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Surface photorefractive wave on the boundary of a photorefractive metal-coated crystal

B.A. Usievich, D.Kh. Nurligareev, V.A. Sychugov, L.I. Ivleva, P.A. Lykov, N.V. Bogodayev

***Abstract*. Special features of light-induced scattering of radiation ($\lambda = 0.44$ μm) with extraordinary polarisation in the SBN-75 photorefractive crystal are studied in detail and an efficient technique is proposed for exciting surface waves in this crystal. In the experiment carried out the efficiency of the surface wave excitation was $\sim 30\,\%$, which is 50 times greater than that achieved earlier in exciting nonlinear surface waves in the optical region. The patterns of the near and far fields of the surface wave are presented. It is found that at small excitation angles ($0 - 1.5°$) the presence of a metal changes the character of arising surface waves.**

Keywords: *photorefractive crystal, surface photorefractive wave, metal-coated crystal surface.*

1. Introduction

The particular interest of researchers to nonlinear surface waves that arose in the last years of the 20-th century have not weakened till the present time [1 – 3].

The surface photorefractive (PR) wave is an electromagnetic radiation (propagating along the interface between a photorefractive crystal and air) weakly penetrating into the air and exponentially decaying in the crystal with formation of a refraction index grating reflecting the wave that propagates away from the surface, so that the energy is localised in the vicinity of the crystal surface.

The localisation of the surface wave near the PR crystal surface means that the propagation of the surface wave is similar to waveguide propagation. The relevant waveguide is of Bragg type, since at the interface between the media the total internal reflection occurs, and the other (Bragg) reflection is implemented by the refraction index grating with layers, located inside the PR crystal parallel to the interface. In our case the periodical variation in the crystal refraction index occurs due to the photorefractive effect, namely, the change in the refraction index under the action of light. In an electro-optical crystal it is associated with the linear modulation of the refraction index by the electric field (the Pockels effect), caused by photoexcitation and spatial redistribution of charge carriers under the inhomogeneous illumination. An important difference between the structure studied here and the Bragg waveguide, considered by Yariv [4], is that the periodical distribution of the refraction index is created by the electromagnetic wave itself propagating in the structure.

A characteristic feature of the propagation of spatially limited beams of light through single-domain PR crystals is the beam fanning, i.e., the effect of light-induced scattering [5 – 7]. In the course of time this scattering usually gives rise to the formation of a noise pattern of outcoming light intensity, i.e., a set of randomly located light spots, each corresponding to a scattered wave, amplified at the expense of power transfer from the incident beam. The directional pattern of the scattered radiation is shifted with respect to the incident beam in the direction, opposite to the vector of spontaneous polarisation $\boldsymbol{P}_{\mathrm{s}}$ (or the axis $\boldsymbol{c}$) of the crystal, i.e., towards the crystal face, along which the surface wave is excited. Studying the features of this effect is of primary importance for understanding the PR wave formation.

We have shown experimentally [8] that nonlinear surface waves can be excited not only at the interface between the crystal (SBN-75) and air, but also in the case when the active surface of the crystal is coated with an electrode, e.g., a layer of aquadag. This observation offers the possibility to study new properties of the surface wave under the external electric field, applied to the crystal. However, many practically important questions still require elucidation. The goal of the present paper is to study the influence of the additional conducting layer on the field profile of the surface wave, as well as on the conditions of its excitation and propagation.

2. Excitation of a surface wave in a metal-coated crystal

The authors of [1] presented the solution for the problem of nonlinear surface waves, excited at the interface between a PR crystal and air, as well as between a PR crystal and metal. According to the calculations [1], the surface wave in a metal-coated crystal does not differ from that in a crystal, contiguous with air. The surface wave under the metal is localised near the PR crystal surface. As was shown [8], the study of the fanning pattern, observed for the radiation of a He – Cd laser with extraordinary polarisation, allows the choice of the crystal surface, at which the nonlinear surface waves can arise. We considered in [8] only the far-field fanning pattern; however, a more complete understanding

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B.A. Usievich, D.Kh. Nurligareev, V.A. Sychugov, L.I. Ivleva, P.A. Lykov, N.V. Bogodayev A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
e-mail: borisu@kapella.gpi.ru

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of the light-induced scattering can be achieved by observing the fanning in the near field, too.

At the wavelength of 0.44 μm the fanning is particularly strong. That is why it was important for us to search for such conditions of excitation of nonlinear waves near the surface of the PR crystal, under which the influence of fanning would be minimal. With this aim the features of fanning were studied at passing the focused laser beam in the vicinity of the crystal surface, coated with a layer of metal.

Figure 1a shows the optical scheme of the experimental setup, used in the present study to observe the specific features of fanning when the laser beam propagates through a crystal and to investigate the peculiarities of surface wave excitation in a metal-coated PR crystal. The angle α of the exciting light beam incidence on the crystal is related to the angle θ of light incidence on the inner surface of the crystal as follows:

$$\sin\alpha = n\cos\theta, \tag{1}$$

where n is the refraction index of the crystal.

This scheme differs from that used in [8] by the additional (removable) lens (*10*), providing the formation of the far-field pattern on the screen (*7*). Without this lens the image of the crystal face (near-field) is displayed on the screen. The lens (*10*) together with the lens (*5*) forms a telescopic system that allows one to obtain the far-field pattern on the same screen.

Figure 2 illustrates the fanning patterns when the laser radiation beam with extraordinary polarisation propagates through the crystal normally to its axis ***c***. The far-field patters were obtained for the beam radius w_0 (at the e^{-1} intensity level) at the input face of the crystal ~ 30 μm (Figs 2a–c) and ~ 150 μm (Fig. 2d). The beam power was 5 mW, the exposure time $t = 1$ s, 5 s, and 3 min. It is seen that already at $t = 1$ s the intensity distribution in the laser beam, passed through the crystal, differs from that in the initial Gaussian beam, namely, the decrease in intensity in the central part of the beam leads to splitting of the intensity maximum into two peaks. At longer exposure times (5 s and 3 min) in the left-hand part of the image a stable speckle pattern is formed, occupying a vast pyriform area. In the right-hand part of the image the light intensity distribution remains regular and localised within the initial Gaussian beam. The observed features of fanning agree with the models, proposed in Refs [5, 7].

As known, many features of light propagation in PR crystals are associated with the beam shape rather than with its intensity and, therefore, the character of the field pattern at the crystal output should not change significantly at variation of the input Gaussian beam size. This is confirmed by the far-field pattern (Fig. 2d), obtained at the increased beam radius ($w_0 \sim 150$ μm) with the beam power (5 mW) being unchanged. The diffraction divergence at the beam radius, increased by five times, must be five times smaller, which is seen in Fig. 2d.

In Fig. 3 the near-field patterns are shown (magnification $M = 330$), obtained when the laser radiation beam with extraordinary polarisation propagates through the crystal perpendicular to its ***c*** axis (parallel to the metal-coated surface of the crystal). The radius of input beam

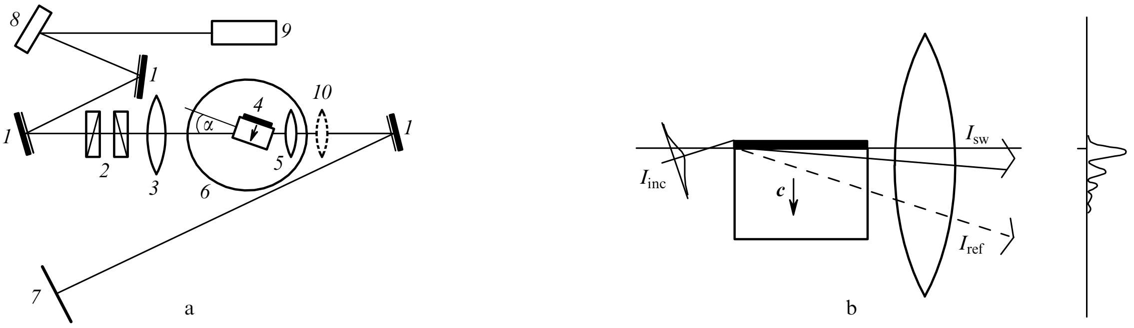
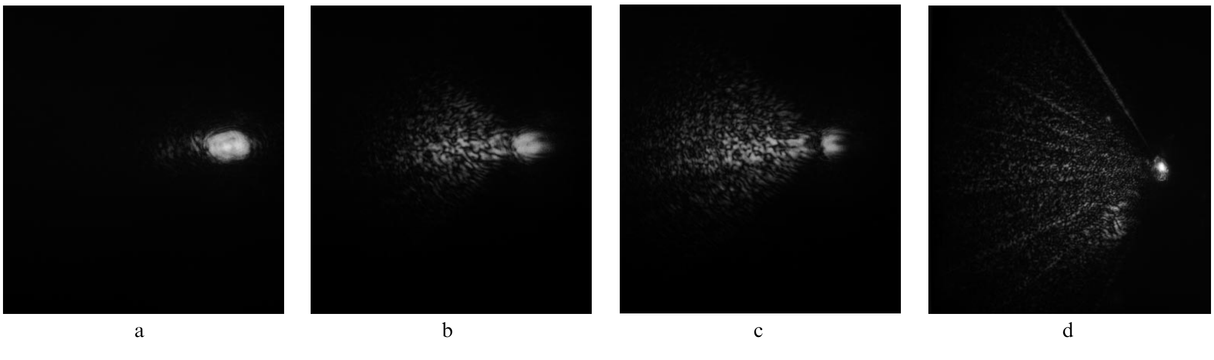


