Calculating properties of non-collinear phase matching in two different polarization for KDP crystal

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Abstract. The properties of non-collinear phase-matching (PM) for potassium dihydrogen phosphate (KDP) crystal were calculated. The properties were calculated numerically for type I phase matching and type II-phase matching. The group delay dispersion (GDD) was determined for KDP at different slant angles and different types of phase matching. The slant angles were 0°, 40°, 60°, and 90°. The pumping, signal, and idler wavelengths were 354.7 nm, 1064 nm, and 532 nm respectively. The time delay deepened on the phase-matching angle for three-wave that interact in KDP crystal founded. Ordinary refractive index and extraordinary refractive index discussed, by calculating these indices the birefringence at each wavelength determined. The group delay dispersion and time delay very important factors for optical communication, laser application, and nonlinear optics.

Keywords: Non-collinear phase matching, KDP crystal, Group delay dispersion, Time delay dispersion, Negative uniaxial crystal, birefringence crystal.

1. Introduction

For a certain nonlinear crystal that should have high efficiently, at a certain wavelength, the crystal also has phase matching[1]. Simply phase matching differs from and is distinguished from quasi-phase-matching and no critical phase-matching technique[2-6]. The distinctions between group velocities of three waves interacting in a nonlinear medium predominating mark the efficient reaction length. If the crystal is not short during the mixing of short pulses then the temporal walk-off can skip the pulse durations [7]. To match the group velocities for three waves, it is occasionally helpful to match only two velocities, like the Idler and signal in parametric amplification, which is often useful, allowing for broad-band parametric amplification [8-10]. The arranging of velocities for the input pulses of the second harmonic generation, providing pulse compression through appropriate conditions [11]. The second-order nonlinear optical process showed that a photon passes through the crystal at high energy and divided into two photons of lower energy called unprompted parametric down-conversion, a photon that possesses high energy called a pumping photon, while two photons with less energy called signal and the idler photons [12]. In 2000 N. Boeuf, et al [13] calculated the characteristics of non-collinear (PM) in both biaxial and uniaxial crystals. They used program FORTRAN intended to solve the (PM) problem for a broad range of crystal materials and pumping conditions. The lengths pumping were 633 nm and 950 nm to achieve phase matching in a crystal KNbO3, the pump beam width constant of 2 mm (FWHM), and different lengths used to achieve phase-matching function for KDP crystals. Also, They calculated the phase-matching function value
for all possible signal wavelength and angle combinations, and they required the value of $\Phi$ is increasing from 0.1 to 1. They found Phase-matching function $\Phi = f (\lambda_{\text{signal}}, \theta_{\text{signal}})$ for a KDP crystal (2 mm pump width and 5mm crystal length) with $\lambda_{\text{pump}} = 351\text{nm}$, $\Phi_{\text{pump}} = 0$, $\theta = 52^\circ$, $\Phi_{\text{signal}} = 0$. In 2009 K. Ogawa and K. Sueda, et al [14], found ultra-broadband optical parametric chirped-pulse amplification of more than 250 nm bandwidth at a center wavelength of 1050 nm by using a partially deuterated KDP crystal as an optical parametric amplifier (OPA). They showed numerically how to change the broadband phase matching (PM) conditions at different wavelengths by adjusted the deuteration level in partially deuterated KDP to match center wavelengths of suitable broadband seed sources. In 2014 Meizhi Zhang, et al [15], Based on an angle-dependent refractive index in biaxial and uniaxial crystals, the phase-matching conditions of the SPDC process were calculated. They calculated the effective nonlinear coefficients $d^{\text{eff}} = 2.2657 \text{pm/V}$, at $\theta = 52.3^\circ$ and $\phi = 15.3^\circ$ at the wavelength of 532 nm, They also discovered the best phase-matching directions for types I and II. They focused on the angular gradient of the pump and emission wave refractive indices near the phase-matching direction. In the year 2017 Dongsheng Song et al [16], Based on the numerical measurement results of non-collinear type-I and type-II phase matching processes for general nonlinear uniaxial crystals of 1cm thickness for a KDP crystal, the ideal angle bandwidth and wavelength bandwidth of the fourth harmonic generation (FHG) and fifth-harmonic generation (FIFHG) of the 1064nm laser was analyzed, FHG and FIFHG non-collinear phase-matching angles and effective nonlinear are calculated. The findings for FHG and FIFHG would be useful experiments and studies in the broadband and effective non-collinear PM.

### 2. Uniaxial Crystals

A birefringent crystal is characterized by three principal indexes: $n_X$, $n_Y$, and $n_Z$. These indexes are also known as Eigen indexes. In uniaxial crystals, the indexes, $n_X = n_Y \neq n_Z$, and the optic axis is along the Z-axis which is related to the principal index, $n_Z$. The other two principal indices $n_X$, $n_Y$ have the same value, known as the ordinary index $n_o$.

The laser passing through a uniaxial crystal is decomposed into two linearly polarized, orthogonal, Eigen polarizations called extraordinary and ordinary waves (e-waves and o-waves). The e-wave has a related extraordinary index $n_e(\theta)$ that is dependent on propagation direction. The angle $\theta$ is defined generally as the angle constructed by the vector (k) and the uniaxial optical axis Z. The index($n_o$) and related with the (o-wave) does not change with propagation direction. In the crystal positive uniaxial is being $n_e > n_o$, and the crystal negative uniaxial is being $n_e < n_o$. For the extraordinary index, two equivalent formulae, uniaxial crystals, are valid for both positive and negative.
3. Theory of a group velocity

Two variables can be configured to monitor the group velocities (VGS) of three constant frequency pulses are the non-collinear phase-matching (PM) angles and the pulse-front slant. [1], This is shown in Figure 2. The pump propagation vector, $k^p$, is tilted by $\theta$ relative to the optic axis of the crystal. The angle signal tilt of $\delta$ relative to the pump is determined by phase-matching (PM). The corresponding idler angle, $\gamma$, must form a triangle with the propagation vectors. Pulse fronts are indicated by a thick bold line slanted by $\phi$ relative to a normal to $k^p$, or that all three pulses have slanted but parallel envelopes. For the pulses to remain temporarily overlapped while passing along a common axis chosen for ease to be $k^p$, they must have the same group velocity (VGS). While phase matching is preserved, independent adjustment of $\delta$ and $\phi$ allows for elastic change of the three group velocities.

Figure 1. The Refractive index for positive uniaxial and negative uniaxial crystal

The polarization directions (e) and (o) are perpendicular to the vector (k). Extraordinary waves are polarized parallel to the optical Z axis, whereas o-waves are perpendicular to the plane. in the plane that contains the k vector [17].
Figure 3. The group velocity of a slanted pulse along z length was measured. The group velocity is \( \mathbf{v} \) of an unslanted pulse, and the propagation vector is tilted by \( \delta \) relative to \( z \). The slant angle is \( \phi \) of the pulse front relative to the normal to axis \( z \) and \( \rho \) is the birefringent walk-off angle. The velocity at which point a sweeps along the z axis is \( \mathbf{v}_z \).
The calculation of group velocity illustrates in figure 3. In this figure, the calculation of group velocity was along \( \hat{z} \) direction for slant pulse. The slanted pulse front is represented by the thick bold line. The group velocity of a pulse whose pulse front is perpendicular to the \( \mathbf{k} \) vector of the pulse's carrier wave is represented by vector \( \mathbf{v} \), which is parallel to the pulse carrier wave \( \mathbf{k} \) vector. When the pulse has extraordinary polarization, the vector Poynting is tilted by \( \rho \) (If the critical phase matches (CPM) a small angle is generated between the direction of the base ray and the second correspondence of the crystal, called (a walk-off angle) relative to \( \mathbf{k} \)). As a result, the group velocity of an unslanted pulse is \( v' \). We can calculate \( v' \) the group velocity along the \( \hat{z} \) direction as follows: [11]

\[
v' = \frac{v}{\cos \rho}, \quad h = v' \sin(\delta - \rho) \tag{1}
\]

\[
v_
_2 = v' \cos(\delta - \rho) - h \tan \phi = v \frac{\cos(\delta - \rho) - \tan \phi \sin(\delta - \rho)}{\cos \rho} \tag{2}
\]

This can be written \( v_2 \) using the small-angle approximation for \( \rho \):

\[
v_2 = v[\cos \delta - \tan \phi \sin \delta + \rho(\sin \delta + \tan \phi \cos \delta)] \tag{3}
\]

