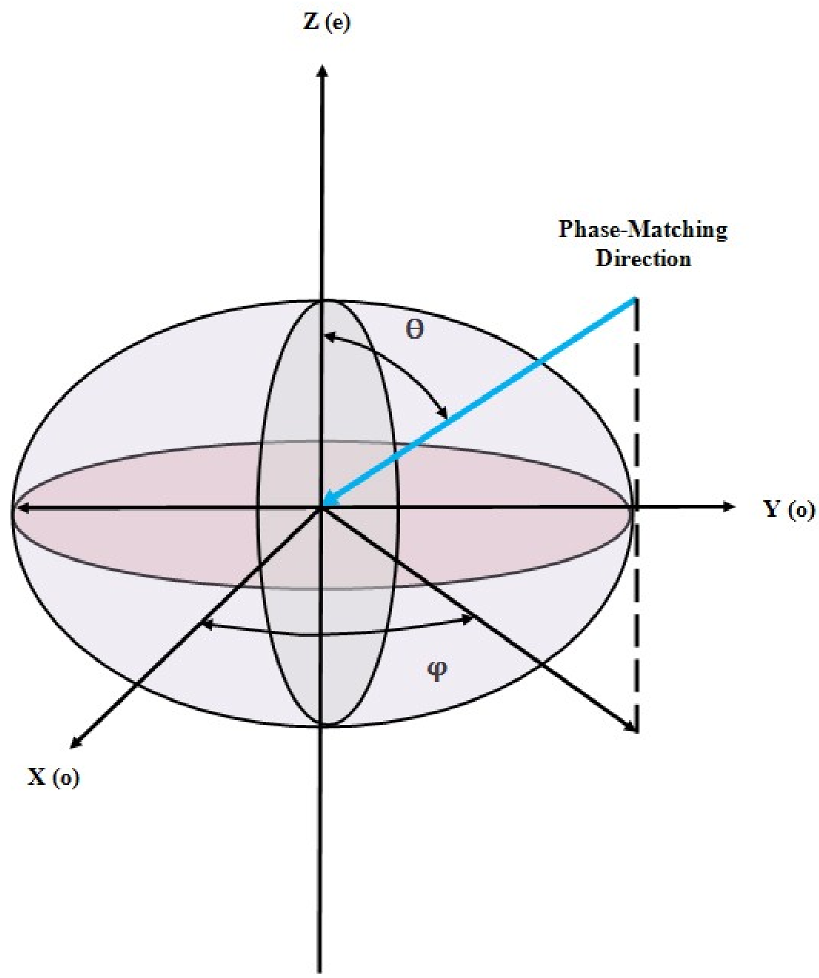
$KTiOPO_4$ (KTP) Data Sheet

Potassium Titanyl Phosphate



I. General Properties:

a. **Crystal Unit Cell Structure [1,2,3]: Orthorhombic**

b. **Hermann-Mauguin Symbol: mm2**

c. **Symmetry Elements: $1A_2$, 2m**

d. **Crystal Optical Class: Positive Biaxial**

e. **Crystal Lattice Constants (Å): a = 12.814, b = 6.404, c = 10.616**

f. **Coordinate System: Right Handed System**

g. **Assignment of Crystallographic and Dielectric Axes: (X,Y,Z) Maps To (a ,b ,c)**

h. **Crystal Unit Cell Length Definitions: l_1 = a, l_2 = b, l_3 = c**

i. **Crystal Unit Cell Angle Dimensions: α = β = γ = 90°**

j. **Unit Cell Volume (Å^3): 871.16**

k. **Formulae/Unit Cell: 8**

l. **Typical Crystal Growth Methods: Hydrothermal or Flux**

m. **Preferred Crystal Growth Directions: Hydrothermal [011], Flux [100]**

II. Optical Properties:

a. **Transparency Range, Zero Transmittance [4]: 350-4500 nm**

b. **Dielectric Matrix and Coefficient Values:**

$$\varepsilon = \varepsilon_0 \cdot \begin{bmatrix} n_a^2 & 0 & 0 \\ 0 & n_b^2 & 0 \\ 0 & 0 & n_c^2 \end{bmatrix}$$

Here, ε is the permittivity, ε_0 the permittivity of free space, and n_a, n_b, n_c the principal indices of refraction in the a, b, c directions respectively.

c. **Thermo-Optic Coefficient Matrix and Coefficient Values (β=dn/dT) (1/K) at 295K [4]**

$$\beta = \begin{bmatrix} \beta_a & 0 & 0 \\ 0 & \beta_b & 0 \\ 0 & 0 & \beta_c \end{bmatrix}$$

β Values Table

β Coefficients	β Values (1/K) (10^{-6})	References
β_a	6.1	[5]
β_b	8.3	[5]
β_c	14.5	[5]

d. Sellmeier Equations (Flux Grown) and Coefficients:

$$n_a^2 = A_a + \frac{B_a}{(\lambda^2 - C_a)} + \frac{D_a}{(\lambda^2 - E_a)}$$

$$n_b^2 = A_b + \frac{B_b}{(\lambda^2 - C_b)} + \frac{D_b}{(\lambda^2 - E_b)}$$

$$n_c^2 = A_c + \frac{B_c}{(\lambda^2 - C_c)} + \frac{D_c}{(\lambda^2 - E_c)}$$

Sellmeier Equations Coefficients [6] at 293 K (λ Expressed in Microns)

Coefficients	Units	n_a	n_b	n_c
A	Dimensionless	3.29100	3.45018	4.59423
B	μm^2	0.04140	0.04341	0.06206
C	μm^2	0.03978	0.04597	0.04763
D	μm^2	9.35522	16.98825	110.80672
E	μm^2	31.45571	39.43799	86.12171

Spectral Range of Validity: 430-3540 nm

e. