Optics and Spectroscopy, 2026, Vol. 134, No. 1

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Generation of half-cycle light pulses upon reflection from a plasma mirror: a comparative analysis of ionization models

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Received October 21, 2025
Revised October 21, 2025
Accepted November 21, 2025

The generation of half-cycle unipolar pulses upon reflection of a femtosecond laser pulse from a plasma mirror was theoretically studied. Numerical simulations were used to compare the quasi-static model and the Ammosov–Delone–Krainov (ADK) model. It was shown that the leading edge of the pulse ionizes the medium, forming a plasma layer, while the trailing edge is reflected from it, generating a quasi-unipolar half-cycle pulse. Qualitative agreement between the pulse shapes was found, despite minor differences in amplitude. The results are important for the development of methods for sub-cycle control of light and the study of nonlinear processes in plasma.

Keywords: nonlinear ionization of atoms in a strong light field, tunnel ionization, plasma mirrors, half-cycle pulses, unipolar pulses, attosecond physics, extremely short pulses.

DOI: 10.61011/EOS.2026.01.63223.8681-25

Introduction

The unidirectional light pulses having a non-zero area of electric field, $\mathbf{S_E} = \int \mathbf{E}(\mathbf{r}, t)dt \neq 0$ [1] ($\mathbf{E}(\mathbf{r}, t)$ — intensity of electric field, $\mathbf{r}$ — radius is the vector of the selected point in space, t — time), represent a promising tool for controlling the motion of charged particles on attosecond time scales. Unlike time-symmetric conventional optical pulses, such waves are capable of transmitting a directed mechanical pulse to electrons, which opens up new possibilities for ultrafast control of quantum states and control of the optical properties of the medium [9,10].

Traditional methods of generating unidirectional pulses based on nonlinear optical processes jcite1-3,11 or accelerated charge radiation jcite12-14 have some limitations in view of complex realization and lack of flexibility in controlling the shape of the pulse. An alternative approach involves the use of a plasma mirror [15–17], formed directly when an intense femtosecond pulse interacts with the medium. In case of a single-cycle incident pulse, reflection from such a mirror can lead to generation of a semi-cyclic quasi-unipolar pulse [18]. At that, the leading half-wave ionizes the substance, creating a plasma layer with a sharp electron concentration gradient, which acts as a mirror for the rear half-wave of the field, which leads to generation of a subfemtosecond pulse.

The key factor determining the transformation efficiency is the dynamics of ionization. In previous study [18] a quasi-static ionization model was used [19–22]. In this study a more generalized model of ADK model (Ammosov–Delone–Krainov) is used [22–24] and a comparative analysis for the two methods is carried out. Computational modeling is performed based on equations for the concentration and velocity of ionized electrons in plasma, taking into account nonstationary processes.

Model and results of the computational modeling

The system under consideration, as in [18], is a flat layer of initially non-ionized atoms (gas) located between the points $x = x_1$ and $x = x_2$. A single-cycle pulse normally incident on the medium:

$$E(t) = E_0\, e^{-t^2/\tau^2} \sin \omega t. \tag{1}$$

The concentration of electrons $n_e(x, t)$ at each point x along the layer is described by the velocity equation

$$\frac{\partial}{\partial t} n_e(x, t) = W_{\mathrm{ST,ADK}}\left[E(x, t)\right]\left(n_0(x) - n_e(x, t)\right) - \frac{n_e(x, t)}{\tau_{\mathrm{rec}}}, \tag{2}$$

where τ_{rec} — recombination time. The rate of ionization in case of a quasi-static model is given by the ratio [19–22]

$$W_{\mathrm{ST}}\left[E(t)\right] = 4\omega_a r_{\mathrm{H}}^{5/2}\left(\frac{E_a}{|E(x, t)|}\right) \exp\left(-\frac{2}{3} r_{\mathrm{H}}^{3/2} \frac{E_a}{|E(x, t)|}\right), \tag{3}$$

where $\omega_a = m_e e^4/\hbar^3$ — atomic frequency, m_e — mass of electron, e — elementary charge, $r_{\mathrm{H}} = U_i/U_{\mathrm{H}}$ — ratio of the studied gas ionization $U_i = 15.76\,\mathrm{eV}$ (Ar) to the hydrogen ionization potential U_{H} (13.6 eV), $E_a = 5.17 \cdot 10^{11}\,\mathrm{V/m}$ — intra-atomic field.

For ADK model the ionization rate is expressed as [22–24]

$$W_{\mathrm{ADK}}[E(t)] = \alpha_{\mathrm{ADK}}\left(\frac{E_a}{|E(x, t)|}\right)^{2n-1} \exp\left(-\beta_{\mathrm{ADK}} \frac{E_a}{|E(x, t)|}\right). \tag{4}$$

Here $\alpha_{\mathrm{ADK}}, \beta_{\mathrm{ADK}}$ — constants with their values expressed as [22]:

$$\alpha_{\mathrm{ADK}} = \omega_{\mathrm{ion}} |C_n|^2 \left(4\sqrt{2} r_a^{3/2}\right)^{2n-1},$$

Abbreviations used in the analysis

Parameter	Its value
E_0	10^{11} V/m
τ	667 as
$\lambda = 2\pi c/\omega$	800 nm
n_0	10^{18} cm^{-3}
τ_{rec}	1 ps
τ_e	100 fs

$$\beta_{\text{ADK}} = 4\sqrt{2}/3\, r_a^{3/2}, \quad \omega_{\text{ion}} = \frac{U_{\text{ion}}}{\hbar},$$

$$n = r_{\text{H}}^{-1/2}, \quad r_{\text{H}} = U_{\text{ion}} U_H,$$

$$|C_n^2| = 2^{2n}\left[n\Gamma(n)\Gamma(n+1)\right]^{-1}, \quad r_a = \frac{U_{\text{ion}}}{U_a},$$

$$U_a \approx 27.2\,\text{eV}, \quad U_{\text{ion}} \approx 15.76\,\text{eV}$$

— potential of the target's atoms ionization (for argon), $U_H = 13.6$ eV — potential of the hydrogen atom ionization , $n = r_{\text{H}}^{-0.5}$ — effective quantum number.

The velocity of ejected electrons $V_e(x, t)$ is calculated according to the Newton's second law based on Drude model with a decay τ_e:

$$\frac{\partial}{\partial t} V_e(x, t) = -\frac{e}{m_e} V_e(x, t) - \frac{V_e(x, t)}{\tau_e},$$

$$V_e(x, 0) = 0, \quad t < t_i, \tag{5}$$

where t_i — moment of the start of ionization . Based on the calculated velocity and concentration of electrons, the current is found $J(x, t) = en_e(x, t)V_e(x, t)$, which is the source of the electric field in the right-hand side of 1D wave equation for the electric field strength $E(x, t)$:

$$\frac{\partial^2 E(x, t)}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E(x, t)}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial}{\partial t} J(x, t). \tag{6}$$

Note that the wave equation (6) has a simple analytical solution for the reflected field strength near the layer (near zone) [25]:

$$E_r(x, t) = -\frac{2\pi}{c}\int_{x_1}^{x_2} J\left(x', t - \frac{x - x'}{c}\right) dx'. \tag{7}$$

As in [18], system of equations (2)-(6) with the incident pulse field (1) was numerically solved using two different models for calculating the ionization rate (3) and (4). The calculation parameters are listed in the table.

The figure shows the results of calculating the reflected field strength for media with a thickness of $d = 0.1\,\mu$m (a) and $d = 0.5\,\mu$m (b). The ionization rate was calculated using a quasi-static model (red curves) and ADK model (blue curves).

In a thin medium (figure, a), a half-cycle pulse is generated due to the reflection of the second half-wave of the field from the plasma mirror formed by the first half-wave. With a growth of the medium thickness, the contributions of individual layers generating half-waves of the field are combined with a time delay resulting in formation of a quasi-unidirectional pulse, close to a square shape [18]. Such pulses are the field petahertz pulses (proportional to the electron current in the near zone, according to the expression (7)), promising for use in ultrafast petahertz electronics [26].

In terms of quality, the time pulse profiles obtained from both models show a similar shape. Quantitative differences are manifested mainly in the amplitude of the generated pulses.

