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Soliton-like mode of terahertz radiation generation by few-cycle optical pulses in a gradient waveguide

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ABSTRACT

We expect an increase in the efficiency of terahertz radiation generation both due to the short period of the optical pulse containing 2–3 oscillations, and due to the fact that the process is modeled in a gradient waveguide. The generation process can be accompanied by the formation of spatiotemporal optical-terahertz solitons (optical-terahertz bullets). In the case of an intense and short optical signal, for the optical component, it is necessary to take into account the group dispersion of the third order, the dispersion of the quadratic optical-terahertz nonlinearity. For the terahertz component, one should take into account its dispersion, intrinsic quadratic nonlinearity, and quadratic nonlinearity, which carries information about the phase of the optical pulse.

Keywords: Terahertz radiation generation, optical-terahertz bullets

1. INTRODUCTION

To improve the efficiency generation of terahertz radiation, it is useful to increase the intensity of optical signal, since the amplitude of the electric field of the generated terahertz component is directly proportional to the intensity of the optical pulse. To this end, one can use a few-cycle laser pulse of high intensity [1-4]. In general, producing terahertz radiation with the help of optical rectification we deal with a broadband (short) optical pulse. At that, an arising THz pulse appears to be as short as containing not more than one oscillation period of THz range. Obviously, for the theoretical study of it one can not use the slowly varying envelope approach. This approach is still valid for the broadband optical signal, but for the terahertz component the unidirectional propagation approximation was proposed [5]. Thus, two nonlinear coupled equations can be used as a model of the optical rectification process. They are equivalent to the well-known integrable Yajima–Oikawa system [6]. In the case of extremely short optical pulses of high intensity, nonlinearity and higher-order dispersion are well pronounced. Manifestation of these effects makes it necessary a generalization of Yajima-Oikawa system. It has been done when analyzing optical rectification at an intense optical signal with a relative duration of only a few light oscillations [7]. Recently, we presented a study of terahertz radiation generation from such optical pulse using numerical simulation and demonstrated the formation of an optical-terahertz bullet in a waveguide [8]. Such spatiotemporal localizations arising when one takes into account the transverse dynamics of pulses, have been earlier considered in[9-11]. We continued to investigate the process of optical-terahertz bullet formation considering also the phase modulation of the optical component and nondispersive cubic nonlinearity [13]. We succeeded in showing the formation of an optical-terahertz bullet and its steady propagation over a distance of about 100 nonlinear lengths in a medium with focusing cubic nonlinearity in the range of the normal dispersion of the group velocity. This result has been achieved when we shortened the initial optical pulse to only three oscillations. Integrability of the generalized Yajima–Oikawa system was proven in [7] provided the coefficients of the system were under strict restrictions. With the help of numerical simulation, we widened the range of coefficient values at which optical-terahertz bullets was demonstrated to be stable [8-9]. Nevertheless, real experiments to study extremely short intensive signals make it clear that one should involve in the theoretical analysis other effects. Among them are optical group dispersion of the third order, dispersion of quadratic optical-terahertz nonlinearity, cubic nonlinearity and its dispersion.

In the current paper we present and discuss the results of our numerical simulation of the process of optical rectification using extremely short optical pulses with only a few oscillations. We take into account the effects just mentioned above.

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Moreover, we generalize the equation for the terahertz component and include the terms describing the dispersion of the electronic and vibrational nature, the intrinsic quadratic nonlinearity and quadratic nonlinearity carrying information about the phase of the optical pulse (phase nonlinearity).

2. MODEL OF OPTICAL-TERAHERTZ INTERACTION

We treat the optical component using the unidirectional propagation approximation [5]. Generalized Yajima-Oikawa system which takes into account the focusing optical and terahertz waveguides is as follows [8,11,15].

$$i\frac{\partial\overline{\psi}}{\partial z}=-\frac{k_2}{2}\frac{\partial^2\overline{\psi}}{\partial\tau^2}+i\frac{k_3}{6}\frac{\partial^3\overline{\psi}}{\partial\tau^3}+aE_T\psi-ib\,\overline{\psi}\,\frac{\partial\overline{E}_T}{\partial\tau}-i\mu\overline{E}_T\,\frac{\partial\overline{\psi}}{\partial\tau}-\omega g_\omega(x)\left(1-\frac{i}{\omega}\frac{\partial}{\partial\tau}\right)\overline{\psi}$$

$$+\frac{c}{2n_\omega\omega}\left(1+\frac{i}{\omega}\frac{\partial}{\partial\tau}\right)\frac{\partial^2\overline{\psi}}{\partial x^2},$$

$$\frac{\partial\overline{E}_T}{\partial z}=\alpha\frac{\partial^3\overline{E}_T}{\partial\tau^3}-\beta\overline{E}_T\,\frac{\partial\overline{E}_T}{\partial\tau}-\sigma\frac{\partial}{\partial\tau}|\overline{\psi}|^2+iq\frac{\partial}{\partial\tau}\left(\overline{\psi}^*\,\frac{\partial\overline{\psi}}{\partial\tau}-\overline{\psi}\,\frac{\partial\overline{\psi}^*}{\partial\tau}\right)-g_T(x)\frac{\partial\overline{E}_T}{\partial\tau}+$$

$$+\frac{c}{2n_T}\;\frac{\partial^2}{\partial x^2}\int_{-\infty}^{\tau}\overline{E}_T d\tau',$$

$\overline{\psi}$ is the complex amplitude of optical component and $\overline{E}_T$ is terahertz field. We determine the physical parameters included in this system just below as applied to the system (1). Here we explain distinctive terms referred to the waveguide. $g_\omega(x)=\dfrac{2\pi\omega}{cn_\omega}\,f_\omega(x)$, $g_T(x)=\dfrac{2\pi}{cn_T}\,f_T(x)$, $f_{\omega,T}(x)=\dfrac{n^2_{\omega,T}(x)-n^2_{\omega,T}}{n^2_{\omega,T}-1}$. $n_{\omega,T}(x)$ are the optical and THz refractive indices, where $n_{\omega,T}$ are the same indices near the waveguide center. Near the waveguide center $g_{\omega,T}(x)=f_{\omega,T}(x)=0$.

With the help of numerical modeling we showed [8,11,15] that the reduction of the number of initial pulse oscillations allowed us to observe a soliton-like spatiotemporal solution of the system given above (optical bullet). In spite of intensity fluctuations, a self-similar pulse propagates, and the transversal profiles of the optical and terahertz components at the distances up to 200 nonlinear lengths are approximated well by Gaussians. At the same time these distances can be estimated as more than 10 diffraction lengths. Soliton formation at quadratic nonlinearity and normal dispersion requires a special medium geometry. In our model we used a waveguide.

Earlier we presented the model describing optical-terahertz interaction for a few-cycle optical signal of high intensity[12]. In the current study we generalize our consideration including in the model the dispersion of the cubic nonlinearity of the optical component and the dispersion of the terahertz component bearing oscillatory nature. The latter processes appear to be especially significant at the propagation of extremely short pulses. Thus, we come to the following generalized Yajima–Oikawa system governing the interaction of the complex amplitude $\overline{\psi}$ of optical component and the terahertz field $\overline{E}_T$.

$$\begin{aligned}&i\frac{\partial\overline{\psi}}{\partial\overline{z}}=-\frac{k_2}{2}\frac{\partial^2\overline{\psi}}{\partial\overline{\tau}^2}+i\frac{k_3}{6}\frac{\partial^3\overline{\psi}}{\partial\overline{\tau}^3}+a\overline{E}_T\overline{\psi}-ib\overline{\psi}\frac{\partial\overline{E}_T}{\partial\overline{\tau}}-i\mu\overline{E}_T\frac{\partial\overline{\psi}}{\partial\overline{\tau}}+\varepsilon|\overline{\psi}|^2\overline{\psi}+h_1|\overline{\psi}|^2\frac{\partial\overline{\psi}}{\partial\overline{\tau}}+h_2\overline{\psi}\frac{\partial|\overline{\psi}|^2}{\partial\overline{\tau}},\\&\frac{\partial\overline{E}_T}{\partial\overline{z}}=\alpha\frac{\partial^3\overline{E}_T}{\partial\overline{\tau}^3}-\overline{\gamma}\int_{-\infty}^{\overline{\tau}}\overline{E}_T d\tau'-\beta\overline{E}_T\frac{\partial\overline{E}_T}{\partial\overline{\tau}}-\sigma\frac{\partial}{\partial\overline{\tau}}|\overline{\psi}|^2+iq\frac{\partial}{\partial\overline{\tau}}\left(\overline{\psi}^*\frac{\partial\overline{\psi}}{\partial\overline{\tau}}-\overline{\psi}\frac{\partial\overline{\psi}^*}{\partial\overline{\tau}}\right),\end{aligned}\tag{1}$$

where we use the notations : $\tau = t - z/v_g = t - z/v_T$, $v_{g,T}$ are the group velocities of the optical component and the THz component phase velocity,

$$\alpha = \frac{\pi}{c}\left(\frac{\partial^2 \chi}{\partial \omega^2}\right)_{\omega=0}, \beta = \frac{4\pi\chi^{(2)}(0;0)}{c}, \sigma = \frac{4\pi\chi^{(2)}(\omega;-\omega)}{cn_T}, q = \frac{4\pi}{c}\left(\frac{\partial \chi^{(2)}}{\partial \omega_1}\right)\Bigg|_{\substack{\omega_1=-\omega \\ \omega_2=\omega}}, k_2 = \frac{2\pi}{c}\left(2\frac{\partial \chi}{\partial \omega} + \omega\frac{\partial^2 \chi}{\partial \omega^2}\right), k_3 = \frac{2\pi}{c}\left(3\frac{\partial^2 \chi}{\partial \omega^2} + \omega\frac{\partial^3 \chi}{\partial \omega^3}\right),$$

$$a = \frac{4\pi\omega}{c}\chi^{(2)}(\omega,0), b = \frac{4\pi}{c}\chi^{(2)}(\omega,0), \mu = \frac{4\pi}{c}\left(\chi^{(2)}(\omega;0) + \omega\frac{\partial}{\partial \omega}\chi^{(2)}(\omega;0)\right), h_1 \sim h_2 = \frac{6\pi\omega}{cn_o}\frac{\partial \chi^{(3)}}{\partial \omega}, \varepsilon = \frac{6\pi\omega}{c}\chi^{(3)}(\omega,\omega,-\omega).$$

χ and $\chi^{(2)}/\chi^{(3)}$ are the linear, second and third order nonlinear optical susceptibilities respectively, ω is the carrier frequency of the optical pulse, $\bar{\gamma}$ is the dispersion of oscillatory nature of the terahertz field, n_T is the terahertz refraction coefficient, *c* is the light velocity in vacuum.

Let us discuss the meaning of certain generalizing terms which concern the processes mentioned above. The first two terms on the right side of the first equation (1) for the optical component describe the group velocity dispersion (GVD) of the second and third orders. The third term refers to quadratic optical-terahertz nonlinearity. As for the fourth and fifth terms, they characterize the dispersion of optical-terahertz nonlinearity. The last three terms describe Kerr nonlinearity, and its dispersion.

Proceeding to the second equation of system (1), we should mention the first two terms of its right side concerning the dispersion of the terahertz component of the electronic and vibrational nature[1], while the third term describes the intrinsic nonlinearity of this component. The fourth term is proportional to the optical radiation intensity. This term specifies the generation of the terahertz signal. The last term refers to the phase nonlinearity of the terahertz signal[13]. In the model (1) we do not take into account the diffraction of both components and do not introduce waveguides.

Numerical simulation was carried out after the following normalization of the system (1). the values included in the system (1): $\bar{\psi} = \psi\psi_0$, $\bar{E}_T = E_T\psi_0$, ψ_0 is the peak amplitude of the initial optical component radiation. Other dimensionless variables and parameters are as follows: $\bar{\tau} = \tau\tau_0$, $\bar{z} = zl_{nl}$, $l_{nl} = 1/(a\psi_0)$, τ_0 is the initial duration of the pulse, $D_{k2} = sign(k_2)\frac{l_{nl}}{l_{dis2}}$, $D_{k3} = \frac{l_{nl}}{l_{dis3}}$, $l_{dis2} = \frac{2\tau_0^2}{|k_2|}$, $l_{dis3} = \frac{6\tau_0^3}{k_3}$. In the present study we deal with extremely short pulses, thus, we introduce the parameter $N = \omega\tau_0$ meaning the number pulse oscillations. Parameter μ goes to $\frac{\mu\psi_0}{\tau_0}l_{nl} \approx \frac{2}{N}$ at the same time parameter b appears to be $\frac{b\psi_0}{\tau_0}l_{nl} \approx \frac{1}{N}$. There are a few more parameters depending on N. α becomes $\frac{\alpha l_{nl}}{\tau_0^3} \approx \frac{1}{4N^2}$, β goes to $\frac{\beta\psi_0}{\tau_0}l_{nl} \approx \frac{1}{N}$, $\bar{\gamma}$ transforms into $\bar{\gamma}\tau_0^2 \approx \gamma N^2$, q is presented as $\frac{q\psi_0}{\tau_0^2}l_{nl} \approx \frac{1}{N}$. We also introduce $D_\sigma = \frac{\sigma\psi_0 l_{nl}}{\tau_0}$, $p = \frac{\varepsilon\psi_0^2 l_{nl}}{\tau_0}$. Transformations of the just mentioned parameters are got provided the following ratio between the coefficients of the system (1): $\frac{q}{\sigma} = \frac{b}{a}, \mu = 2b$ [7]. Taking into account the described normalization, we have the dimensionless system given below.

$$\frac{\partial\psi}{\partial z}=iD_{k_2}\frac{\partial^2\psi}{\partial\tau^2}+\frac{D_{k3}}{N}\frac{\partial^3\psi}{\partial\tau^3}-iE_T\psi-\frac{1}{N}\psi\frac{\partial E_T}{\partial\tau}-\frac{2}{N}E_T\frac{\partial\psi}{\partial\tau}+ip\left(|\psi|^2\psi+\frac{1}{N}|\psi|^2\frac{\partial\psi}{\partial\tau}+\frac{1}{N}\psi\frac{\partial|\psi|^2}{\partial\tau}\right),$$
$$\frac{\partial E_T}{\partial z}=\frac{1}{4N^2}\frac{\partial^3 E_T}{\partial\tau^3}-\gamma N^2\int_{-\infty}^{\tau}E_T d\tau'-\frac{1}{N}E_T\frac{\partial E_T}{\partial\tau}-D_\sigma\frac{\partial}{\partial\tau}|\psi|^2+\frac{i}{N}\frac{\partial}{\partial\tau}\left(\psi^*\frac{\partial\psi}{\partial\tau}-\psi\frac{\partial\psi^*}{\partial\tau}\right). \quad (2)$$

Terahertz radiation generation is ensured be the initial optical pulse launched into the left boundary of the nonlinear medium.

$$\psi(z=0,\tau)=\psi_0\exp\left(-(\tau-L_\tau/2)^2\right),$$
$$E_T(z=0,\tau)=0. \quad (3)$$

Value L_τ in (3) refers to the dimensionless duration of the observation of the process governed by (3). We choose it so that at the time moments $\tau=0$ and $\tau=L_\tau$ there is neither optical ψ nor terahertz E_T radiation. Then we can write down the integrals of motion for the system (2) - (3) [12]. Besides important physical meaning, they serve as a tool for the control of our calculations:

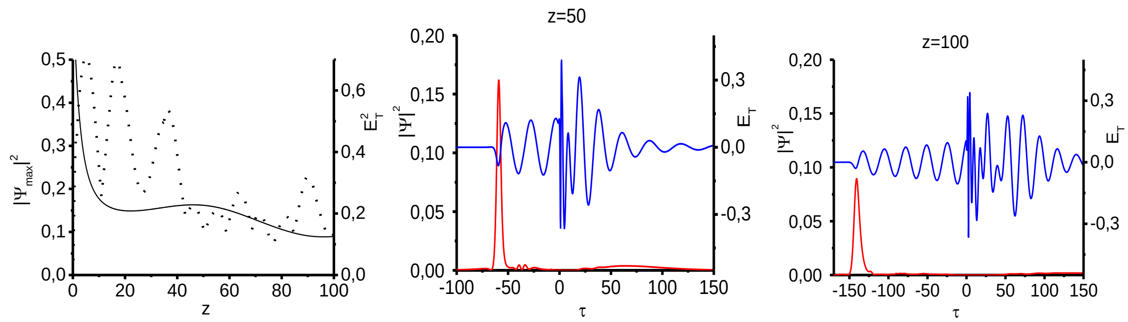
$$N_0=\int_{-L_\tau}^{L_\tau}|\psi|^2 d\tau=const,\ \ A_T=\int_{-L_\tau}^{L_\tau}E_T d\tau=const. \quad (4)$$

Let us remind that the parameter N_0 in (4) is proportional to the photon number in the optical component. Each photon loses a part of its energy which moves to the terahertz range. Thus, the number of terahertz photons $N_T=\int_{-L_\tau}^{L_\tau}E_T^2 d\tau$ increases, at the same time the frequency of optical photons decreases. The second integral (4) means that the electric area of a broadband pulse remains constant. Since the terahertz pulse is absent at the left boundary of the nonlinear crystal, the integral over τ of the generated terahertz pulse field at any cross section *z* is equal to zero.

3. DISCUSSION OF NUMERICAL SIMULATION OUTPUT

As it was shown in the previous Section, the integrals (4) are intrinsic to the system (2) - (3) governing the process of optical rectification by a few-cycle pulse. Thus, to be sure that our simulation appropriately reflects the regularities of this process we chose a so called conservative numerical method preserving integrals (4) [8].

