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Effect of external electric field and background illumination on the intensity distribution of optical surface waves in the metal – photorefractive crystal system

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Abstract. **The influence of the external electric field and background illumination on the intensity distribution of optical photorefractive surface waves at the metal – photorefractive crystal interface has been numerically simulated. The simulation is performed for a strontium – barium niobate (SBN) crystal using the parameters corresponding to the experimental data. The replacement of a real metal with an ideal one and the choice of the corresponding boundary conditions (depending on the wave power) in the numerical simulation have been substantiated. The calculation results have shown good agreement with the previously published experimental data on the effect of background illumination and a significant discrepancy for the data on the effect of the external electric field. It is found that the effect of the external electric field can be significantly enhanced by reducing the optical power of the photorefractive wave to values close to the threshold ones.**

Keywords: *photorefractive crystal, photorefractive surface wave, surface-wave power.*

1. Introduction

There is a steady interest in the problems related to the physics of photorefractive surface waves (PSWs) [1 – 3]. Progress in this field is expected to facilitate further developments in the fields of optical data processing and nonlinear optics. Nevertheless, most of the published studies were devoted to theoretical calculations. There is no detailed comparison with calculation results in the studies containing experimental data. One of possible reasons is the absence of satisfactory agreement between the experiment and theory. This is quite natural, because this field of optics is still actively developing and the results of the corresponding studies are actively discussed. Unified experimental techniques, technologies, and theoretical models in this field are far from developed to the same extent as in the related field of optics: classical integrated optics [4]. Thus, in our opinion, the experimental results published in this stage must be thoroughly analysed and compared with theoretical models; this approach should facilitate further improvement in experimental methods, development of theoretical models, and establishment of their application limits.

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In this context, we paid attention to study [5], which contains some new experimental data on the properties of PSWs excited on the surface of a promising photorefractive crystal SBN-61. In particular, the observation of a strong effect of additional external background optical illumination and external electric field on the PSW intensity distribution is of special interest. This effect could facilitate development of a radically new elemental base of optoinformatics, including optical switches and light – light modulators. The data we are interested in were described in detail in [5] and illustrated by many experimental photographs; hence, they can be compared with the results of numerical simulation. At the same time, detailed analysis and interpretation of experimental data and their comparison with calculation results were not performed in [5]. The purpose of our study was to fill in this gap.

It should also be noted that the description in the theoretical section of [5] was carried out based on the theory developed by Kukhtarev [6], which, as was recently shown by us [7] and some other researchers, on the whole allows one to describe well the PSW excitation in SBN – metal structures. However, the question of applicability of this theory to the effect of external potential applied to electrodes remains open. On the one hand, purely theoretical calculations were performed in [8, 9] and, on the other hand, some experimental results were published in [5, 10, 11]. However, these data have not been compared in detail. The same holds true for the effect of additional light field on the PSW field.

In this work, we theoretically analysed the effect of background optical illumination and external electric field on the intensity distribution of PSW optical field and compared the results obtained with the experimental data in the literature.

2. Theoretical model

We will consider the optical scheme for exciting and observing PSWs in the metal – photorefractive crystal system that was implemented in a number of studies [5, 11, 12] and described within the theoretical model based on the relations derived for the first time by Kukhtarev et al. [6]. The experimentally studied strontium – barium niobate single crystal SBN-61 occupies the region $L > x > 0$; its optical axis is directed parallel to the X axis; and metal electrodes are deposited on the crystal faces $x = 0, L$, to which a potential difference V can be applied. PSWs with extraordinary polarisation propagate along the Z axis in the surface region ($x \simeq 0$) of the photorefractive crystal with a characteristic width of ~100 μm.

A PSW is formed as a result of interference of an optical wave incident on the interface ($x = 0$) from the crystal side at an angle θ and the optical wave reflected from the interface.

The nonlinear photorefractive effect leads to the formation of a volume phase diffraction grating, which impedes penetration of the interference optical field into the crystal bulk [9]. The diffusion component of photorefractive nonlinearity plays a key role in this process. The drift component, which arises in the presence of the nonzero external electric field, can also affect the PSW characteristics; however, its influence has been considered as minor to date [8, 9]. Specifically for this reason we paid attention to the experimental results of [5], which demonstrated a significant change in the PSW intensity profile under an external electric field of ~1000 V cm^{-1}, which manifested itself, in particular, in a change in the optical intensity distribution width. In addition, the experiment revealed a significant change in the PSW profile under additional background illumination with an intensity of the same order of magnitude as the PSW intensity.

