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Unipolar and quasi-unipolar electromagnetic pulses

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A brief review of the authors' latest work in the field of extremely short electromagnetic pulses, including unipolar pulses, is presented.

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Extremely short electromagnetic pulses are in demand for creating super-strong fields, diagnostics and control of ultrafast processes, information transfer and other applications [1–4]. At present, pulses containing only a few optical cycles and „half-waves" of the opposite polarity are available. But the shortest pulses would consist of only one such half-wave, i.e. they would be unipolar. Their efficiency in influencing micro-objects would be higher than that of bipolar pulses, due to their unidirectional action on the charges.

Although pulses having non-zero electric area — zero-frequency component of spectrum $\mathbf{S}_E = \int \mathbf{E}\,dt$, where $\mathbf{E}$ — electric field strength, were considered by E. G. Bessonov as early as 1981 [5], in the references until now, there are opposite opinions about the possibility of such pulses, which is caused by the singularity of their physics. Below, we will briefly list the authors' recent results in this area.

It can be shown that in an unbounded vacuum, in which there have never been charges anywhere, pulses with finite energy and non-zero area cannot propagate [6]. This question is partly academic, because in a vacuum without charges, it is impossible to form any electromagnetic pulses. At the same time, in hollow coaxial waveguides, which have no cutoff frequency, the propagation of unipolar pulses with finite energy is acceptable, which is actually one-dimensional [3,7].

In the presence of stationary charges and just a static component of the field, the electric area $\mathbf{S}_E = \infty$; we exclude such a case from consideration. But a localized system of moving charges is capable of forming pulses with a finite and non-zero area, an example of which is the temporary separation and subsequent merging of positive and negative charges in the vacuum [3,6,8]. In the far area, for a system of charges with zero total charge, the first term of the expansion is the „dipole" term, showing that the electrical area decreases with distance from the system r as r^{-3}. It is possible to obtain an exact solution of Maxwell's equations for the vacuum with a continuously distributed density of charge and current, describing a unipolar field pulse localized in a restricted area [6]. Note, that the electromagnetic field division into static and radiative components, which is used in a number of works, does not seem useful here, since there is no static component in this case, and field detectors do not divide the field into such components. However, the issue acuteness is reduced by the fact that the impact on micro-objects of a pair of pulses with opposite polarity, sufficiently separated by time, is equivalent to their impact separately. This is illustrated by Fig. 1, which shows that if the probability of ionization of a hydrogen atom by the first pulse of the pair is noticeable, the second pulse has almost no effect on the total probability of ionization.

The formation and generation of pulses with non-zero area have been considered in a large number of papers, references to which are given in [2,3]. Such pulses can be obtained by nonlinear optical conversion of a bipolar pulse. The previously mentioned separation of the bipolar pulse into unipolar components is possible both when propagating in a medium with resonant nonlinearity [9,10] and when reflecting from a medium layer with quadratic or cubic nonlinearity [11]. In this case, the plane-parallel layer of the linear medium does not reflect the zero-frequency component of the pulse spectrum at all, since it corresponds to an infinitely long wavelength. This introduces difficulties in the construction of resonator circuits of unipolar pulse generation for both fixed and moving linear mirrors; they can be bypassed, for example, by eliminating the reflection from the second face of the layer by its inclination or roughness [12]. Among other methods of generating pulses with non-zero area, let us mention the use of the effects