We carried out a few series of calculations. Our focus was on the influence of the pulse duration and Kerr nonlinearity on an optical-terahertz soliton trapping and stable propagation. To this end we varied values of N and p while other parameters included in (2) remained unchanged. Figure1- Figure 3 accumulate the results of the first series when we launched rather long initial optical signal with oscillation number $N=30$. In this series and in the following ones we present the spectra of both optical and terahertz components which are important characteristics when studying optical-terahertz soliton formation. At that, we show pictures for optical spectra depending on $\Delta\omega$ which means the detuning of the current frequency ω from the carrier one. Figure 1 demonstrates the generation of a terahertz signal in the absence of cubic nonlinearity. In this case, the optical signal gradually spreads out, and no steady propagation of the soliton is observed. The spectrum of the optical signal shifts to the red region. The terahertz spectrum has a maximum at low frequencies.



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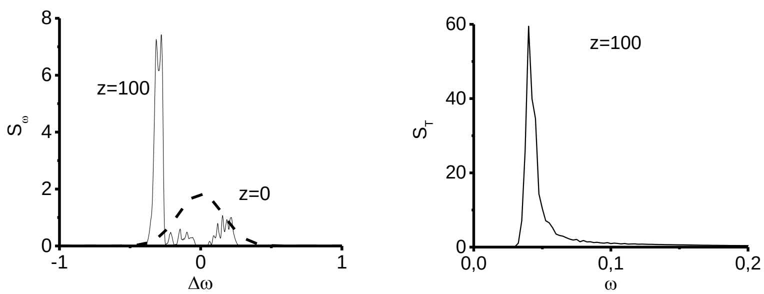
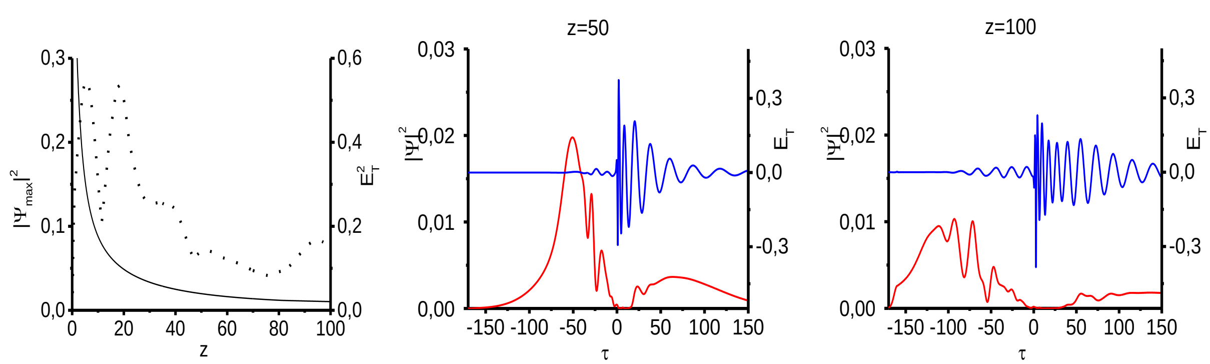


(d) (e)

Figure 1. Peak intensities (a) of the optical (solid line) and THz (dotted line) components, profiles of the optical (red lines) and terahertz (blue lines) components at different distances (b, c), spectra of the optical (d) and terahertz components at $z=100$ (e). Initial amplitude $\psi_0=1$, second and third order dispersion coefficients $D_{k2}=0.5$, $D_{k3}=0.5$, quadratic and cubic nonlinearities $D_\sigma=1$, $p=0$, dispersion of oscillatory nature of the terahertz field $\gamma=10^{-4}$, oscillation number $N=30$.

We proceed including in our consideration cubic nonlinearity. Figure 2 shows the case of defocusing nonlinearity. In this case, the optical signal is blurred at the initial stage, after that, the efficiency of generating a terahertz signal sharply decreases. An optical terahertz soliton is not observed as it was noticed in the previous case. Comparison of the spectra of the terahertz signal in Fig.1 and Fig.1. 2 shows that defocusing nonlinearity negatively influences on the efficiency of generation of terahertz radiation.



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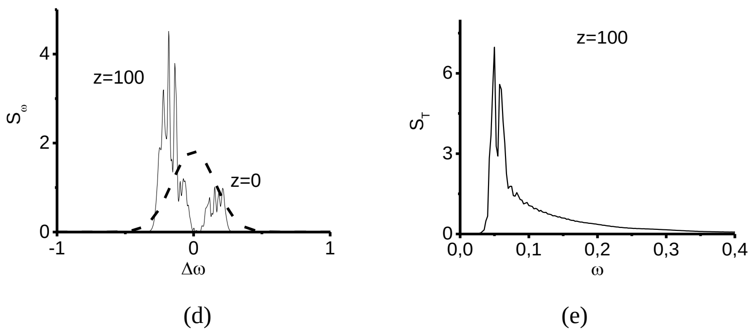


Figure 2. The same as in Figure 1 except for defocusing cubic nonlinearity $p=1$.

Then we change cubic nonlinearity to focusing one. Figure 3 shows an optical-terahertz soliton is formed, which propagates with small oscillations practically without changes. This soliton generates a terahertz signal during propagation, which can be seen by comparing the spectra at z=50 and z=100. The shape of the spectra does not vary significantly, but the amplitude increases with propagation.

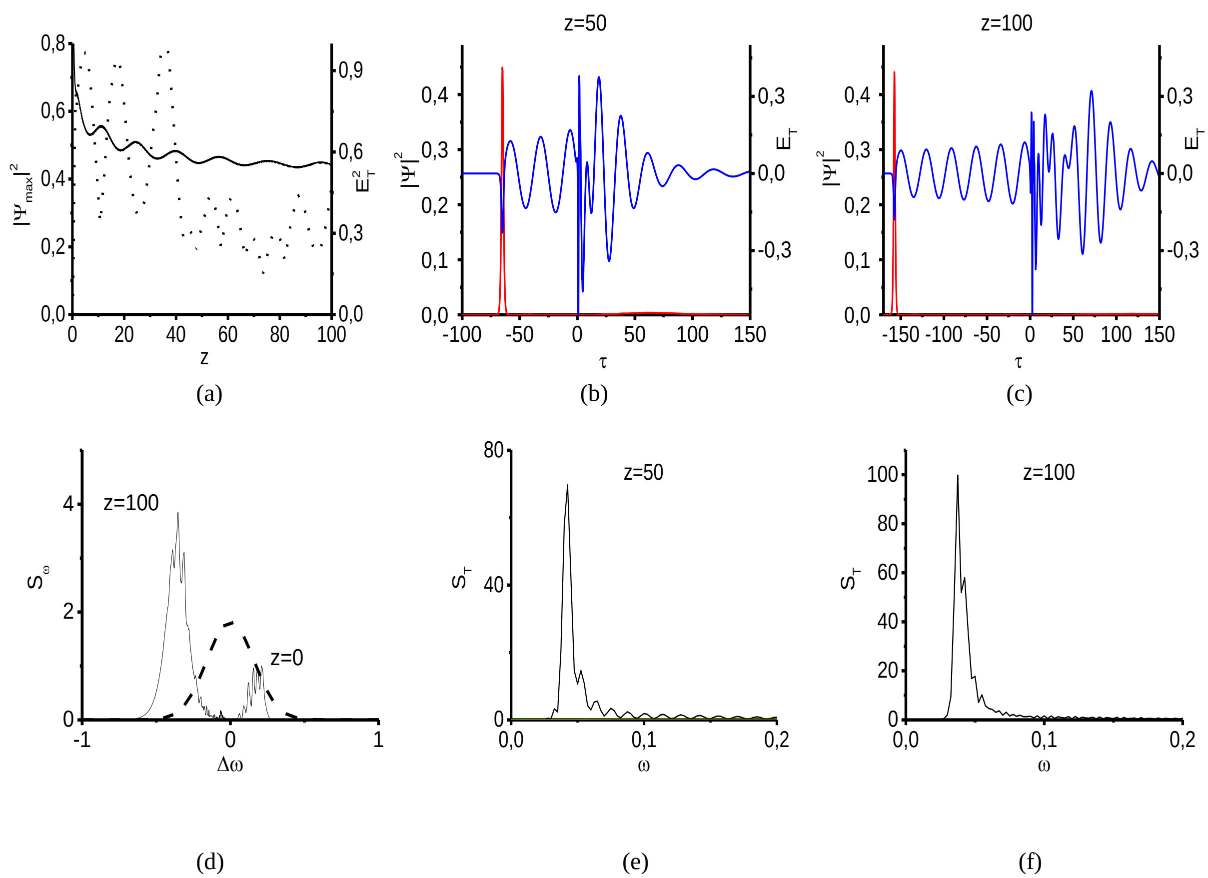


Figure 3. Peak intensities (a) of the optical (solid line) and THz (dotted line) components, profiles of the optical (red lines) and terahertz (blue lines) components at different distances (b, c), spectra of the optical (d) and terahertz components at $z=50$ (e) and $z=100$ (f). Initial amplitude $\psi_0=1$, second and third order dispersion coefficients $D_{k2}=0.5$,

$D_{k3} = 0.5$, quadratic nonlinearity $D_\sigma = 1$ and focusing cubic nonlinearities, $p = -1$, dispersion of oscillatory nature of the terahertz field $\gamma = 10^{-4}$, oscillation number $N = 30$.

In the second series of our computations we decrease the duration of the initial optical signal. Figure 4 - Figure 6 show the results which are organized in a similar way as those presented above. Figure 4 illustrates the case of the absence of the Kerr nonlinearity. We observe an optical-terahertz soliton-like signal forming and gradually losing its intensity.