Let us now pass to numerical simulation of this experiment. Since the crystal thickness L is about 5 mm and the characteristic width of PSW distribution along the X axis is 10–100 μm, the allowance for the finite crystal thickness is important for only estimating the external electric field strength $E_0 \sim V/L$. When calculating the PSW field distributions, the crystal was assumed to be infinitely long in the direction of the X axis.

A solution for the PSW field is sought for in the form of stationary modes. For the Y component of the magnetic field strength of a surface TM-polarised wave, the mode field $H(x, z) = H_y(x)\exp(\mathrm{i}\beta z)$, where β is the propagation constant. The fundamental nonlinear differential equation for the PSW magnetic field amplitude $H_y(x)$ can be written as [8, 9]

$$\frac{\mathrm{d}^2H_y(x)}{\mathrm{d}x^2}+\gamma\frac{I(x)}{I(x)+I_\mathrm{d}}\frac{\mathrm{d}H_y(x)}{\mathrm{d}x}-a\frac{I_\infty+I_\mathrm{d}}{I(x)+I_\mathrm{d}}H_y(x)+cH_y(x)=0, \quad (1)$$

where $k_0 = 2\pi/\lambda_0$ is the wave number in vacuum; $\gamma = 2k_0n_\mathrm{e}^4r_{33}k_\mathrm{B}T/q$ is the damping coefficient; $a = k_0^2n_\mathrm{e}^4r_{33}E_0$; $\beta = k_0\cos\theta$; $c = k_0^2n_\mathrm{e}^2-\beta^2$; $I(x)$ and I_∞ are the mode field intensities at the point x and at infinity, respectively; I_d is the equivalent optical dark intensity; r_{33} is the electro-optical tensor component; n_e is the extraordinary refractive index; q is the elementary charge; k_B is the Boltzmann constant; and T is absolute temperature.

The second and third terms of this equation correspond to the diffusion and drift nonlinearities, respectively.

In addition, we assume that $H_y(x)|_{x=\infty} = 0$ (this is the condition for stable PSW propagation [8, 9, 13]) and $I(x)|_{x=\infty} = I_\infty = 0$.

It is convenient to calculate PSW field distributions using dimensionless amplitudes and intensity. Within this approach, the mode field amplitudes are normalised to the magnetic field amplitude H_d, which corresponds to the equivalent optical dark intensity and is related to it, according to the Poynting theorem, through the expression [14] $I_\mathrm{d} = (H_\mathrm{d}^2/2n_\mathrm{e})Z_0$, where $Z_0 = (\mu_0/\varepsilon_0)^{1/2}$ is the vacuum impedance.

We will also take into account that $I(x) = (H_y^2(x)/2n_\mathrm{e})Z_0$ and the dimensionless normalised magnetic component of the PSW field is $A(x) = H_y(x)/H_\mathrm{d}$; then, Eqn (1) takes the form

$$\frac{\mathrm{d}^2A(x)}{\mathrm{d}x^2}+\gamma\frac{A^2(x)}{A^2(x)+1}\frac{\mathrm{d}A(x)}{\mathrm{d}x}-a\frac{A(x)}{A^2(x)+1}+cA(x)=0 \quad (2)$$

or, in the presence of background illumination with intensity I_b and the corresponding amplitude H_b [8, 9],

$$\frac{\mathrm{d}^2A(x)}{\mathrm{d}x^2}+\gamma\frac{A^2(x)}{A^2(x)+A_\mathrm{b}^2(x)+1}\frac{\mathrm{d}A(x)}{\mathrm{d}x}-a\frac{1+A_\mathrm{b}^2}{A^2(x)+A_\mathrm{b}^2+1}A(x)+cA(x)=0, \quad (3)$$

where $I_\mathrm{b} = (H_\mathrm{b}^2/2n_\mathrm{e})Z_0$ and $A_\mathrm{b}(x) = H_\mathrm{b}/H_\mathrm{d}$.

In the absence of the external field and background illumination, we have

$$\frac{\mathrm{d}^2A(x)}{\mathrm{d}x^2}+\gamma\frac{A^2(x)}{A^2(x)+1}\frac{\mathrm{d}A(x)}{\mathrm{d}x}+cA(x)=0. \quad (4)$$

Equations (3) and (4) may have solutions in the form of modes of different types [7]; however, in the experiment analysed here, as well as in some other studies [3, 10], PSWs in the form of

$$A(x) = A_0\exp(-\delta x)\cos(k_xx+\varphi) \quad (5)$$

are excited. Here, the effective damping coefficient $\delta \sim \gamma A^2(x) \times [A^2(x)+1]^{-1}$ determines the characteristic width of mode distribution, $\Delta x \sim 1/\delta$, or, in other words, the mode penetration depth into the crystal bulk along the X axis. Concerning practical applications, the modes with a minimum Δx value and, correspondingly, with a maximum $\delta \sim \gamma$ value are of primary interest. Even under the condition $\delta \ll \gamma$, the distribution described by formula (5) can be formally considered as the PSW intensity distribution; however, in this case it barely differs from the conventional interference pattern formed by a laser beam incident at an angle θ and a reflected beam. As follows from the expression for the effective damping coefficient δ, there is a threshold mode field intensity $A_0^2 \sim A_0 \sim 1$, above which $\delta \sim \gamma$ and below which $\delta \sim \gamma A_0^2 < \gamma$. This circumstance allows one to estimate the laser power P_th that is necessary for PSW excitation with a minimum distribution width under our experimental conditions. On the assumption that the characteristic width of intensity distribution δ_y along the Y axis and the distribution width δ_x along the X axis amount to ~100 μm, we obtain $P_\mathrm{th} \sim I_\mathrm{d}\delta_x\delta_y \sim 10^2$ (W m^{-2}) $\times 10^{-8}$ (m^2) ~ 1 μW.

The PSW power in the experiment considered here was ~1 mW, i.e., significantly exceeded the P_th value. In the absence of the external field and external illumination and with the mode power at this level, Eqn (4) can be replaced with a good accuracy by a linear one, having an analytical solution [7]. Nevertheless, we cannot restrict ourselves to the linear approximation for the PSW equation, because our main goal is to consider specifically the effect of the external field and background illumination; to this end, nonlinear equation (3) must be solved. Let us set the boundary conditions at the interface $x = 0$ as in the case of an ideal metal with infinite conductivity:

$$A(x)|_{x=0} = 0,\ A'(x)|_{x=0} = \frac{\mathrm{d}A(x)}{\mathrm{d}x}|_{x=0} = B, \quad (6)$$

where B is a constant (the choice of this parameter will be discussed below).

3. Calculation results and discussion

Fundamental equation (3) cannot be solved analytically; however, under specified boundary conditions, it can be integrated numerically. Since we chose the boundary conditions for the crystal–ideal conductor interface, it is necessary to set a numerical value of the derivative $A'(x)|_{x=0} = B$. It can be estimated from the following considerations. The power of the excited PSW in the experiment analysed here was ~1 mW, which corresponds to the intensity $I \sim 10^5$ W m^{-2} (at $\delta_x = \delta_y =$ 100 μm). On the assumption that the equivalent optical dark intensity $I_d \sim 10$ W m^{-2} [15], we have $A'(x)|_{x=0} \sim \sqrt{I/I_d}/\delta x \sim 10^7$. Here, δx is the characteristic width of the first maximum in the PSW field distribution, which can be estimated as ~10 μm [7]. Thus, we have $B \sim 10^7$.

We will solve numerically the nonlinear equation by the fourth-order Runge–Kutta method using specifically this B value. To justify the replacement of the real boundary conditions with ideal ones, we will compare the analytical solution for a real metal with the numerical solution for an ideal metal in the region where nonlinear equation (3) passes into linear, which has an exact analytical solution [3, 7]. To this end, we will specify $B = 10^9$ for the numerical solution and the complex refractive index of real metal $n_1 = 0.04 - 2.56$i to be substituted into the exact analytical solution [7]. Note that, when $A_0^2 \sim A_0 \sim 1$, the threshold PSW mode power P_{th} corresponds to $B \sim 10^5$. The calculations will be performed with the following values of the main physical parameters of the system under consideration [2, 5]: $r_{33} = 420$ pm V^{-1}, $n_e = 2.27$, $\lambda_0 =$ 0.53 μm, $\theta = 0.01$ rad, and $T = 3000$ K.