(It represents the velocity at which the pulse is moved along an axis \( z \))

On the other hand, we can derive \( v_2 \) analytically starting with

\[
\frac{1}{v_2} = \frac{d\mathbf{k}_2}{d\omega} = \frac{d(k \cos \delta)}{d\omega} = \frac{d\mathbf{k}}{d\omega} \cos \delta - k \sin \delta \frac{d\delta}{d\omega} \quad \text{......... (4)}
\]

The angular dispersion of the pulse frequencies is indicated by a slanting pulse front. Since the refractive index is angle-dependent when there is birefringence, the frequency and angle variance of \( k \) must be considered. We rewrite Eq. (4) as

\[
\frac{1}{v_2} = \left( \frac{\partial k}{\partial \omega} + \frac{\partial k}{\partial \delta} \frac{d\delta}{d\omega} \right) \cos \delta - k \sin \delta \frac{d\delta}{d\omega} \quad \text{......... (5)}
\]

And by group velocity definitions \( \nu = \partial \omega / \partial k \), and birefringent walk-off, \( \rho = (1 / n) \partial n / \partial \delta \), we can rewrite Eq. (5) as

\[
\frac{1}{v_2} = \left( \frac{1}{\nu} + k \rho \frac{d\delta}{d\omega} \right) \cos \delta - k \sin \delta \frac{d\delta}{d\omega} \quad \text{......... (6)}
\]

to correct \( (d\delta / d\omega) \) inside a birefringent crystal to generate a slanted pulse. Consider diffraction an unslanted pulse of an embedded diffraction grating aligned parallel with the incident pulse front, as
shown in Figure 3. If the diffraction angle is, a pulse with a slant angle relative to its k vector is produced. If the diffraction angle is $\Psi$ Diffraction must obey

$$k(\omega, \psi) \sin \psi = k_g \quad \ldots (7)$$

where $k_g$ is the grating vector, $2\pi/d$, $d$ being distance between grating lines. Differentiating for $\omega$

$$\left(\frac{\partial k}{\partial \psi}\frac{d\psi}{d\omega} + \frac{\partial k}{\partial \omega}\right) \sin \psi + k \cos \psi \frac{d\psi}{d\omega} = 0 \quad \ldots (8)$$

Again we use the definition of group velocity and walk-off, Eq. (8) gives

$$\frac{d\psi}{d\omega} = \frac{1}{k} \left(\frac{\sin \psi}{\rho \sin \psi + \cos \psi}\right) \quad \ldots (9)$$

Using the relations $(d\delta/d\omega) = (d\psi/d\omega)$ and $\psi = \phi + \delta$ gives

$$\frac{d\delta}{d\omega} = \frac{1}{k} \left(\frac{\sin(\phi + \delta)}{\rho \sin(\phi + \delta) + \cos(\phi + \delta)}\right) \quad \ldots (10)$$

replace with Eq. (10) into Eq. (6) and simplifying yields Eq. (3).

$$\Delta k_z^{(1)} = \frac{d k_p^p}{d\omega} \Delta \omega_p - \frac{d k_s^s}{d\omega} \Delta \omega_s - \frac{d k_i^i}{d\omega} \Delta \omega_i \quad \ldots (11)$$

Where vector $k_p^p, k_s^s, k_i^i$ are the wavenumber of pumping, signal, and idler respectively. if it was the all group velocities along $z$ are equal to $v_z$, Eq.(11) reduces to

$$\Delta k_z^{(1)} = \frac{1}{v_z} (\Delta \omega_p - \Delta \omega_s - \Delta \omega_i) \quad \ldots (12)$$

Where $\omega_p, \omega_s, \omega_i$ Angular frequency for pumping, signal, and idler wave respectively. The (pulse slant) contributes to the dispersion of group velocity [18], Combining it with standard group velocity dispersion (GVD) results in a quadratic contribution in the z-direction.

$$\Delta k_z^{(2)} = \frac{1}{2} \frac{d^2 k_p^p}{d\omega^2} (\Delta \omega_p)^2 - \frac{1}{2} \frac{d^2 k_s^s}{d\omega^2} (\Delta \omega_s)^2 - \frac{1}{2} \frac{d^2 k_i^i}{d\omega^2} (\Delta \omega_i)^2 \quad \ldots (13)$$

If group-velocity matching is achieved, the permissible crystal length or chirp range will be limited by using this (GVD). To begin with

$$\frac{d^2 k_z}{d\omega^2} = \frac{d}{d\omega} \left(\frac{1}{v_z}\right) = \frac{-1}{v_z^2} \frac{d}{d\omega} \quad \ldots (14)$$

and using Eq. (3) and (10), we find that
\[ \frac{d^2 k_x}{d\omega^2} = -\frac{GVD}{v_{z_1}} + \frac{1}{k_x v_{z_1}} \left[ \tan(\phi + \delta) \right] \left[ \frac{\rho - \tan(\phi + \delta)}{1 + \rho \tan(\phi + \delta)} \right] \text{... (15)} \]

\[ \frac{d^2 k_y}{d\omega^2} = -\frac{(GVD)_p}{v_{z_1}} + \frac{1}{k_y v_{z_1}} \left[ \tan(\phi + \delta) \right] \left[ \frac{\rho - \tan(\phi + \delta)}{1 + \rho \tan(\phi + \delta)} \right] \]

\[ \frac{d^2 k_z}{d\omega^2} = -\frac{(GVD)_i}{v_{z_1}} + \frac{1}{k_z v_{z_1}} \left[ \tan(\phi + \delta) \right] \left[ \frac{\rho - \tan(\phi + \delta)}{1 + \rho \tan(\phi + \delta)} \right] \]

\[ \Delta k_x^{(2)} = \frac{1}{2} \left[ -\frac{(GVD)_p}{v_{z_1}} + \frac{1}{k_p v_{z_1}} \left[ \tan(\phi + \delta) \right] \left[ \frac{\rho - \tan(\phi + \delta)}{1 + \rho \tan(\phi + \delta)} \right] \right] (\Delta \omega_p)^2 \]

\[ -\frac{1}{2} \left[ -\frac{(GVD)_i}{v_{z_1}} + \frac{1}{k_i v_{z_1}} \left[ \tan(\phi + \delta) \right] \left[ \frac{\rho - \tan(\phi + \delta)}{1 + \rho \tan(\phi + \delta)} \right] \right] (\Delta \omega_i)^2 \]

\[ -\frac{1}{2} \left[ -\frac{(GVD)_i}{v_{z_1}} + \frac{1}{k_i v_{z_1}} \left[ \tan(\phi + \delta) \right] \left[ \frac{\rho - \tan(\phi + \delta)}{1 + \rho \tan(\phi + \delta)} \right] \right] (\Delta \omega_i)^2 \]

GVD is the ordinary group velocity dispersion along the propagation vector of an unslanted pulse [11].