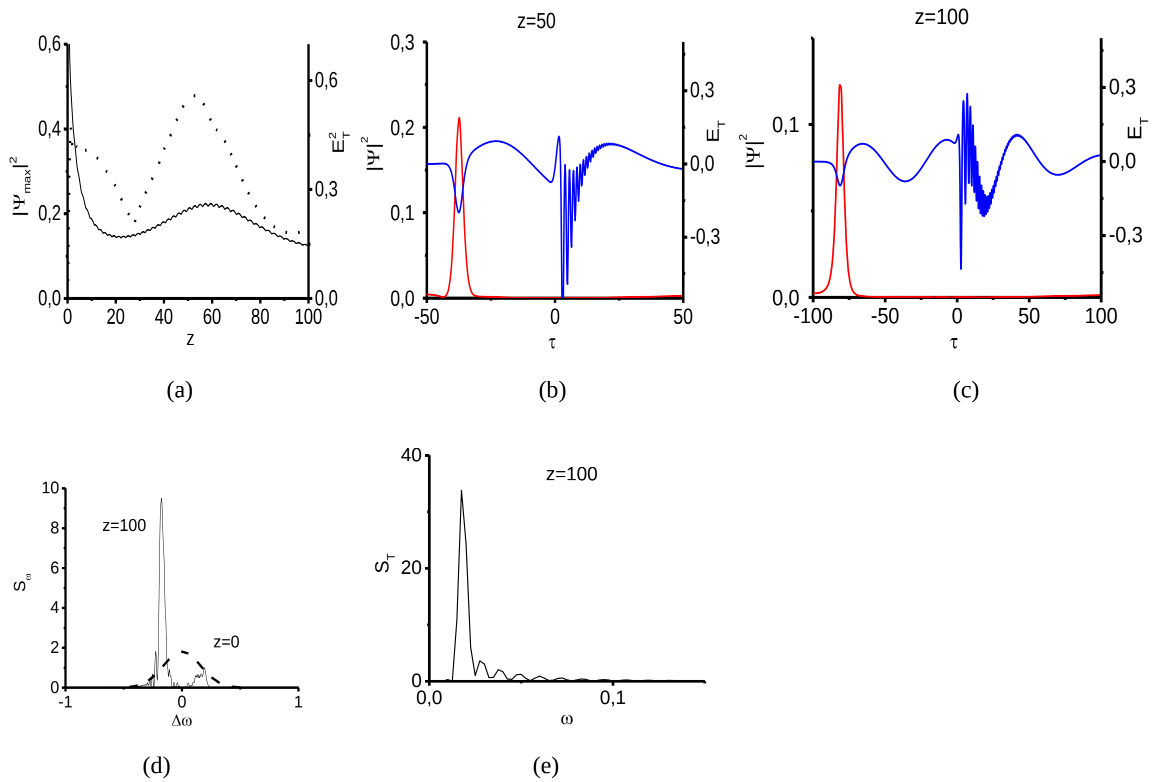
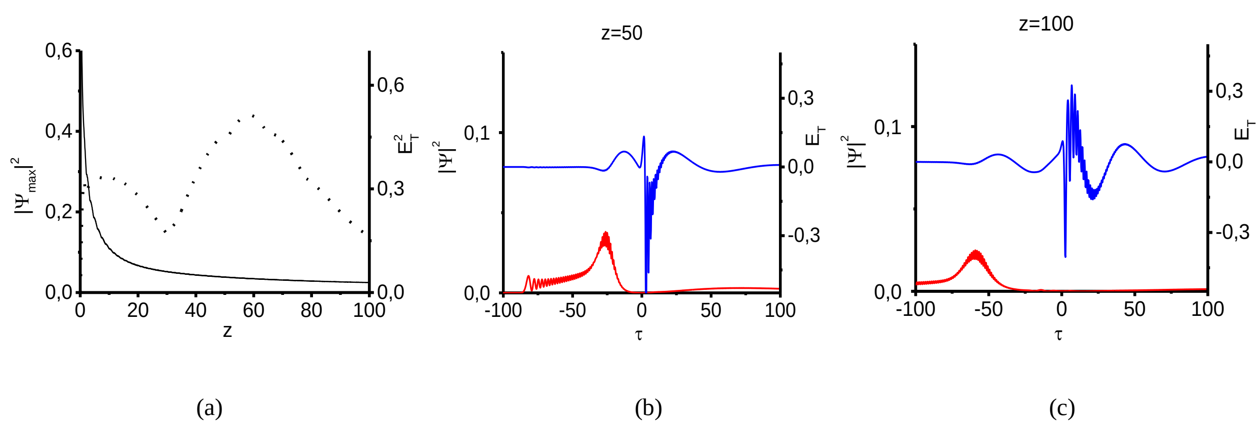
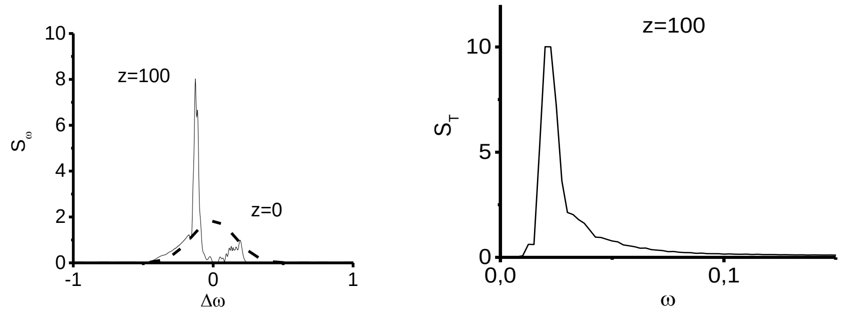


Figure 4. The same as in Figure 1 except for $N = 10$.

Figure 5 demonstrates the case of defocusing nonlinearity when the initial optical signal has 10 oscillations. We see that as it was for a longer initial pulse of 30 oscillations (see Figure 2) the optical signal is blurred at the initial stage, effective generation of the terahertz component does not occur.

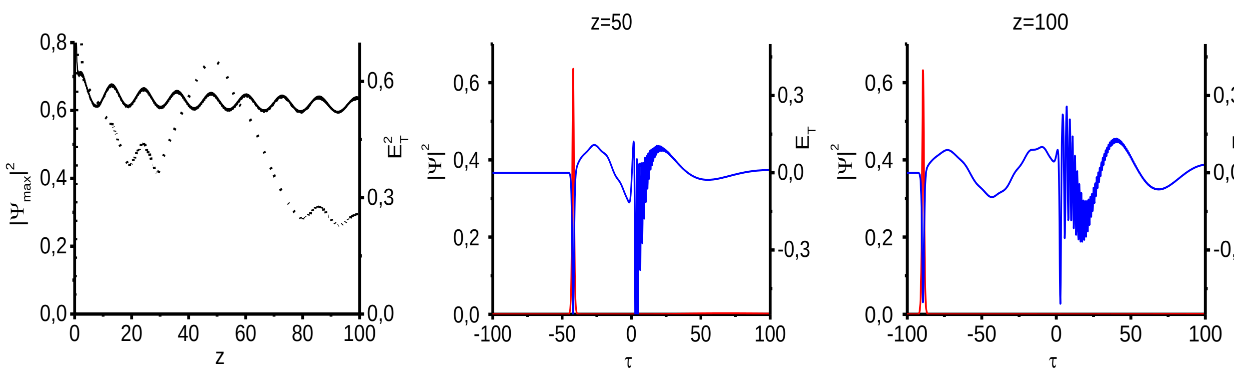




(d) (e)

Figure 5. The same as in Figure 1 except for $N = 10$ and defocusing nonlinearity $p = 1$.

Then, as we did in the previous computational series, we simulate the process at focusing cubic nonlinearity. In Figure 6 the formation of an optical-terahertz soliton is presented, although the generation of the terahertz component is rather less efficient than for the case $N = 30$ (compare with Figure 3).