The plots $A(x)$ corresponding to the numerical and analytical solutions are shown in Fig. 1. It can be seen that the solutions practically coincide everywhere except for the narrow interfacial region $|x| \ll 1$ μm with a negligible field amplitude (see the insets in Figs 1a and 1b). Thus, we can conclude that the approximation we used (i.e., the replacement of a real metal with an ideal one) is justified. Note also that, strictly speaking, the interfacial region $|x| < 1$ μm calls for individual consideration, because one must take into account the effect of complex contact phenomena at the metal–photorefractive crystal interface on the PSW optical field [1]. According to [1] (one of the first studies on this subject), the contact phenomena induce an electric field at the interface. Here, the field strength is maximum and exponentially decreases at a characteristic distance on the order of the Debye length $l_D \sim 1$ μm. This pattern may affect the distribution of the PSW optical field near the interface. However, according to our estimates based on the results of [1], the contribution of these effects, in comparison with the effects induced by external fields in question, can be neglected. In addition, we showed previously [7] that the use of the boundary conditions neglecting the contact phenomena at the metal–SBN interface allows one to obtain optical-field distributions that are well consistent with the experimental ones.

Let us now consider the results of simulating the effect of additional background illumination and an external field on the PSW optical field. In the former case, it is convenient to use the normalised background illumination intensity I_{b0} as the main parameter of the problem. This intensity is defined as the ratio of the background illumination intensity to the PSW field intensity: $I_{b0} = I_b/I_0 = A_b^2/A_0^2$.

The numerical simulation results suggest that the background optical illumination significantly affects the intensity of PSW field distribution. If the effective distribution width Δx_{eff} is defined at a level of –3 dB of the maximum intensity, it increases by factors of two and four for $I_{b0} = 0.1$ and 1, respectively. Figure 2 shows the intensity distributions for the PSW optical field at $I_{b0} = 0$ and 1. Our result is in good correspondence with the results of [5], where the number of field extrema doubled under external illumination, a pattern corresponding to approximately twofold increase in the effective width of PSW distribution. This effect can qualitatively be explained as follows: an increase in the external illumination intensity leads to a decrease in the effective damping coefficient $\delta \sim \gamma A^2(x)/[A^2(x) + A_b^2]$ and the corresponding increase in the effective width Δx_{eff} of the mode intensity distribution. At $I_{b0} = 1$ the damping coefficient decreases by half in comparison with the case $I_{b0} = 0$, which corresponds to an approximately fourfold increase in the effective width of the mode intensity distribution. Thus, the influence of external illumination on the PSW intensity distribution, which was experimentally observed in [5], is in good correspondence with the results of numerical calculations in the framework of Kukhtarev's theory.

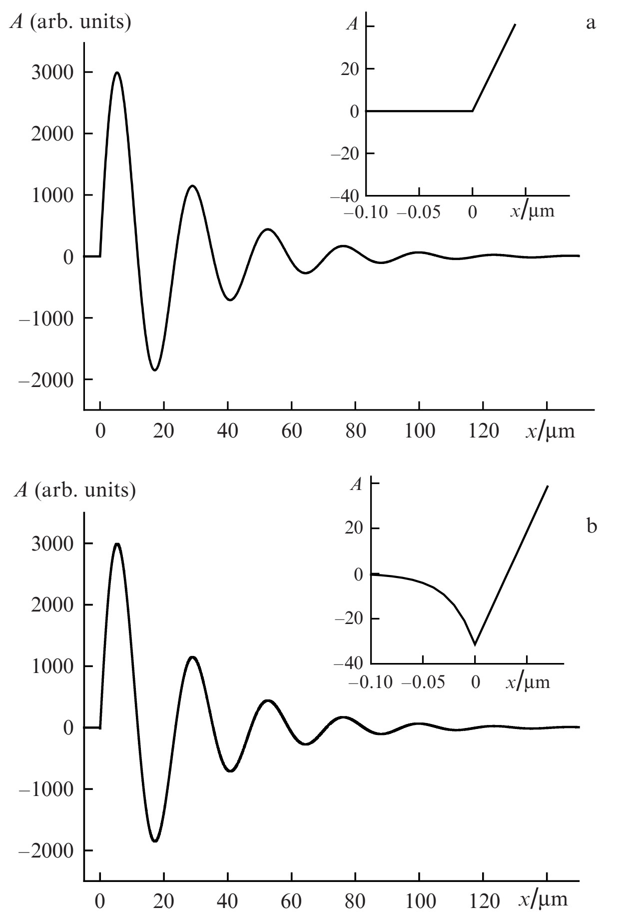

Figure 1. Normalised PSW field distribution $A(x)$ at $B = 10^9$, obtained (a) numerically for an ideal metal and (b) analytically for a real metal. Both insets show the dependence $A(x)$ in the narrow interfacial region.