Discussion of the results

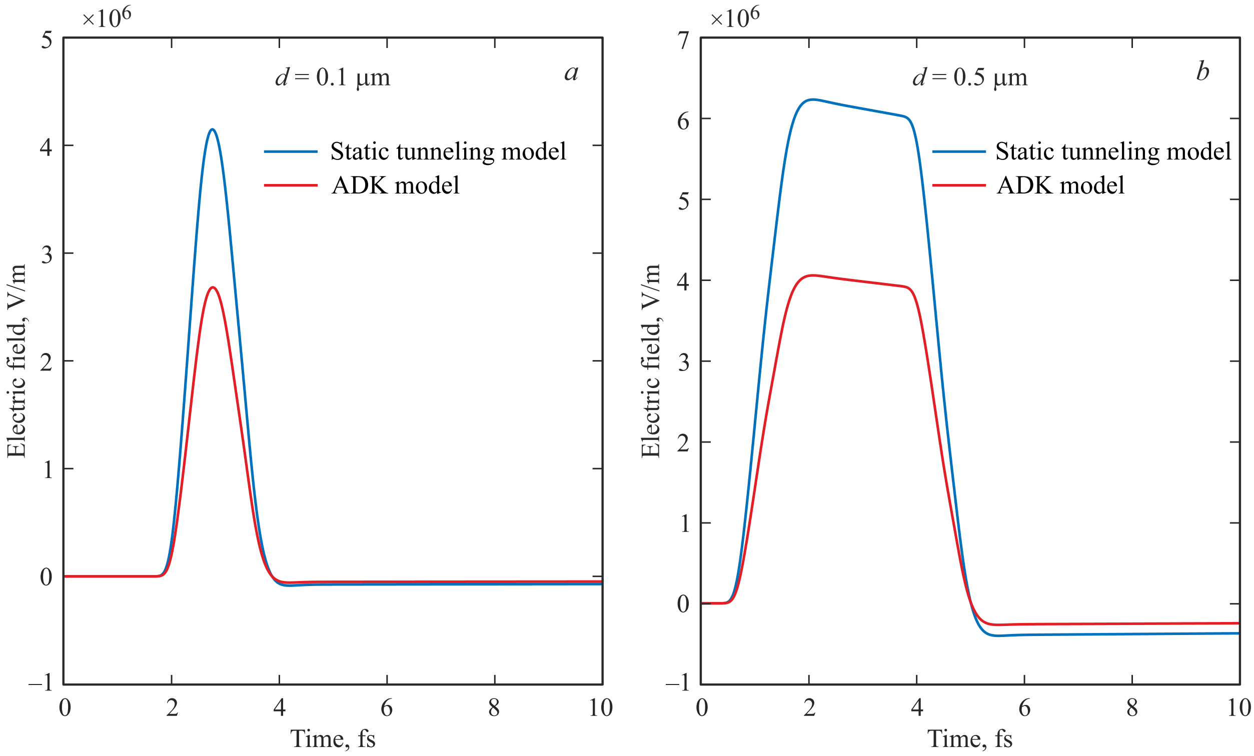
The observed differences in the amplitudes of generated pulses obtained using quasi-static model and ADK model may be due to the following physical reasons. Based on the quasi-static model (3) it is assumed that the field changes rather slowly, and the ionization rate at each moment depends only on the instantaneous value of the field $E(t)$. It does not take into account the inertia of the tunneling process and may overestimate the ionization rate at rapidly changing pulse fronts. The ADK (4) model, being also quasi-static in nature, but more strictly justified for complex atoms, can give a quantitatively different dependence of the ionization rate $W(E)$ due to allowing for the quantum numbers of the ground state of the atom and the inertia of electrons during photoionization.

This leads to different dynamics of plasma accumulation, i.e., different rates of electron concentration increase. Since current $J(x, t) = en_e(x, t)V_e(x, t)$ is the source of the field, even a small difference in the calculated ionization rate $W(E)$ leads to the electron concentration $n_e(x, t)$ found using these two models reaching a critical value (necessary for the formation of a „mirror“) at slightly different points in time. As a result, the reflection coefficient of the pulse trailing edge and its duration may vary slightly, which directly affects the amplitude of the reflected unidirectional pulse.

Also, the process of generating a reflected pulse is significantly nonlinear: it is determined by reflection from a moving plasma boundary with a rapidly changing density. In such a system, even small differences in the initial ionization dynamics may cause noticeable differences in the amplitude of the resulting reflected field.

