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Multiple noncritical phase-matchings in biaxial KTP crystal

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A general approach is developed and conditions of noncritical phase matchings (PM) of different multiplicity for the sum frequency generation process are analyzed taking a biaxial KTP crystal as an example. The approach is based on the consideration of general properties of a PM surface constructed in the frequency and angle coordinates, analysis of their singular lines and intersection points of those lines. The lines of non-criticality in signal frequency or in the propagation angles of the interacting waves have been considered on the PM surface. The classification of double-uncritical (in frequency and one of the angles or in two angles) PMs is proposed. The possibility to realize a triple non-criticality in three independent quantities, for example, frequency and two angles, has been shown. It is found that the double non-criticality (in frequency and IR signal divergence) region can be scanned over the whole transparency range of KTP under frequency tuning of the long-wavelength laser pumping. Multiple non-critical PMs allow visualizing the broadband IR spectra and IR images.

На примере двухосного кристалла КТР развит общий подход и проведен анализ условий некритичных фазовых синхронизмов (ФС) различной кратности для процесса генерации суммарной частоты. Подход основан на рассмотрении общих свойств поверхности ФС, построенной в координатах частот и углов, анализе их особых линий, а также точек пересечения этих линий. На поверхности ФС рассмотрены линии некритичности по частоте сигнала или углам распространения взаимодействующих волн. Предложена классификация двукратных некритичных ФС (по частоте и одному из углов или по двум углам). Показана возможность реализации некритичности по трем независимым величинам, например, частоте и двум углам. Установлено, что область двукратной некритичности по частоте и расходимости ИК сигнала может сканироваться по всей области прозрачности КТР при перестройке частоты длинноволновой лазерной накачки. Кратные некритичные ФС позволяют визуализировать широкополосные ИК спектры и ИК изображения.

Interest in investigation of three-wave interactions in nonlinear anisotropic crystals is considerably increased during last decades. These crystals make it possible to convert infrared (IR) signals and images into visible or near–IR and UV spectral regions convenient for recording [1–4]. This interest is caused by the availability of fast-acting broadband and multichannel radiation receivers in visible and near-IR, including high-sensitivity CCD chambers. It is significant that the converted signal keeps in general the information contained in the spectral-angular distribution, and consequently in temporary and spatial structure of converted radiation, that forms a base for visualization of invisible signals and images [2–5]. The phase-matching conditions for interacting waves are of great importance for frequency conversion of signals based on sum- and difference-frequency generation $\omega_R = \omega_P \pm \omega_S$ (indexes P, S and R correspond to pumping, signal, and resulting waves, respectively). In the vicinity of critical phase-matching (PM), the wave mismatch Δk for processes of frequency conversion increases linearly with frequency and the signal propagation angle. In this case, the spectral width of PM $\delta\nu \sim 1\text{–}10\ \mathrm{cm}^{-1}$ and angular width $\delta\varphi$ about ten angular minutes are typical values. However, for the purposes of nonlinear spectroscopy, it is necessary to convert into visible range as wide IR radiation spectrum as possible at minimum of distortions [4]. Because of strong dependence of PM conditions on frequencies and directions of interacting waves, a problem of great importance in nonlinear optics is the creation of special (so-called noncritical) PM conditions admitting rather wide actual range of frequencies and wave propagation angles. Scientifically, this problem is reduced to an optimum combination of anisotropy and dispersion of medium for the purposes of nonlinear-optical frequency conversion. Practically, it is reduced to a choice of necessary functional materials to solve a specific problem. For effective conversion of thermal radiations with a large angular aperture, it is necessary to use the known vectorial scheme of tangential phase-matching (Warner's scheme) [3, 5, 6]. The schemes of PM uncritical in angle were used to convert the images with a far and close situation of object in uniaxial [3, 6 – 8] and biaxial crystals [9]. There are considerably wider possibilities to realize the broadband conversion of IR radiation. For this purpose, the group PM [5, 10, 11] can be used, when, along with the usual vectorial PM conditions $\omega_R = \omega_P \pm \omega_S$, $\mathbf{k}_R = \mathbf{k}_P + \mathbf{k}_S$, the group velocity matching conditions for signal and generated radiation are met, that, at narrow-band pumping, can provide the usual PM conditions to be met in a wide frequency range. In particular, in the collinear interaction, this needs equality of group velocities $\partial\omega/\partial k_S = \partial\omega/\partial k_R$ taken at the central frequencies of pumping and generated radiation. The region of group phase-matching can be tuned in frequency by changing the pumping wavelength or using different nonlinear crystals. Some scanning possibilities of the group PM region when using vector interaction of waves were studied in [11, 12], however, the problem of uncritical PMs remained insufficiently investigated for a long time.