Let us further consider the results of the numerical simulation of the effect of external electric field on the PSW intensity distribution. The simulation was performed in the absence of background illumination, for three values of external electric field strength: $E = -10^5$, 5×10^4, and 10^5 V m^{-1}. Note that $E =$ 5×10^4 V m^{-1} corresponds to the threshold value [8, 9]

$$E_{th} = (k_0^2 n_e^2 - \beta^2)/(k_0^2 n_e^4 r_{33}), \quad (7)$$

above which the PSW becomes unstable. In numerical calculations, this manifests itself in the form of nonzero compo-

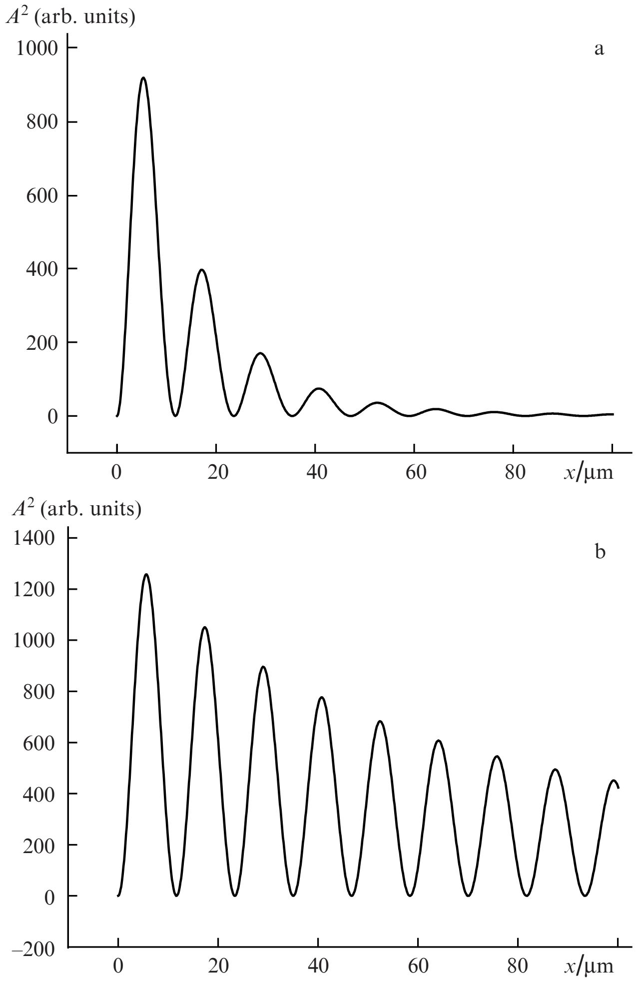

Figure 2. Effect of the background illumination intensity I_{b0} on the PSW intensity distribution at I_{b0} = (a) 0 and (b) 1; $B = 10^7$.