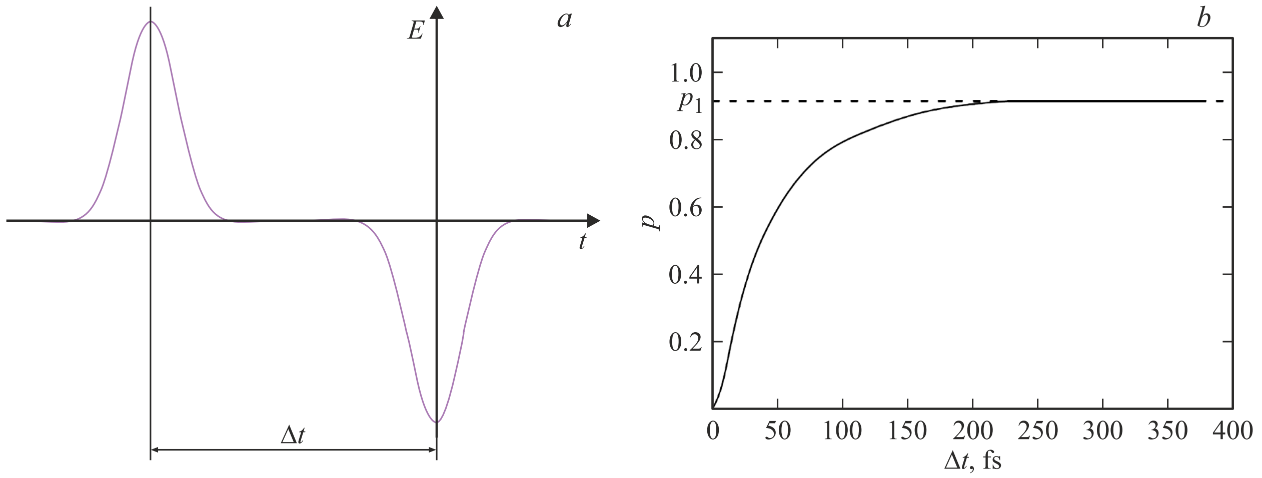

Figure 1. Ionization of a hydrogen atom by a pair of antiphase unipolar pulses following with a time delay Δt (*a*). At (*b*) p — total probability of ionization, p_1 — probability of ionization by the first pulse (dashed line). $E(t) = E_1(t) - E_1(t - \Delta t)$, $E_1(t) = E_0 \exp(-t^2/\tau^2)\cos(\omega t)$, $E_0 = 28.2$ a.u., which corresponds to peak power $2.8 \cdot 10^{19}$ W/cm^2, $\omega = 2.5 \cdot 10^{17}$ s^{-1}, $\tau = 1.1$ as.

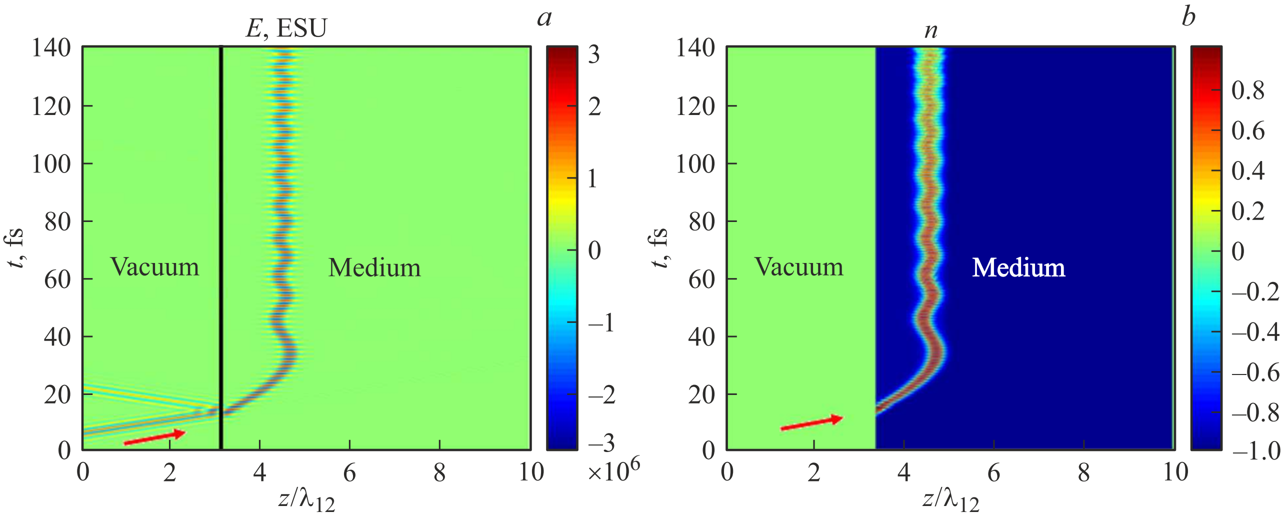

Figure 2. The dynamics of electric field strength E (*a*) and level population difference n (*b*) for a single-cycle pulse falling from a vacuum onto a medium with resonant nonlinearity.

of self-induced transparency and superradiance [3,13,14]. In particularly, the analysis of self-induced transparency in lasers [15] opens up the possibility of building compact compressors and producing attosecond pulses [16]. It is also possible to form a pair of unipolar pulses of opposite polarity during pulse diffraction with a trapezoidal profile in the near zone [17], control the shape of quasi-unipolar pulses [13,18], as well as „differentiation“ and „integration“ their profile [19,20].