The optimum condition for IR radiation conversion is the combined group and tangential PM, that is, realization of double non-criticality both in frequency and angle. For the first time, such conditions were realized experimentally by Midwinter and Warner in a $LiNbO_3$ crystal [5, 6]. When using pumping at $\lambda_P = 1.064$ μm, the values of $\delta\nu = 260$ cm^{-1} and $\delta\varphi = 35$ mrad (at half intensity height) were attained near the signal wavelength of $\lambda_S = 3.5$ μm. The problem of noncritical (in the signal radiation frequency and propagation angles of the interacting waves) PM was considered theoretically in a series of our works [13–17]. The analytical consideration of this problem allowed us to formulate the general concept of noncritical in frequency vectorial group PM and also double and triple PMs noncritical in frequencies and wave propagation directions. In the previous works, more attention was paid to the demonstration of noncritical PM possibilities when using uniaxial crystals. However, in the last decade, novel high-quality nonlinear crystals, in particular, biaxial crystal of potassium titanyl phosphate $KTiOPO_4$ (KTP) and its isomorphs RTP, KTA, In:KTA, RTA, CTA [18] are appeared. The use thereof together with the developed concept of multiple noncritical PMs can favor improvements in up-converters of signals and images [19, 20], and also creation of new generation of spectrometers.

The KTP crystal is one of the most perspective nonlinear materials in its transparency range 0.35–4.5 μm. It is characterized by high nonlinear optical coefficients ($\sim 7 \cdot 10^{-12}$ m/V) and high optical damage threshold ($\sim$500 MW/cm^2) [20, 29, 30]. Because of weak temperature dependence of birefringence ($\sim 10^{-5}$/K), the PM tuning is provided by changing the wave interaction geometry or tuning the pumping wavelength, that can be realized using, for example, tunable Ti:sapphire laser ($697 < \lambda_P < 1100$ nm) or other long-wavelength lasers with fixed wavelengths [21]. In this work, taking a KTP crystal as an example, the general approach to consideration of multiple uncritical PMs in biaxial crystals is developed. It is shown that broad-band and wide-angle PMs are realized along the singular lines on the PM surface, and double PM non-criticality in frequencies and angles is attained at intersection points of those lines. We have established the possibility of tuning the double non-criticality region practically over the whole transparency range of KTP when changing the laser pumping wavelength. As the PM surface size is decreased, the triple PM uncriticality in frequency and the propagation directions of the interacting waves can be realized.

Optical parametric interaction in a nonlinear crystal goes on most effectively when the PM conditions are fulfilled:

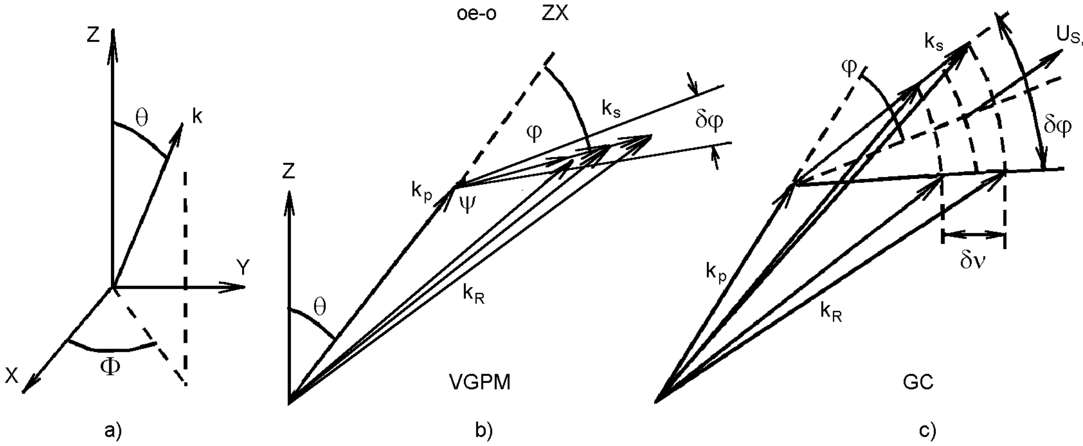

Fig. 1. (a, b, c) Diagrams showing vectorial group phase-matching nouncritical in frequency of signal radiation (VGPM) and phase-matching noncritical in frequency and angle (GC — "the group center") in a KTP crystal.

$$\omega_R = \omega_P + \omega_S, \qquad (1)$$
$$\Delta \mathbf{k} = \mathbf{k}_P\left(\omega_P,\theta_P,\Phi_P\right) + \mathbf{k}_S\left(\omega_S,\theta_S,\Phi_S\right) - \mathbf{k}_R\left(\omega_R,\theta_R,\Phi_R\right) = 0,$$

where the angles θ_j and Φ_j represent the propagation directions of the interacting waves relative to the main dielectric axes X, Y, Z of the crystal (see Fig. 1a). We restrict ourselves to the case of monochromatic pumping ($\omega_P = const$) providing the unique determination of frequency ω_R at pre-specified ω_P and ω_S. The equations (1) contain 9 parameters; however, only 6 of them are independent. Taking into account the dispersion law $\mathbf{k}_j = \mathbf{k}_j(\omega_j, \theta_j, \Phi_j)$, the PM conditions describe the surface in the space of 6 coordinates, for example $\omega_{P,S}$, $\theta_{P,S}$, $\Phi_{P,S}$, which topology defines the observable frequency-angular structure of generated radiation. On propagating the three waves in any plane, this PM surface has a rather sophisticated general shape. However, some general laws of the parametric frequency conversion, important for the practical applications, can be understood by consideration of vectorial wave interactions in the main planes of a crystal, XZ, YZ and XY. In doing so, the PM surface is defined at fixed pumping frequency in the three-dimensional space ω_S, θ_P, θ_S or ω_S, Φ_P, Φ_S that is more evident and easier for the analysis.

In one of our previous works [14], the conditions for vectorial noncritical PMs for sum frequency generation in uniaxial nonlinear crystals were analyzed using the sections $\theta_P = const$. As is shown in that work, the conditions for vectorial group PM (VGPM) can be expressed as

$$V_S = V_R \frac{\cos(\psi - \gamma_R)}{\cos \gamma_R}, \qquad (2)$$

where $V_j = \partial\omega_j/\partial k_j = \mathbf{u}_j \mathbf{e}_j$ ($j = (S,R)$, $\mathbf{u}_j$ are the group velocities of the waves ω_j; $\psi = \theta_S - \theta_R$ (see Fig. 1b); and $\gamma_R = -\arctan(k_R^{-1}\, \partial k_R/\partial\theta_R)$ is the birefringence angle. The wave interaction geometry in the XZ plane and the possibilities for realization of broad-band and double noncritical (simultaneously in frequency and angle) PM are shown schematically in Figs. 1b and 1c, respectively. At VGPM, in accordance with (2), the group velocity mismatch is compensated in the propagation direction of the signal radiation at the expense of interaction geometry and the crystal anisotropy. It is important to note that, in this case, the angle φ does not change despite the change in lengths of wave vectors $\mathbf{k}_S$ and $\mathbf{k}_R$ (see Fig. 1b). The exact VGPM conditions, admitting the broadband conversion, reduce to the equality of projections of group velocities for the signal and generated waves, having central frequencies ω_{S0} and ω_{R0}, respectively, onto the propagation direction of the signal radiation $\mathbf{e}_S = \mathbf{k}_S/k_S$ (see [14] for details)

$$\mathbf{u}_S \mathbf{e}_S = \mathbf{u}_R \mathbf{e}_S. \qquad (3)$$

Later, similar conditions were obtained in [22].

The KTP crystal ($mm2$ symmetry class) is a biaxial crystal with an angle between optical axes of about 34.6° (1.064 μm) [23]. As the optical axis is located in the XZ plane, the interaction of waves in this plane is of the greatest interest. KTP is a positive crystal in the optical plane XZ at $V < \theta \le 90°$ because $n_e > n_o$, and the generated sum-frequency radiation should be an o-wave. This is necessary to compensate the positive dispersion of the crystal by its anisotropy when creating PM conditions. Therefore, we have considered oe-o, eo-o and ee-o interactions in the XZ plane (the pumping, signal, and generated radiation wave types are designated in the above sequence). Similar types of interactions are also possible in the YZ plane at arbitrary θ_P values. All calculations for the KTP crystal are carried out using Sellmeier equations given in [20].

In Figs. 2a,b, values of angles θ_P and φ are shown at which the VGPM is realized in some range of IR radiation wavelength λ_S at certain pumping wavelengths λ_P. The VGPM in the XZ plane is seen to be realized for oe-o interaction in short-wavelength IR region and for eo-o one, in long-wavelength region. As a result, both these interactions allow to tune VGPM practically in the whole the KTP transparency range except for a narrow interval of 1.81 to 2.32 μm. The widest range of VGPM frequency tuning overlapping the whole KTP transparency range is attained at ee-o interaction in the XZ and YZ planes, however, in this case, effective nonlinear coefficient $d_{eff} = 1/2(d_{15} - d_{24}) \sin 2\theta \sin 2\Phi$ is zeroed at $\Phi = 0°$ and $\Phi = 90°$, i.e. in the XZ and YZ planes. Therefore, this type of interaction is of importance at interaction of waves in intermediate planes going through the Z axis (for example, at $\Phi \approx 45°$). The dashed curves shown in Fig. 2 demonstrate the VGPM tuning possibility outside of the main dielectric planes of a crystal, where $d_{eff} \neq 0$.

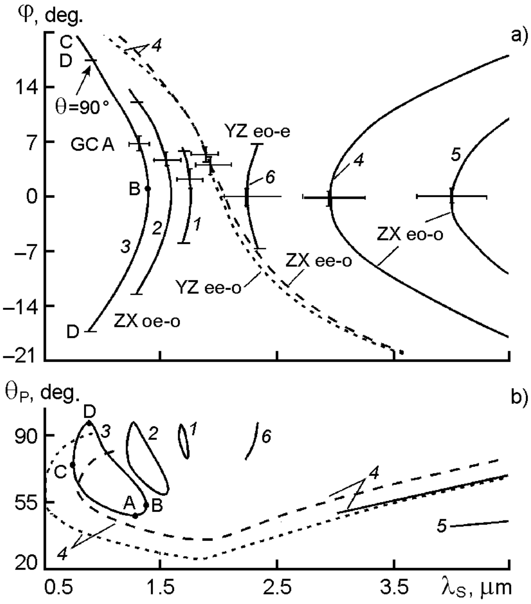

Fig. 2 (a, b) Tuning curves illustrating the possibilities of frequency and angular tuning of the VGPM regions for broadband conversion of IR radiation at different wave interaction types in the XZ and YZ planes of a KTP crystal. — λ_P = 1.064 μm (*1*), 1.337 μm (*2*), 1.750 μm (*3*), 1.833 μm (*4*), 1.0795 μm (*5*), 3.8 μm (*6*). Particular points in one of tuning curves are marked as A, B, C, D. The horizontal and vertical line segments show the spectral and angular conversion width in a crystal of 1 cm length.

In $\varphi(\lambda_S)$ curves (Fig. 2a), the points are marked corresponding to conditions of double non-criticality (in frequency ω_s and IR radiation divergence angle φ) where conditions for vector group and tangential PM are satisfied simultaneously, what is shown schematically in Fig. 1c. The horizontal and vertical line segments show the value of frequency and angular mismatch, respectively, at which the intensity of generated radiation becomes halved. From here on, such double PMs noncritical in frequency and one of angles will be referred to as "group centers" (GC). It is obvious that at eo-o interaction, the double non-criticality occurs at collinear interaction. A more non-trivial case is realized at oe-o interaction. In this case, as it is seen from Fig. 2b, the VGPM occurs at two values of λ_S at fixed angle θ_P. At fixed pumping wavelength, the GC at $\varphi > 0$ corresponds to allowable minimum value of θ_P (point A). Except for some interval from the point *A* to a point *B*, where $\varphi = 0$, the smaller λ_S values for VGPM correspond to the case $\varphi > 0$, while larger ones, to the case $\varphi < 0$. The minimum IR wavelength λ_S of VGPM is attained in the point *C* (Fig. 2b) at allowable maximum value of angle φ (Fig. 1b). The maximum λ_S value in the VGPM scheme occurs at collinear interaction in the point *B*. Two branches in the $\theta_P(\lambda_S)$ dependence are interconnected in the point *D* at $\theta_P = 90°$. In this case, the solutions with $\varphi > 0$ and $\varphi < 0$ are equivalent. Note that for oe-o and eo-o interactions at

VGPM, the range of angle φ, describing the deviation of the interaction geometry from collinear one, decreases when approaching the $1.81 < \lambda_S < 1.32$ μm interval; the range of angular tuning of VGPM also becomes narrower, and the angle θ_P approaches 90°. Below, it will be shown that these cases correspond to decrease of the PM surface size and its contraction towards a critical point.