Figure 1. Optical scheme of the experimental setup (a) and the scheme of the surface wave excitation in the SBN-75 crystal (b): (*1*) mirrors; (*2*) polarisers; (*3*) long-focus lens; (*4*) sample; (*5*) microscope objective; (*6*) goniometer table; (*7*) screen; (*8*) polarisation rotation unit; (*9*) He–Cd laser; (*10*) removable lens; I_{inc}, I_{sw}, and I_{ref} are the incident, surface and reflected wave, respectively.



a b c d

Figure 2. Far-field patterns, obtained at passing the laser beam with the radius $w_0 = 30$ (a – c) and 150 μm (d) through the SBN-75 crystal for the exposure times $t = 1$ s (a), 5 s (b), and 3 min (c, d).

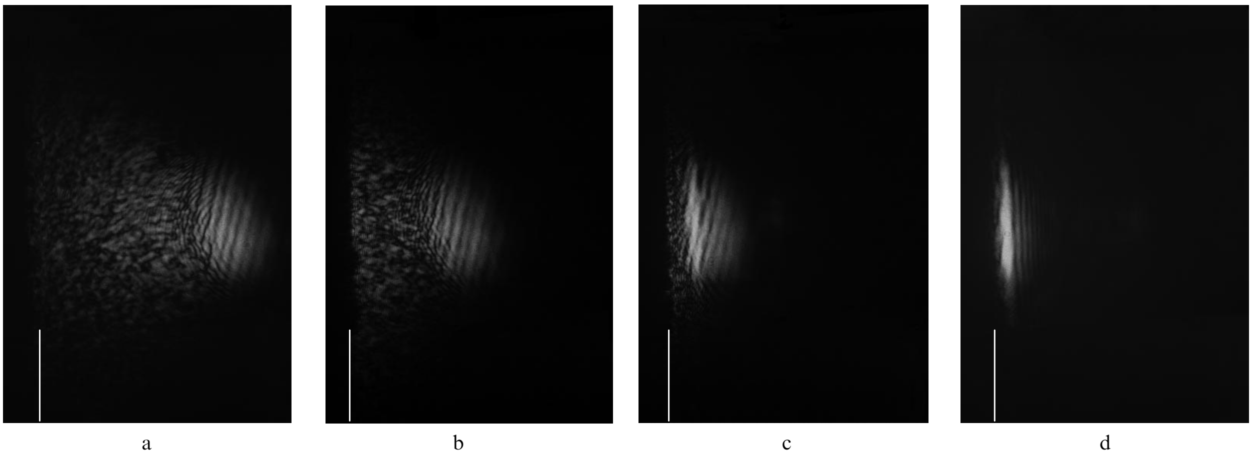


Figure 3. Distributions of the light intensity at the output face of the crystal at shifting the centre of the exciting beam from the metal electrode in the direction of the $\boldsymbol{c}$ axis by the distances $z_0 \approx 300$ (a), 150 (b), 0 (c), and -50 μm (d). The white lines show the crystal boundaries.

