrons and electronically excited nitrogen molecules is several times greater than the background value of their concentration. This also could result in a substantial decay of ozone concentration because of acceleration of the hydrogenic catalytic cycle

$$H+O_3 \rightarrow OH+O_2,$$

$$OH+O_3 \rightarrow HO_2+O_2,$$

$$HO_2+O_3 \rightarrow OH+2O_2,$$

$$OH+O \rightarrow H+O_2,$$

$$H+O_2+M \rightarrow HO_2+M.$$

However, this is not actually the case, since the concentration of the HO_x particles is rather heavily limited by the reactions of odd hydrogen binding

$$OH+HO_2 \rightarrow H_2O+O_2 \quad \text{and so on.}$$

As a result, within an hour after the discharge the value of the quantity $[HO_x]$ is already practically indistinguishable from the background one.

Production of nitrous oxide N_2O in the AIR ($\approx 7.2\times 10^8$ cm^{-3} at the center of the region) also essentially exceeds the background value of the N_2O concentration at the altitude of 55 km, $[N_2O]_b \approx 1.4\times 10^8$ cm^{-3} [15,23]. Nitrous oxide itself does not react with ozone, but on interaction with excited oxygen atoms $O(^1D)$ it yields the NO oxide [10]

$$N_2O+O(^1D) \xrightarrow[k_7]{} 2NO, \quad k_7 = 7.2\times 10^{-11} \ cm^3/s, \quad (33)$$

entering the catalytic cycle of ozone destruction. However, as had been shown in paper [9], in the case of a narrow AIR consisting of a small number of plasma layers, this additional source of NO particles does not exert any essential influence on the O_x family dynamics, since within the characteristic time of proceeding of reaction (33) the region with an elevated content of the N_2O extends due to diffusion so much that the additional amount of nitrogen oxide thus formed constitute only a small fraction of the NO_x background concentration. The aforesaid is confirmed in full measure by more correct self-consistent calculations performed in the present work.

Thus, the only important ozone-destroying chemical product resulting from a prolonged maintenance of the AIR under the regime being considered is nitrogen oxide NO. However, its destroying effect on the ozone component of air is substantially limited in this case by the diffusion process. The minimum concentration of ozone at the postdischarge stage constitutes $\approx$87% of the background ozone concentration and is achieved within approximately 3.5 hours after the discharge. With further spreading of the NO, the background concentration of the O_3 is gradually reestablished. Taking also into consideration that the altitude of 55 km corresponds to the upper boundary of the ozone layer (the bulk of the layer is located at the altitudes of $15<h<45$ km), it may be concluded that a prolonged maintenance of the AIR in the regime considered is not a threat to the ozone layer as a whole.

Analogous investigation of the ecological safety of the AIR maintenance regimes at lesser altitudes (45 and 50 km) has led to essentially worse results. The uniqueness of the regime corresponding to the altitude of 55 km obtained in such a manner is conditioned by the fact that, starting from the specified altitude, the relative contribution of nitrogen oxides to the total rate of odd oxygen losses decreases drastically [15] (the main role belongs here to the reactions of the hydrogen cycle and to the reaction: $O+O_3 \rightarrow 2O_2$), and, on the other hand, the concentration of the HO_x radicals actively produced by the discharge is rigidly limited by the reactions of their mutual binding.

VI. CONCLUSIONS

This work presents a mathematical model of the artificial ionized region created in the atmosphere in the intersection zone of two beams of powerful coherent TE microwaves. The model is based on the solution of the nonstationary system of Maxwell equations and kinetic Boltzmann equation for electrons, as well as on a vast ramified kinetic scheme of plasmachemical processes in humid air. In the framework of such a model, it is possible to calculate, in a correct and self-consistent way, the electrodynamic and kinetic characteristics of the AIR created in air at various altitudes.

The calculations conducted for the stratosphere had revealed the possibility of realization at great altitudes ($\sim$55 km) of the regimes of the AIR prolonged maintenance that simultaneously have the following advantages: they require the minimum energy expenditures, ensure good radio-reflecting properties of the plasma structure and do not lead even to local degradation of the ozone layer. Modeling of the kinetic and photochemical processes proceeding at the post-discharge stage had shown that the destructive action of the NO_x molecules produced in the discharge on the stratospheric ozone is substantially limited by their diffusive transport beyond the AIR boundaries. Production of excess active hydrogen radicals HO_x in the discharge does not exert any essential influence on ozone due to fast proceeding of the reactions of their mutual binding.

It is necessary to emphasize that the results of this work had been obtained on the basis of numerical modeling of the discharge kinetics in the stratosphere and thereby should be considered not as a final proof of the ecological safety of the selected regime of the discharge excitation, but rather as qualitative evidence for the possibility of the ecologically safe realization of the AIR. Further studies of this problem may require creation of more detailed theoretical models as well as performance of test experiments.

ACKNOWLEDGMENTS

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