At ee-o interaction, GC also corresponds to a minimum of $\theta_P(\lambda_S)$, but its short-wavelength branch is close to a low-frequency one at oe-o interaction, while the long-wavelength branch is similar to eo-o interaction at $\varphi < 0$. As a whole, in order to realize the broadband vectorial PM in KTP crystal, as well as in the majority of other crystals, a long-wavelength pumping radiation with $\lambda_P > 1$ μm is to be used.

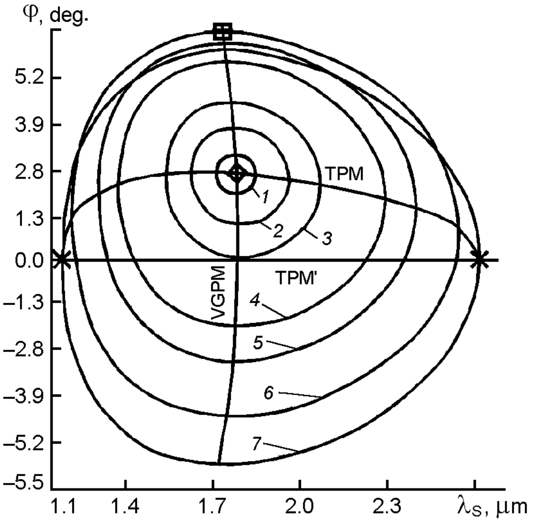

Fig. 3. Sections of the phase-matching surface by planes $\theta_P = const$ for sum-frequency generation in the ZX plane of a KTP crystal at oe-o interaction and the pumping wavelength $\lambda_P = 1.064$ μ: $\theta_P = 73.1°$ (*1*), 73.5° (*2*), 74.25° (*3*), 77° (*4*), 79° (*5*), 86.3° (*6*), 90° (*7*). Lines *a*, *b* and *c* correspond to vectorial group PM and that tangential both in signal and pumping. Symbols ◊, ×, □ denote group, tangential and conditional centers of double non-criticality, respectively.

The broadband conversion curves in Fig. 2a are the singular lines of a PM surface in the three-coordinate space λ_S, φ and θ_P of general view shown in Fig. 3. Here, in λ_S, φ coordinates, the section lines of the PM surface for sum frequency generation ($\lambda_P = 1.064$ μm, oe-o interaction) by $\theta_P = const$ planes are presented. This surface has is convex, though can include special features (in particular, breaks). To all possible vectorial schemes of interaction (including collinear and critical), certain points in this surface can be correlated. By virtue of symmetry of PM conditions with respect to substitution $\theta_P \to 2\pi - \theta_P$, $\varphi \to -\varphi$, only one half of this surface is shown in Fig. 2. Using the general view of the PM surface sections, it is possible to classify the PMs noncritical in one variable as singular lines on that surface. The VGPM is realized in the line connecting the points of horizontal tangents $d\varphi/d\lambda_S = 0$ to the PM surface sections. It is clear that the top and bottom points of these sections correspond to two considered branches of the $\theta_P(\lambda_S)$ dependence in Fig. 2b. By coordinated change in values θ_P and φ, VGPM can be scanned within some λ_S region. Unlike the group matching line, most points of the PM surface correspond to narrow-band PMs which can occur in a wide λ_S range. The line passing the extreme right and left points of considered sections where $d\varphi/d\lambda_S \to \infty$, corresponds to tangential PM (TPM) noncritical in the angle φ. It is realized at a touch of the wave vector surfaces $\mathbf{k}_{S,R}$, (and consequently at coincident directions of group velocities $\mathbf{u}_S$) and corresponds to the condition $\psi = \gamma_R - \gamma_S$.