$w_0 \sim 150$ μm the power is 5 mW. The patterns are obtained at shifting the laser beam centre from the metal-coated surface in the direction of the axis $\boldsymbol{c}$ by the distance z_0, equal to 300, 150, 0, and -50 μm. At $z_0 \approx 2w_0$ (Fig. 3a) the influence of the metal coating on the light wave field distribution in the illuminated region of the crystal can be considered as negligible. The diagonal stripes visible in the right-hand part of Figs 3a–c are due not to the excitation process, but to the presence of crystal imperfections in the region of beam passing.

At $z_0 \approx 2w_0$ (Fig. 3b) one can notice weak influence of the metal coating on the fanning pattern, which manifests itself in the small-scale interference fringes appearing in the area of the speckle pattern and is due to the reflection of a part of scattered waves at the interface with metal.

A further decrease in the beam shift ($w_0 > z_0 > 0$, Fig. 3c) leads to the reduction of the transverse size of the region, occupied with the speckle pattern, and in the right-hand part of the Gaussian beam an interference fringe of enhanced brightness appears. At $z_0 < 0$ (Fig. 3d) the small-scale spots of scattering are not observed, and actually all the power of the light wave, introduced into the crystal, is concentrated (in the transverse direction) in a band ~ 20 μm wide.

The scheme of surface wave excitation in a metal-coated crystal, presented in Fig. 1b, substantially repeats the prism technique of a common waveguide excitation. It is known, that to achieve high efficiency of the surface wave excitation it is important to obtain a suitable distribution of the exciting wave field. Earlier the excitation of nonlinear surface waves was implemented using two methods. The first method [9] is the excitation through the sample face, the exciting radiation propagating along the same crystal face as the surface wave. At the end of this face the problem of separating these waves for registration arises. The authors of [9] used a near-field microscope to reveal the field intensity distribution for the surface wave at the output face of the crystal.

In the second excitation method [10], besides the basic exciting wave with TM polarisation, an additional illumination with incoherent radiation was applied. At the angle of incidence, used by the authors, the surface and the exciting wave were separated primordially, because the surface wave arises due to the total internal reflection of the exciting light, incident on the crystal surface. Unfortunately, in the region of angles, chosen by the authors of Ref. [10], the efficiency of the surface wave excitation appeared to be not high. At the power of the exciting beam 60 mW, the power of the surface wave appeared to be 300 μW.

The results of Ref. [1] and the revealed features of fanning in PR crystals allow one to conclude that the efficiency of the surface wave excitation can be substantially increased using grazing incidence of the exciting beam ($\theta \approx 89°$). Moreover, for optimal excitation of the surface wave we used only one part of the beam, whose intensity decreases with moving off the boundary, for which the effect of fanning is minimal. The other part of the beam falls on the metal layer and is absorbed. With our way of excitation the surface wave appears as a result of total internal reflection of the inhomogeneous beam, incident on the metal-coated surface of the crystal. The surface wave propagates along the crystal surface. At the power of the exciting beam 6.7 mW (measured behind the long-focus lens), the shift $z_0 \approx 0$ and the angle of incidence $\alpha = 3°$ we managed to obtain the surface wave with the power 1.8 mW (measured behind the microscope objective). Hence, the scheme, proposed by us, allows increasing the surface PR wave excitation efficiency by more than 50 times.

3. Radiation pattern of the excited wave in the metal-coated crystal at changing the exciting wave incidence angle

The surface wave can be represented as a result of interaction of the incident and the reflected inhomogeneous waves, whose amplitudes decrease exponentially with penetration depth [1]. In the case of the incidence angles $\theta \sim 90°$ these waves in the output plane are not spatially separated. As was shown in [8], in the near field the pattern of the wave on a crystal, contacting with air, behaves periodically with the period Λ determined by the angle θ between the wave vector of the incident wave in the PR crystal and the normal to its surface:

$$\Lambda = \frac{2\pi}{\left(k_0^2 n_2^2 \cos^2\theta - \gamma^2/4\right)^{1/2}}. \tag{2}$$

Here

$$\gamma = \frac{2k_0^2 n_2^2 r_{\mathrm{eff}} k_{\mathrm{B}} T}{q}$$

is the nonlinear constant of the crystal; $k_0 = 2\pi/\lambda_0$; λ_0 is the wavelength of the light; q is the elementary charge; r_{eff} is the effective electrooptical coefficient; k_{B} is the Boltzmann constant; T is the crystal temperature.

The revealed features of the photorefraction of waves near the boundary of the metal-coated crystal make it possible to assert that the waves, excited near such a surface, may also possess specific features, which are not observed in a crystal, contacting with air.

To check this hypothesis, we studied the surface waves in a metal-contacting crystal at different angles of incidence of light onto the input face of the crystal. Figure 4 shows the near-field patterns at different angles of incidence α. In Fig. 5 the corresponding patterns of the far field are presented.

We managed to register the surface waves with characteristic periodical distribution of radiation intensity in the region of the incidence angles $\alpha \sim 2.5° - 7°$. A typical near-field pattern of the surface wave is presented in Fig. 4a ($\alpha = 4°$). The wave field is a result of interaction of two waves, whose presence may be clarified by observing the radiation pattern in the far-field zone, which is just what is shown in Fig. 5a ($\alpha = 4°$). The far-field pattern demonstrates two distinct peaks, corresponding to two waves, forming the surface wave. It is worth noting that the metal coating shifts the lower boundary of the range of consistent surface wave excitation towards greater angles of incidence. The surface waves in the crystal, contacting with air, were excited in the region of angles $\alpha \approx 1.5° - 5°$ [8].

At the angles of incidence on the input face of the crystal $\alpha < 2.5°$ the periodical character of the radiation pattern is disturbed and depends of the position of the exciting Gaussian beam. At $\alpha = 2°$ (Fig. 4b) the intensity maximum nearest to the surface is broadened and shifted into the crystal. In the far field (Fig. 5b) the pattern looks more complex and the peaks, corresponding to two interacting waves that form the surface wave, are less pronounced. The

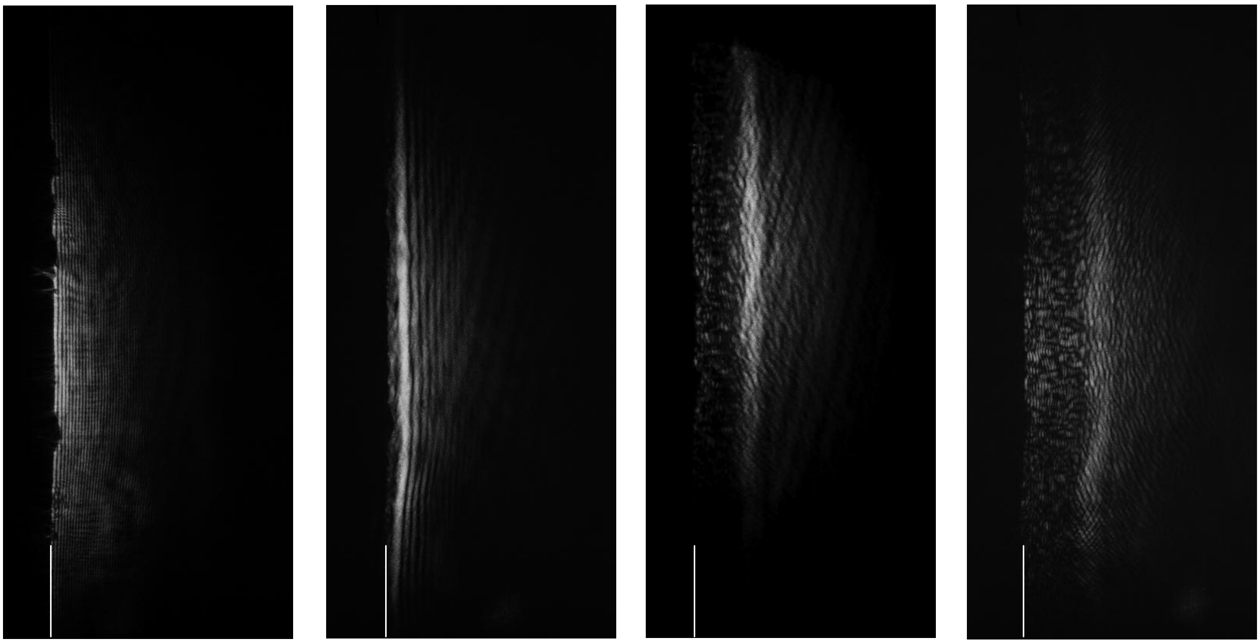


Figure 4. Distributions of light intensity at the output face of the crystal under the excitation of the surface wave. The angles of incidence of the exciting wave are $\alpha = 4°$ (a), 2° (b), 0.5° (c), and 0 (d). The white lines show the boundaries of the crystal.