Thus, the observed difference in amplitudes is not an artifact, but rather is an evidence of fundamental differences in the two models for describing ionization in a strong laser field. The qualitative agreement of the results confirms that both approaches correctly describe the basic physics of the phenomenon — generation of a unidirectional pulse due to reflection from a plasma mirror.

Radiation polarization is another pivotal issue. This concept is strictly defined for monochromatic radiation. It is



Intensity of the reflected field with the medium thickness of $d = 0.1\,\mu$m (*a*) and $d = 0.5\,\mu$m (*b*). The ionization rate is calculated using a static ionization model (3) (red lines) and ADK model (4) (blue lines).

logical to relate the characterization of the vector structure of low-cycle and subcycle electromagnetic pulses with the properties of the hodograph of the electric intensity vector $\mathbf{E}(\mathbf{r}, t)$ — the trajectory of the end of this vector with a fixed starting point during time changes t (see [27] and cited literature). At different spatial points $\mathbf{r}$, the type of hodograph can be different. In general, it is a closed three-dimensional curve oriented in accordance with increasing time, since the field at a fixed point $\mathbf{r}$ vanishes before and after the pulse. For monochromatic radiation, hodographs are flat curves and ellipses, moreover, the strictly linear and strictly circular polarizations are being their degenerate cases. For the low-cycle pulses in a vacuum with moving charges, the hodograph can be a site with finite (for example, a trefoil) or infinite topological complexity. Flat hodographs may serve as an example which formally are not ellipses themselves.

Due to the variety of polarization structure of electromagnetic pulses, the issue of specific polarization type which ensures their most effective effect on micro-objects is relevant. In this case, we are talking about the processes of atoms ionization and electrons movement. The answer follows from the fact that for sufficiently short pulses, the efficiency is determined by the square of the modulus of the electrical area of the pulse $\mathbf{S_E} = \int \mathbf{E}(\mathbf{r}, t)dt$. With the same electric intensity modulus $|\mathbf{E}(\mathbf{r}, t)|$, the modulus $\mathbf{S_E}$ will be maximal if the electric intensity has the same direction at all moments of time. Then, the hodograph represents a straight line segment, and the polarization is linear. That is why the linear polarization of radiation was selected in the present study (see ratio (1)).

Conclusion

Computational modeling of generation of semi-cyclic unidirectional pulses upon reflection from a plasma mirror has shown a qualitative consistency between the results of quasi-static model and ADK model. The quantitative differences in pulse amplitudes are caused by fundamental differences in the description of tunneling ionization, but they do not affect the overall physical properties of the phenomenon.

It was found that the key parameter determining the shape of the generated pulse is the thickness of the ionized layer. In case of thin media, a classical semi-cyclic pulse is formed, whereas with increasing layer thickness, spatiotemporal summation of contributions from successive plasma layers occurs, leading to the formation of quasi-rectangular unidirectional pulses. These pulses are petahertz current pulses, which is promising for their use as compact sources of ultrahigh-frequency electromagnetic radiation for petahertz electronics devices.

The findings confirm the universality of the unidirectional radiation generation mechanism if reflected from a plasma mirror and demonstrate the option of flexible control of the pulse shape by varying the target parameters. A comparative analysis of the ionization models has shown that both the quasi-static model and ADK model can be used to qualitatively describe the dynamics of the process, which expands the methodological arsenal of research in the field of attosecond physics and plasma physics.

Funding

The study was financially supported by the Russian Science Foundation under the scientific project 23-12-00012 (computational modeling of reflection from plasma mirror) and under the state assignment of Ioffe Institute of Physics and Technology, topic 0040-2019-0017 (numerical analysis of the ionization rate using ADK model and static model and the polarization structure of low-cycle pulses).

Conflict of interest

The authors declare no conflict of interest.