The intersection point of two considered lines in the PM surface corresponds to the region of double non-criticality, i.e. GC. The joint consideration of conditions for vectorial group and tangential PM, i.e. equality of projections of the group velocities $\mathbf{u}_S$, $\mathbf{u}_R$ onto the signal direction $\mathbf{k}_S$, and also equality of directions of these velocities, results in equality of group velocities $\mathbf{u}_S = \mathbf{u}_R$ in GC. Such regions of double non-criticality were found sometimes in some experimental works [5, 6, 11, etc.], however, we were the first to show that VGPM conditions are realized for all nonlinear crystals in wide λ_S ranges.

Besides of TPM for signal radiation, the tangential phase-matching for pumping radiation ω_P is also possible. In the PM surface, together with the VGPM line, the lines of tangential PM with respect to signal and similar line for tangential PM with respect to pumping (coincident with the $\varphi = 0$ line) are also shown. Both lines intersect at $\theta_P = 90°$, $\varphi = 0$ in the extreme left and right points of the PM surface, which correspond to regions of double non-criticality in angles φ and θ_P, and 90° collinear PM. The region of double noncriticality in angles φ and θ_P is further referred to as "tangential center" (TC). This type of double noncritical PM admitting the largest angular apertures of signal and pumping, however, has a small PM spectral width. In Fig. 2b, the minimum $\theta_{P\ min} = 73.03°$ in the $\theta_P(\lambda_S)$ dependence corresponds to the region of double non-criticality in ω_S and φ, and the extreme (in λ_S) points *B* and *C* define regions of double non-criticality in ω_S and θ_P. The point *B* corresponds to the region of broadband PM collinear and tangential with respect to pumping, while the point *C*, to maximal value $\varphi_{max} = 6.43°$ in the PM surface, which is attained at $\theta_P = 83.57°$. In this region, at fixed angle between wave vectors $\mathbf{k}_P$ and $\mathbf{k}_S$, the significant changes in the angle θ_P are allowed. Because the angular changes occur under the constraint $\theta_P - \theta_S = \varphi$, this non-criticality type can be referred to as "conditional" PM. The corresponding line in the PM surface goes from the region φ_{max} to the TC points. Near the intersection point of the considered curve with the VGPM line (the "conditional" center (CC)), the double non-criticality in ω_S and θ_P is also attained. In practice, the CC can be used to convert the broadband IR images at cylindrical focusing of radiation $\omega_{P,S}$. As far as we know, such possibility is not realized experimentally till now.

Thus, as seen in Fig. 3, there are three closed lines in the PM surface corresponding to PMs noncritical in one of λ_S, φ and θ_P parameters and the line of conditional PM, along which significant coordinated changes of θ_P and θ_S directions are possible. The intersection points of the three first lines form two pairs of group centers having double non-criticality in λ_S and φ or θ_P, as well as two tangential centers at minimal and maximal λ_S values (left and right TC). As already mentioned, the conditional PM line always passes through TC, and its intersection point with the VGPM line forms the conditional center. The systematization of the double PM non-criticality regions allows for their purposeful experimental search.

To solve a number of applied tasks, it would be expedient to use double PMs uncritical in (ω_S, φ) or (ω_S, θ_P), that provides a wide spectral band of conversion at large receiving angle and high-efficient parametric conversion of thermal radiation. To scan the central frequency of converted wide spectral band in the region of the group or conditional centers, it is possible to change the plane of wave interaction or to tune the pumping wavelength. We have studied in detail the frequency tuning for group centers, i.e. regions of double non-criticality in λ_S and φ. The tuning possibilities for the group centers in λ_S by changing the pumping wavelength are shown in Fig. 4. Along each tuning line, the equality $\mathbf{u}_S = \mathbf{u}_R$ is satisfied and non-criticality in frequency and the signal wave propagation direction is realized within a wide IR and visible range. In addition, the θ_P and φ dependences on λ_S are presented at which either GC of the GC ensemble is realized. As is seen from Fig. 4, the group centers for oe-o and eo-o interactions exist within the whole KTP transparency region except for a narrow range of signal wavelengths from 1.8127 to 2.3182 μm. For completeness, the dashed lines show the tuning of GC for ee-o interaction having nonzero d_{eff} value only when the interaction plane leave the main planes ZX and YZ. This type of interaction can provide smooth tuning of GC within the whole transparency region of KTP.

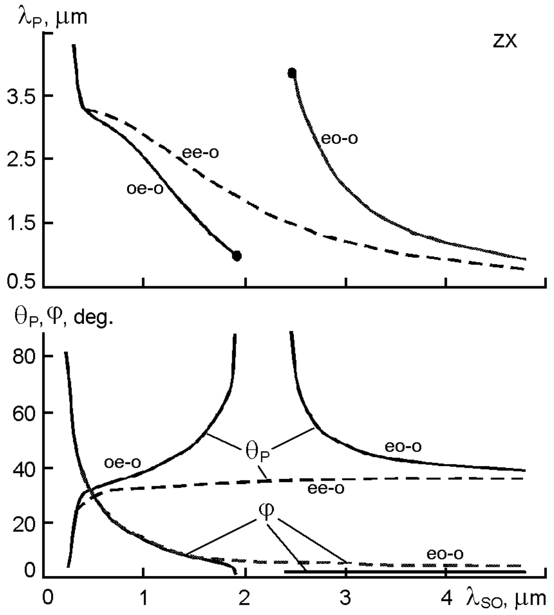

Fig. 4. Scanning of the group centers for sum-frequency generation at vectorial interactions of different types in the ZX plane of a KTP crystal. The circles designate limiting points of the triple non-criticality.

The CC region may be conditionally considered as a triple noncritical PM in the variables λ_S, θ_P and θ_S. Triple non-criticality in λ_S, φ and θ_P is attained as the PM

Table 1. Spectral and angular conversion widths in the double PM non-criticality regions at sum-frequency generation in a KTP crystal of L cm thickness (λ_P = 1.064 µm, oe-o interaction in the XZ plane).

Type of double noncriticality	λ_S, µm	φ, deg	θ_P ,deg	$\sqrt{L}\delta\nu$, cm$^{-1/2}$	$\sqrt{L}\delta\varphi$, cm$^{1/2}$ deg	$\sqrt{L}\delta\theta_P$, cm $^{1/2}$ deg
GC	1.754	2.37	73.03	513.5	1.27	–
CC	1.693	6.43	83.57	532.4	0.11	3.22
TC (left)	1.132	0	90	43.8	1.09	2.59
TC (right)	2.611	0	90	36.8	1.45	4.04

surface decreases when changing the pumping wavelength λ_P. In this case, all singular lines and points of double non-criticality become contracted into a small region (into a point in the limit), and thereafter, the PM conditions are no more satisfied ($k_P + k_S < k_R$). The triple non-criticality is attained at well-defined values of $\lambda_{S,P}$. In the case of oe-o interaction, the PM surface decreases in size in near IR at $\lambda_P \rightarrow 1$ µm, $\theta_P \rightarrow 90$ ° and $\varphi \rightarrow 0$. In the limit, at $\lambda_P = 0.9994$ µm and $\lambda_{S0} = 1.8127$ µm, it is contracted into a point, the vicinity thereof being corresponding to the triple uncritical PM in ω_S and two angles φ and θ_P. In the case of eo-o interaction, the triple non-criticality is realized at $\lambda_P = 3.8304$ µm and $\lambda_{S0} = 2.3182$ µm. When approaching these points, vectorial PMs tend to collinear PM ($\varphi = 0°$) in the X axis direction. In connection with the further violation of PM conditions, this limiting point can be named "critical point". In the case of ee-o interaction, the θ_P value does not approach 90° in the KTP crystal transparency region, therefore, the triple non-criticality region is not realized. The use of other crystals allows to extend the triple noncritical PM existence regions.

The conditions of PMs uncritical in frequency and angles are defined by zeroing the linear members in the wave mismatch Δk expansion for frequency mixing processes in terms of frequency and angular mismatch from exact conditions of PM. For PMs uncritical in frequencies and angles, expansion of the wave mismatch contains only small quadratic members, which define the attainable spectral ($\delta\nu$) and angular ($\delta\varphi$, $\delta\varphi_P$) widths of phase matching [13, 14]. The signal wavelengths, angles θ_P and φ, as well as both spectral and angular widths of conversion in points of the double non-criticality, calculated at $\lambda_P = 1.064$ µm and interaction oe-o in the XZ plane, are listed in Table.