Examination of the interaction of extremely short pulses with a large number of different micro-objects –the classical electron [21], the electron with spin [22–24], atoms, molecules and quantum dots [25–32] — confirms that the effectiveness of sufficiently short pulses on them is determined by the electrical area of those pulses. The permissible duration of pulses is such, that during this time, external conditions should not change, and all changes in the state of the micro-object would be reduced to the acquisition of the mechanical momentum transmitted to it by the field pulse. For a classical electron — this is the time of its exit during acceleration from the accelerating radiation packet. For quantum objects at their moderate excitation — this is the Keplerian period of electron orbit, and at a stronger excitation, as in the conditions of Fig. 1, this is the characteristic ionization time. It is important to estimate the scale of the electrical area of the pulse, at which the pulse has a significant impact on the object. To do this, compare the mechanical momentum $\delta p = eS_E$, where e — the charge of the electron, with the characteristic momentum of the „unperturbed“ object

p_0. For a classical electron with mass m $p_0 = mc$, where c — the speed of light in the vacuum. Hence, the scale of electrical area $S_{E,0} = mc/e$. For quantum objects with characteristic size a_0, the characteristic momentum, due to the uncertainty relation, $p_0 = \hbar/a_0$ ($\hbar$ — the reduced Planck constant). For such objects $S_{E,0} = \hbar/(ea_0)$ [28,29].

Along with the recently obtained theoretical results, it is important to note the first quantitative experimental measurement of the electrical area of terahertz pulses [33]. Qualitatively, its non-zero value in this area of the spectrum was recorded earlier in a large number of works.

Vivid features of extremely short electromagnetic pulses arise in relation to the problem of slow light. Previously, a significant slowing of the propagation of multicycle light pulses was obtained in their resonant interaction with the medium under conditions of electromagnetically induced [34,35] or self-induced [36] transparency. However, such methods do not allow to stop the extremely short pulses completely. In [37] it is shown that complete self-stopping of a single-cycle pulse can be achieved in a homogeneous stationary medium with resonant nonlinearity (Fig. 2). Self-stopping occurs because of self-action of pulses in the medium with deep modulation — periodic energy transfer between the radiation and the medium. In this case, the oscillating distribution of population levels in the medium forms a long-lived local quasi-resonator, from which light cannot escape and is self-locking.

The available theoretical and experimental data provide grounds for a discussion of various applications of extremely short pulses, including unipolar pulses. An important application is the recording and control of light-induced gratings [38,39]. When attracting unipolar pulses, there is no need for direct interference of light pulses in a medium with long relaxation times. Here, it is not necessary to overlap the pulses in the medium, because the pulse interferes actually with the polarization wave in the medium. This fact allows to use unipolar pulses for holography of fast-moving objects with high temporal resolution [40].

The above results emphasize, in the opinion of the authors, the importance of developing theoretical and experimental studies of extremely short and unipolar electromagnetic pulses, interesting both because of their new and unusual physics and because of their potential for unique applications.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] E.A. Khazanov, Quant. Electron. **52**, 208 (2022).

[2] R.M. Arkhipov, M.V. Arkhipov, N.N. Rosanov. Quant. Electron. **50**, 801 (2020).

[3] N.N. Rosanov. *Dissipativnyye opticheskiye i rodstvennyye solitony* (Fizmatlit, 2021) (in Russian).

[4] R.M. Arkhipov, M.V. Arkhipov, A.V. Pakhomov, P.A. Obraztsov, N.N. Rosanov. JETP Lett., 117, 8 (2023).

[5] E.G. Bessonov. Sov. Phys. JETP., **53**, 433 (1981)].

[6] A.B. Plachenov, N.N. Rosanov. Izv. vuzov. Radio physics, (in Russian) **65** (12), 1003 (2022).

[7] N.N. Rosanov. Opt. Spectrosc., **127** (6), 1050 (2019).

[8] N.N. Rosanov. Opt. Spectrosc., **128** (4), 490 (2020).

[9] V.P. Kalosha, J. Herrmann. Phys. Rev. Lett., **83**, 544 (1999).

[10] R.M. Arkhipov, M.V. Arkhipov, S.V. Fedorov, N.N. Rosanov. Opt. Spectr., **130** (13), 2020 (2022).

[11] V.V. Kozlov, N.N. Rosanov, C. De Angelis, S. Wabnitz. Phys. Rev. A, **84**, 023818 (2011).

[12] N.N. Rosanov. Opt. Spectrosc., **130** (12) 1936 (2022).

[13] A. Pakhomov, M. Arkhipov, N. Rosanov, R. Arkhipov. Phys. Rev. A, **106**, 053506 (2022).

[14] R.M. Arkhipov, A.V. Pakhomov, M.V. Arkhipov et al. Phys. Rev. A, **101** (4), 043838 (2020).

[15] R. Arkhipov, M. Arkhipov, A. Pakhomov et al. Phys. Rev. A, **105** (1), 013526 (2022).

[16] R. Arkhipov, A. Pakhomov, I. Babushkin et al. Optics Express, **29** (7), 10134 (2021).

[17] M.V. Arkhipov, R.M. Arkhipov, N.N. Rosanov. Opt. Spectrosc., **129** (11), 1193 (2021).

[18] A.V. Pakhomov, R.M. Arkhipov, M.V. Arkhipov et al. Scientific reports, **9**, 7444, 1 (2019).

[19] A. Pakhomov, R. Arkhipov, M. Arkhipov, N. Rosanov. Optics Letters, **46** (12), 2868 (2021).

[20] A.V. Pakhomov, R.M. Arkhipov, M.V. Arkhipov, N.N. Rosanov. Quantum Electron. **51** (11), 1000 (2021).

[21] N.N. Rosanov, N.V. Vysotina. JETP, **130** (1), 52 (2020).

[22] I.A. Aleksandrov, D.A. Tumakov, A. Kudlis et al. Phys. Rev. A, **102**, 023102 (2020).

[23] N.N. Rosanov. JETP Lett. **113** (3), 145 (2021).

[24] I.A. Aleksandrov, D.A. Tumakov, A. Kudlis et al. Phys. Rev. A, **106**, 033119 (2022).

[25] N.N. Rosanov. Opt. Spectrosc., **124** (1), 75 (2018)., (in Russian)

[26] R.M. Arkhipov, A.V. Pakhomov, M.V. Arkhipov et al. Optics Letters, **44** (5), 1202 (2019).

[27] R. Arkhipov, A. Pakhomov, M. Arkhipov et al. Optics Express, **28** (11), 17020 (2020).

[28] R.M. Arkhipov, M.V. Arkhipov, A.V. Pakhomov, N.N. Rosanov. JETP Lett., **114** (3), 129 (2021).

[29] N. Rosanov, D. Tumakov, M. Arkhipov, R. Arkhipov. Phys. Rev. A **104** (6), 063101 (2021).

[30] A. Pakhomov, M. Arkhipov, N. Rosanov, R. Arkhipov. Phys. Rev. A, **104** (4), 043103 (2022).

[31] R.M. Arkhipov, M.V. Arkhipov, A.V. Pakhomov, N.N. Rosanov Opt. Spectrosc., **130** (3), 350 (2022).

[32] R.M. Arkhipov, P.A. Belov , M.V. Arkhipov et al. Kvant. elektron., **52** (7), 610 (2022) (in Russian).

[33] M.V. Arkhipov, A.N. Tsypkin, M.O. Zhukova, A.O. Ismagilov, A.V. Pakhomov, N.N. Rosanov, R.M. Arkhipov, JETP Lett. **115** (1), 1 (2022).

[34] M.M. Kash, V.A. Sautenkov, A.S. Zibrov et al. Phys. Rev. Lett., **82**, 5229 (1999).

[35] L.V. Hau, S.E. Harris, Z. Dutton, C.H. Behroozi. Nature (London), **397**, 594 (1999).

[36] G.L. Lamb, Jr. Phys. Rev. Lett., **31**, 196 (1973).

[37] M. Arkhipov, R. Arkhipov, I. Babushkin, N. Rosanov. Phys. Rev. Lett., **128**, 203901 (2022).
[38] R.M. Arkhipov. JETP Lett., **113** (10), 611 (2021).
[39] R. Arkhipov, A. Pakhomov, M. Arkhipov et al. Scientific Reports, **11**, 1961 (2021).
[40] R.M. Arkhipov, M.V. Arkhipov, N.N. Rosanov JETP Lett. **111** (9), 484 (2020).

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