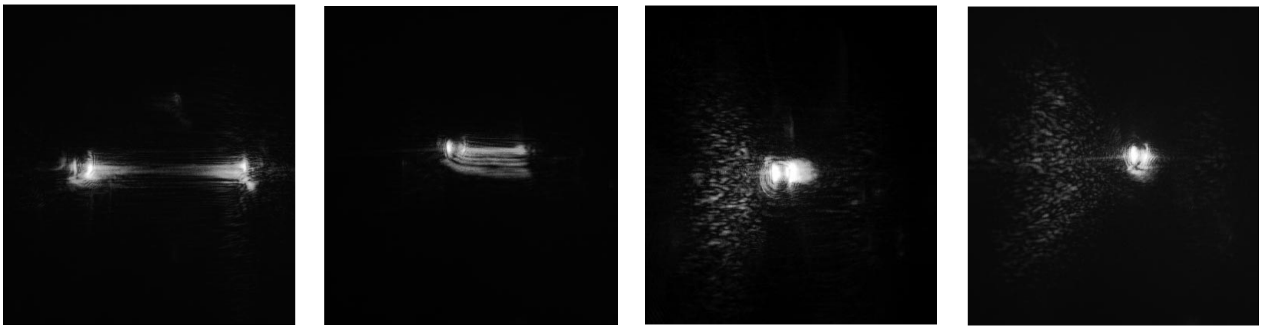


Figure 5. The radiation patterns in the far-field zone. The angles of incidence of the exciting wave are $\alpha = 4°$ (a), 2° (b), 0.5° (c), and 0 (d).

comparison of Figs 4a and b shows that at smaller angles α the excited waves are more sensitive to the surface defects.

In Figs 4c ($\alpha = 0.5^\circ$) and d ($\alpha = 0$) the radiation patters at $z_0 \approx 0$ are presented. In this case the observed pattern essentially changes, i.e., the intensity distribution in the excited wave becomes non-periodic and the scattering (fanning) become noticeable. For the wave detected at the output of the metal-coated crystal, a characteristic feature to be noticed is the wide bright stripe in the region of the crystal, not adjacent to the metal layer. Note that with the decrease of α a shift of the stripe into the crystal is observed. These features are most distinctly pronounced in the range of the exciting radiation angles $\alpha \sim 0 - 2^\circ$. In our opinion, their appearance may be associated with the change in the electrostatic field distribution produced by the bulk charges in the illuminated region of the crystal due to the presence of the metal coating. The observed wave may be called near-surface, because the intensity maximum is localised inside the crystal (a few tens of microns from the crystal – metal interface).

4. Conclusions

As a result of the performed experimental study of the features of light-induced scattering in the nonlinear SBN-75 crystal and the surface waves, excited at its metal-coated surface, it is found that in the course of propagation of a light beam with extraordinary polarisation not only the scattering effect arises in the crystal, but also the effect of self-limitation for a part of the beam, propagating in the crystal without appreciable diffraction divergence. With the revealed features of fanning taken into account, a technique for the excitation of surface waves in a PR crystal is proposed.

The surface PR wave, propagating along the PR crystal – metal interface, is studied. In the course of its propagation near the metal-coated surface of the crystal we found peculiar features in the wave field distribution, consisting in the appearance of a broadened stripe of radiation and in its shift from the origin of the pattern, i.e., the metal-coated surface edge. The range of incidence angles for the exciting radiation is determined ($\alpha \approx 0 - 2^\circ$) in which these specific features manifest themselves most clearly. The peculiarities of the excited nonlinear waves, revealed in the presence of metal coating, require further theoretical analysis.

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