4. Results and discussion

Figure 4 illustrates the relationship between the group delay dispersion (GDD) and phase-matching angle of KDP crystal for type I phase matching. From this figure, we can see that the signal wave starts linearly, then sweeps at (GDD) equal -1000, and decreased until it meets with the idler wave and they converge at angle 52.2º. The group delay dispersion for both signal and idler waves was (-1500). In figure 4.a the pumping wavelength was 354.7nm, signal and idler wavelengths were 1064nm and 532nm respectively. Figure 4.b shows the relationship between the group delay dispersion and phase matching angle for type I of KDP crystal. This figure explains that the signal wave starts linearly and then sweeps at (GDD) equal (-7000) and decreased until match the idler wave at an angle (50.1º). The group delay dispersion for both signal and idler wave was (-750). The matching point for signal and idler was short. Figure 4.c shows the variation of group delay dispersion of the KDP crystal at type II phase-matching for the phase matching angle at slant angle 40º. As can be seen from figure 4.c when the phase-matching angle 65.2º, the group delay dispersion for signal and idler wave was -1250. The signal begins to sweep at θ equal 59º and then decrease that also happened for idler wave. The group delay dispersion of KDP crystal for type II changes with phase matching angle shown by figure 4.d. The group delay dispersion of signal and idler waves start linearly and then both waves meeting at θ equal 63.5º where GDD was -6000. The signal changed his path at GDD equal -3000 while the idler wave changes his path at GDD equal -8000.
Figure 4. The dependence of group delay dispersion on phase matching angle of KDP crystal for (a) type I and slant angle 40°, (b) type I and slant angle 60°, (c) type II and slant angle 40°, (d) type II and slant angle 60°.
Figures 5e-h show the variation of the group delay dispersion with the phase-matching angle of KDP crystal for type I and type II at angles $0^\circ, 900^\circ$. It can be seen that for longer wavelength (1064nm) the group delay dispersion was negative while for pumping and idler was positive. We could also see that the group delay dispersion for pumping and idler approximately linearly while the group delay dispersion for signal wave decreases with increasing phase-matching angle. For the positive region of group delay dispersion, the long-wavelength travel faster than the shorter and the dispersion will be normal. The idler wave travels faster than the pumping wave. From figures 5f and 5h, it can be seen that the group delay dispersion of signal wave has two regions, and that happened for slant angles $0^\circ, 900^\circ$ at type II phase match. It means that the signal wave suffered dispersion started at GDD equal $5$ and $\theta$ equal $57.6^\circ$. Figures 6a-6d show the dependence of time delay dispersion on the phase-matching angle of KDP crystal for type I and type II at slant angles $40^\circ$ and $60^\circ$. As can be seen from figures that there is no phase matching ($\Delta k \neq 0$) so there is phase mismatch ($\Delta k$) at these conditions. Figure 6e shows the relationship between time delay and phase matching angle for type I of KDP crystal at slant angle equal to zero. From the figure, it can be seen that there is a phase match ($\Delta k=0$) at angle $\theta$ equal $66^\circ$. The signal, idler, and pumping wave convince at this value. From figure 6f it can be seen that there is no matching between the interacting waves so that mismatch occurred for type II of KDP crystal at slant angle $0^\circ$. Figures 6g and 6h show the variation of time delay with the phase-matching angle of KDP crystal for type I and type II at slant angle $900^\circ$. As can be seen from figure 6g when $\theta$ equal $67^\circ$ the phase-matching occurred for type I. Figure 6h explain that there is no phase match between the waves for type II at a slant angle $900^\circ$ ($\Delta k \neq 0$).
Figure 5. The dependence of group delay dispersion on phase matching angle of KDP crystal for (e) type I and slant angle 0°, (f) type II and slant angle 0°, (g) type I and slant angle 90°, (h) type II and slant angle 90°.
Figure 6. The dependence of Time delay dispersion on phase matching angle of KDP crystal for (a) type I and slant angle 40°, (b) type II and slant angle 40°, (c) type I and slant angle 60°, (d) type II and slant angle 60°.
Figure 6. The dependence of Time delay dispersion on phase matching angle of KDP crystal for (e) type I and slant angle 0°, (f) type II and slant angle 0°, (g) type I and slant angle 90°, (h) type II and slant angle 90°
Figure (7) explain the variation of ordinary and extraordinary refractive index with wavelength. From the figure, it can be seen that the ordinary refractive index for KDP crystal is larger than the extraordinary refractive index. The refractive index decreased with increasing wavelength. The birefringence at 1064nm was 0.033 and for 532nm was 0.04. The formula for ordinary and extraordinary refractive index respectively given by following [12]:

\[
\begin{align*}
    n_o^2 &= 2.259276 + \frac{13.00522\lambda^2}{\lambda^2 - 400} + \frac{0.01008956}{\lambda^2 - 0.0129426} \\
    n_e^2 &= 2.132668 + \frac{3.2279924\lambda^2}{\lambda^2 - 400} + \frac{0.008637494}{\lambda^2 - 0.0122810}
\end{align*}
\]

![Figure 7](image_url)  
*Figure 7. Refractive index as function of wavelength for a KDP crystal*
5. Conclusion
The group delay dispersion for three waves of KDP crystal for slant angles (40º, 60º) at type I and type II has only a negative region so the short wavelength has velocity more than the longer wavelength and the dispersion will be anomalous. For slant angles (0º,90º) the group delay dispersion that depends on a phase-matching angle for two type phase matching located in two regions negative and positive so the crystal at these values of slant angle possesses normal and anomalous dispersion. The group delay dispersion of KDP crystal for type I at slant angles 0º and 90º decreased with increasing phase-matching angle. The phase-matching occurred for type I at angles 0º and 90º and this allows getting high efficiency, which we were able to use nonlinear optical operations. The refractive index of KDP crystal decreased with increasing wavelength, the ordinary refractive index larger than extraordinary refractive index so the crystal negative uniaxial.

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