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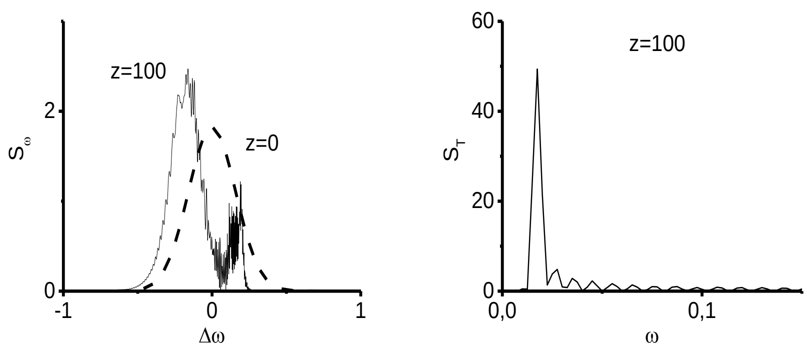


(d) (e)

Figure 6. The same as in Figure 1 except for $N = 10$ and focusing nonlinearity $p = -1$.

In the final series of our computations in the current study we launched at the input of the nonlinear crystal extremely short pulses. Precisely, in (2)-(3) we take $N = 3$. In Figure 7 - Figure 9 we summarize the results which we got in this case. Similar to the previous two series of computations, firstly we simulated the process neglecting Kerr nonlinearity (Figure 7). Three optical-terahertz oscillating solitons are formed. In this case, the spectrum of the generated terahertz signal has a maximum in the low-frequency region, but also a long tail in the high-frequency region. This suggests that, in addition to terahertz radiation, infrared radiation of a fairly wide spectrum is also generated.

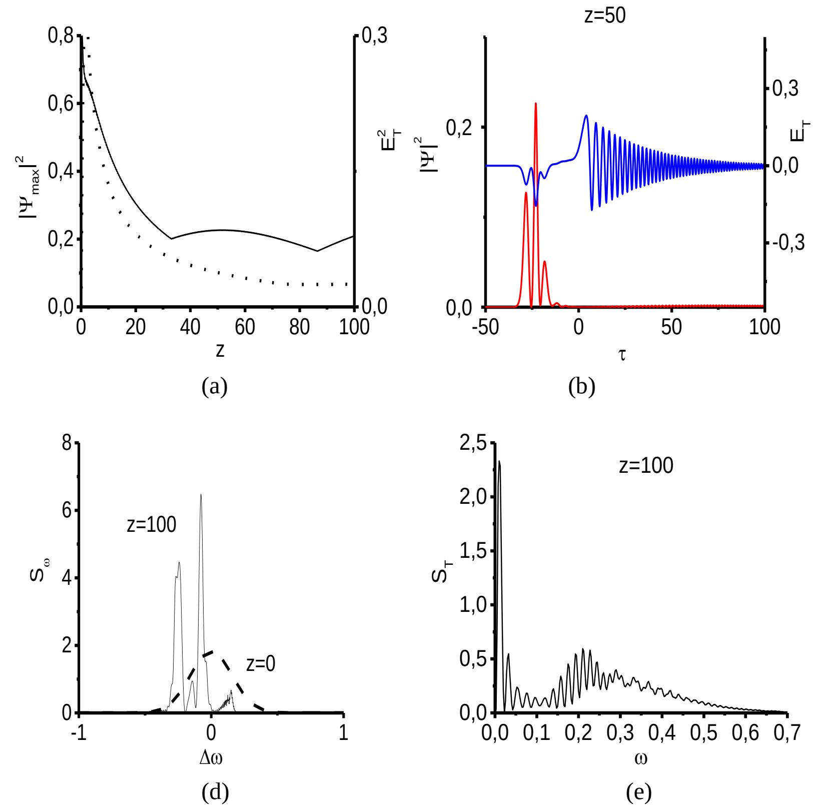
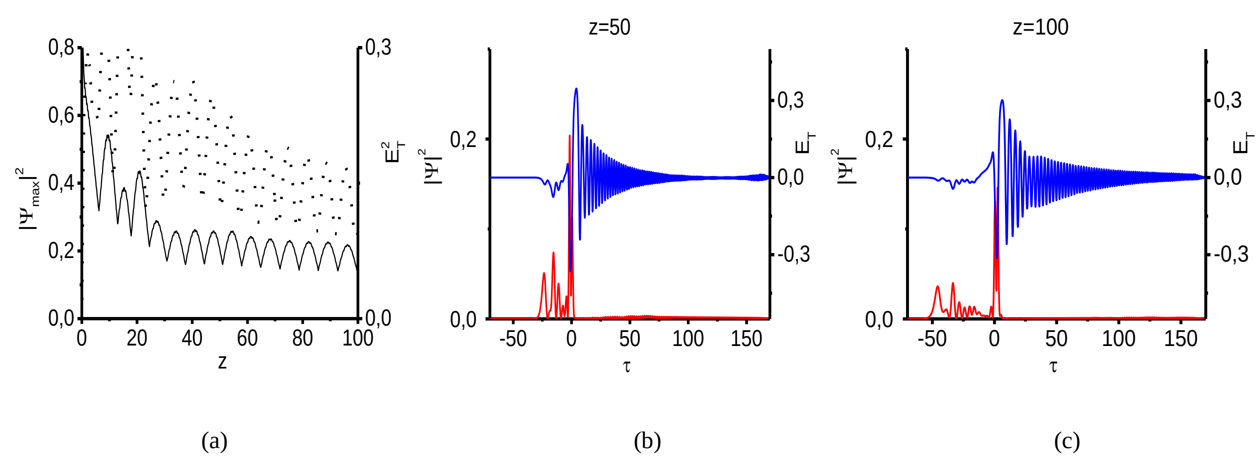
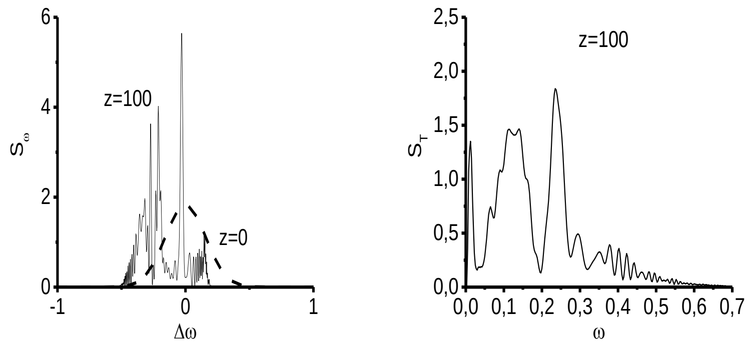


Figure 7. The same as in Figure 1 except for $N = 3$.

Further, we consider the influence of defocusing nonlinearity on the terahertz radiation generation by the extremely short optical pulse (Figure 8). The initial optical signal quickly spreads out, at that, in this case an optical-terahertz soliton is formed and it is well pronounced. In this case, the spectrum of the generated terahertz radiation is quite wide. Comparing Figure 2, Figure 5 and Figure 8, we can conclude that to generate optical-terahertz solitons in media exhibiting Kerr defocusing nonlinearity, it is expedient to use a few-cycle optical pumping.

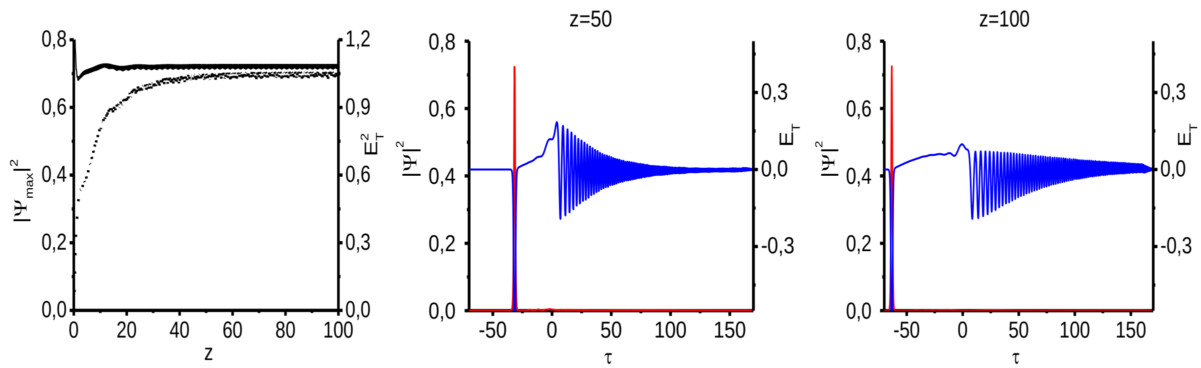




(d) (e)

Figure 8. The same as in Figure 1 except for $N = 3$ and defocusing nonlinearity $p = 1$.

Results for focusing Kerr nonlinearity in the case of the few-cycle initial optical signal are presented in Figure 9. We observe an intense optical-terahertz soliton forming. The stable propagation of this soliton over a distance of 100 nonlinear lengths is traced. The spectrum of the generated terahertz radiation has a low-frequency maximum, but also a long tail to the high-frequency region. This indicates the generation of both terahertz and infrared radiation.



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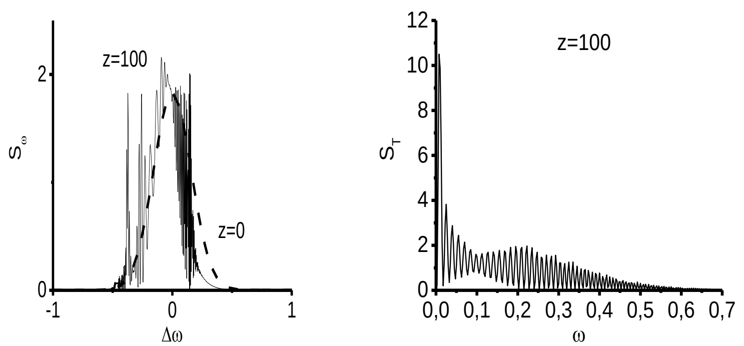

(d) (e)

Figure 9. The same as in Figure 1 except for $N = 3$ and focusing nonlinearity $p = -1$.

In conclusion of this Section we estimate some parameters of the optical-terahertz pulses under consideration. Using the relationship $I_0 = c\psi_0^2 / 4\pi$ between the peak intensity of the input optical pulse I_0 and its peak amplitude ψ_0, we write down the expression for the nonlinear length l_{nl} in the form $l_{nl} = \frac{c}{4\pi\omega\chi^{(2)}}\sqrt{\frac{c}{4\pi I_0}}$. Taking for a uniaxial crystal of lithium niobate $\chi^{(2)} \sim 10^{-8}$ SGSE [14], $\omega \sim 10^{15}\, s^{-1}$, $I_0 \sim 10^{11}\, W/cm^2$, we get $l_{nl} \sim 0{,}1 cm$. Thus, the distances 100 nonlinear lengths mentioned above correspond to the distance interval in a given crystal from 1 to 10 *cm*. In Figure 9 one can see that the amplitudes and, consequently, the intensities of the optical and terahertz components are of the same order of magnitude. It means a rather high efficiency of generation. Thus, the intensities I_{opt} and I_T of both components at the advanced stage of generation can be estimated as $I_{opt},\, I_T \sim 0{,}1 I_0 \sim 10^{10}\, W/cm^2$. Their typical time durations are on the order of ten femtoseconds.

4. CONCLUSIONS

We numerically study terahertz pulse generation at the process of optical rectification. Our simulation is based on the generalized Yajima-Oikawa system with taking into account the cubic nonlinearity dispersion of the optical component and the terahertz component dispersion of oscillatory nature. We believe that these factors are especially important when extremely short optical pulses propagate.

The presented results show that both optical terahertz solitons and terahertz signals can be efficiently generated by a few-cycle laser pulse. At that, in the case of defocusing Kerr nonlinearity, extremely short optical pulses are more efficient for generation than longer ones.

Focusing cubic nonlinearity promotes the formation of optical-terahertz solitons when taking into account the influence of nonlinearity dispersion in the case of extremely short optical signals only three electric field oscillations.

In the case of extremely short pulses, in addition to the terahertz component, a broadband infrared component is also generated at focusing Kerr nonlinearity.

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