References

[1] N.N. Rosanov, M.V. Arkhipov, R.M. Arkhipov, A.V. Pakhomov. Contemporary Physics, **64** (3), 224 (2023).
[2] N.N. Rosanov, M.V. Arkhipov, R.M. Arkhipov. Phys. Usp., **67** (11), 1129 (2024).
[3] N.N. Rozanov, M.V. Arkhipov, R.M. Arkhipov. *Teragertsovaya fotonika*, edited by V.Ya. Panchenko, A.P. Shkurinov (RAS, M., 2023), p. 360–393 (in Russian).
[4] A. Wetzels, A. Gürtler, L.D. Noordam, F. Robicheaux, C. Dinu, H.G. Muller, M.J.J. Vrakking, W.J. van der Zande. Phys. Rev. Lett., **89**, 273003 (2002).
[5] M.T. Hassan, T.T. Luu, A. Moulet, O. Raskazovskaya, P. Zhokhov, M. Garg, N. Karpowicz, A.M. Zheltikov, V. Pervak, F. Krausz, E. Goulielmakis. Nature, **530**, 66 (2016).
[6] X. Chai, X. Ropagnol, S.M. Raeis-Zadeh, M. Reid, S. Safavi-Naeini, T. Ozaki. Phys. Rev. Lett., **121**, 143901 (2018).
[7] N. Rosanov, D. Tumakov, M. Arkhipov, R. Arkhipov. Phys. Rev. A, **104** (6), 063101 (2021).
[8] R. Arkhipov, P. Belov, A. Pakhomov, M. Arkhipov, N. Rosanov. JOSA B, **41**, 285 (2024).
[9] R. Arkhipov, M. Arkhipov, N. Rosanov. Opt. Lett., **50**, 4914 (2025).
[10] R. Arkhipov, M. Arkhipov, N. Rosanov. JOSA B, **42** (11), 2583 (2025).
[11] M. Glazov, N. Rosanov. Phys. Rev. A, **109**, 053523 (2024).
[12] L. Qin, Z. Chen, M. Sun, J. Yan, Y. Tian, Z. Chen, Y. Wang, X. Ma, X. Yan, Y. Wang. Phys. Rev. E, **112**, 045202 (2025).
[13] H. Dang, J. Gao, H. Wu, Y. Zhang, X. Guo, L. Tong. Phys. Rev. A, **112**, 013510 (2025).
[14] L. Qin, Z. Chen, M. Sun, J. Yan, Y. Tian, Z. Chen, Y. Wang, X. Ma, X. Yan, Y. Wang. Phys. Rev. E, **112**, 045202 (2025).
[15] Ch. Pan, X. Song, Y. Cao, L. Xiong, X. Lan, S. Wang, Y. Len, Y. Pan. Laser & Photonics Rev., **19** (22), e01986 (2025).
[16] S.V. Bulanov, T.Zh. Esirkepov, M. Kando, A.S. Pirozhkov, N.N. Rosanov. Phys. Usp., **56**, 429–464 (2013).
[17] S. Gorelov, A. Novokovskaya, S. Bodrov, M. Sarafanova, M. Bakunov. Appl. Phys. Lett., **126**, 011104 (2025).
[18] R. Arkhipov, A. Pakhomov, O. Diachkova, M.V. Arkhipov, N. Rosanov. Opt. Lett., **50**, 6181 (2025).
[19] L.V. Keldysh. Sov. Phys. JETP, **20**, 1307 (1965).
[20] W.P. Leemans, C.E. Clayton, W.B. Mori, K.A. Marsh, P.K. Kaw, A. Dyson, C. Joshi, J.M. Wallace. Phys. Rev. A, **46**, 1091 (1992).
[21] A.M. Zheltikov. Phys. Usp., **60**, 1087 (2017).
[22] H.G. Roskos, M.D. Thomson, M. Kreß, T. Löffler. Laser & Photonics Rev., **1**, 349–368 (2007).
[23] M.V. Ammosov, N.B. Delone, V.P. Krainov. Sov. Phys. JETP, **64** (6), 1191 (1986).
[24] N.B. Delone, V.P. Krainov. Phys. Usp., **41**, 469–485 (1998).
[25] M.V. Arkhipov, R.M. Arkhipov, A.V. Pakhomov, I.V. Babushkin, A. Demircan, U. Morgner, N.N. Rosanov. Opt. Lett., **42**, 2189 (2017).
[26] C. Heide, P.D. Keathley, M.F. Kling. Nat. Rev. Phys., **6**, 648 (2024).
[27] N.N. Rosanov, S.V. Fedorov. Phys. Rev. A, **112**, 063518 (2025).

Translated by T.Zorina