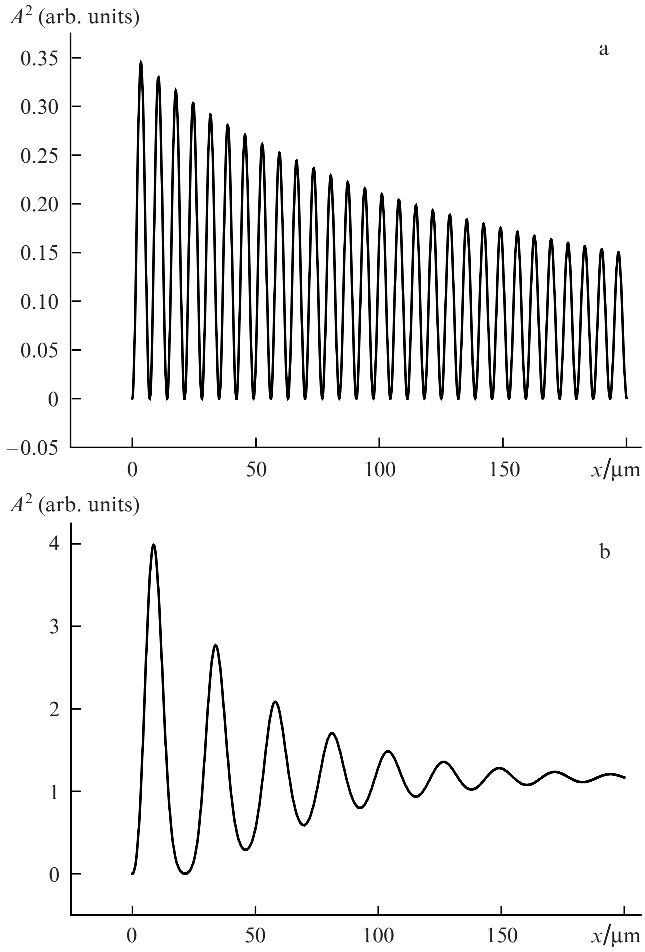

Figure 3. Effect of the external field on the PSW intensity distribution at E = (a) -10^5 and (b) 10^5 V m^{-1}; $B = 10^5$.

nent of the mode field at infinity, i.e., $I(x)|_{x=\infty} = I_\infty \neq 0$, which obviously contradicts the initially specified condition used to search for a solution to Eqn (1). Experimentally, this effect can be observed in the form of modulation instability [13].

In this case, the simulation results significantly differ from the experimental data considered here. The differences in the calculated intensity distributions for the PSW optical field begin to manifest themselves only in the region $x > 20$ μm, where, in the absence of the external field and background illumination, the optical intensity decreases by more than an order of magnitude in comparison with its maximum value (Fig. 2a). And, although the changes in the period and amplitude of intensity oscillations in this region with a change in E from -10^5 to 10^5 V m^{-1} reach several tens of percent, the effect is on the whole weakly pronounced against the background of the entire distribution, i.e., in the region $x > 0$. This obviously contradicts the experimental results (see photographs in [5]) demonstrating at least a twofold change in the effective width of the field intensity distribution at the same variations in the external electric field.

This discrepancy can be explained by both the shortcomings of the theory and the experimental errors. It should be noted that the theory used, as a whole, has been considered adequate to date by different researchers, including the authors of [5]. We verified our numerical simulation by comparing the results with the data in the literature [8, 9] for other simulation parameters and obtained good correspondence. Nevertheless, we do not exclude that the theory may call for further refinement, in particular, by taking into account the nonuniform distribution of applied external field in the crystal bulk and the contact phenomena at the metal–photorefractive crystal interface. In our opinion, careful check of the experimental results considered here is also expedient and useful for further development of this field of optics.

In regards to the possibility of enhancing the effect of the external field on the PSW field distribution, as follows from Eqn (3), the influence of the drift term $a(1 + A_б^2)\times[A^2(x) + A_б^2 + 1]^{-1}A(x)$ decreases both when the mode field amplitude A_0 tends to zero and at $A_0 > 1$. Therefore, the maximum effect of the external electric field on the mode field distribution should be expected at an amplitude $A_0 \sim 1$, i.e., near the threshold of the optical power intensity.

To verify this suggestion, we performed additional numerical simulation of the effect of the external field at $B \sim 10^5$ (a value corresponding to the mode field amplitude $A_0 \sim 1$ in the absence of the external field). In this case, the external field was found to significantly affect the intensity distribution of the PSW field. At $E = -10^5$ V m^{-1} (Fig. 3a), the effective intensity distribution width of the PSW field decreases by a factor of about four in comparison with its value at $E = 5\times10^4$ V m^{-1}, while at $E = 10^5$ V m^{-1} (Fig. 3b) the PSW becomes unstable, which manifests itself in a nonzero intensity at infinity. However, as was shown above, the PSW field amplitude A_0 ~1 corresponds to the PSW optical power ~1 μW, which is several orders of magnitude lower than the PSW power experimentally observed in [5].

4. Conclusions

We performed numerical simulation of the effect of background optical illumination and external electric field on the optical field intensity distribution in a PSW excited in an SBN crystal. The simulation was performed by numerical solution of the nonlinear differential equation based on Kukhtarev's theory, with the parameters corresponding to the recently published experimental data [5]. It was established that the experimentally observed effect of external illumination is in good correspondence with the results of numerical simulation. At the same time, the significant effect of external field on the PSW intensity distribution, which was revealed in the experiment, is inconsistent with the numerical simulation data. The analysis of the nonlinear equation and the simulation results show that the effect of external field can be enhanced with a decrease in the PSW power to a level close to threshold. The results obtained indicate that the analysis of this problem with additional experimental investigations should be continued.

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