It is seen from Table that the use of VGPMs makes it possible to increase more than by one order the spectral range of the convertible IR radiation ($\delta\nu > 500$ cm^{-1} at $L = 1$ cm). The use of a less than 1 cm thick crystal allows to realize the spectral width of conversion exceeding 1000 cm^{-1} that is quite enough for the purposes of nonlinear spectroscopy. The double noncriticality at the group center makes it possible simultaneously to increase essentially the angular aperture of signal emission and the conversion efficiency of the output radiation from thermal sources. Still larger angular divergence of convertible IR signal is allowed for the conditional center with the use of laser radiation with cylindrical divergence within several degrees.

Thus, a general approach is developed and theoretical analysis of the conditions for multiple noncritical (in parameters ω_S, θ_S, θ_P) phase-matching in biaxial crystals (taking of potassium titanyl phosphate (KTP) as an example), for the case of sum-frequency generation is carried out. The research is based on the analysis of PM surface topology in the space of frequency-angular coordinates, as well as of properties of the singular lines of this surface and points of their intersection. The broadband character of signal radiation and possibilities of frequency scanning of a narrow-band laser pumping are taken into account. It is shown that in a KTP crystal, the PM noncritical in frequency of the IR signal ω_S or the propagation directions of pump and signal waves $\theta_{P,S}$ can be attained along closed lines of a PM surface. In the regions close to intersection points of these lines, the PMs double noncritical (in pump frequency and one of angles θ_S or θ_P, as well as in two angles) are realized. It is found that at vectorial group phase-matching, the equality of projections of the group velocities of the IR signal and sum-frequency waves onto the signal IR radiation propagation direction is fulfilled. At intersection of lines of the vectorial group PM and tangential one at the group center, the equality of group velocities of signal and generated radiation is valid. The spectral and angular conversion widths for the group center have been calculated when using the neodymium laser radiation (1.064 μm). The realization possibility of non-criticality in angles θ_S and θ_P has been considered when the condition $\theta_P - \theta_S = \varphi$ is fulfilled. It is determined that the angle φ increases linearly when θ_P deviates from 90°. The simultaneous realization possibility of vectorial group PM and conditional one has been shown in the region of the largest possible angles φ_{max} between the propagation directions of the interacting waves. Such interaction scheme as well as GC allow us to realize conversion of not only broadband signals but also IR images. It is shown that at change of the laser pumping wavelength in the long-wavelength region $\lambda_P > 1$ μm, the group centers are tunable in the region of 0.7 to 1.81 μm in the case of the oe-o interaction, and they can be scanned in the range of 2.32 to 4.5 μm at eo-o interaction. At the ee-o interaction, the double non-criticality regions are tunable within the whole transparency range of KTP. The critical PM points are realized in the extreme points of frequency tuning lines of the group centers, when the PM surface decreases in size at $\theta_P \to 90°$. In that case the triple non-criticality in the signal frequency and the propagation directions of $\theta_{P,S}$ is attained. The critical points in the XZ plane are realized at $\lambda_P = 0.9994$, $\lambda_S = 1.813$ μm (oe-o) and $\lambda_P = 3.830$, $\lambda_S = 2.318$ μm (eo-o). The use of the multiple noncritical PMs allows us to select purposefully nonlinear crystals when developing new quantum electronic devices for frequency conversion of various radiations, including those intended to visualize the wide IR spectra and non-monochromatic IR images.

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Кратні некритичні фазові синхронізми у двовісному кристалі КТР

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На прикладі двовісного кристала КТР розвинуто загальний підхід і проведено аналіз умов некритичних фазових синхронізмів (ФС) різної кратності для процесу генерації сумарної частоти. Підхід заснований на розгляді загальних властивостей поверхні ФС, побудованої у координатах частот і кутів, та аналізі особливих ліній і точок їхнього перетину. На поверхні ФС розглянуто лінії некритичності за частотою сигналу чи кутами поширення взаємодіючих хвиль. Запропоновано класифікацію двократних некритичних ФС (за частотою й одном з кутів чи за двома кутами). Показано можливість реалізації трикратної некритичності за трьома незалежними величинами, наприклад, частотою і двома кутами. Встановлено, що область двократної некритичності за частотою та розбіжністю ІЧ сигналу може скануватися вздовж всієї області прозорості КТР при зміні частоти довгохвильової лазерної накачки. Кратні некритичні ФС дозволяють візуалізувати широкосмугові ІЧ спектри та ІЧ зображення.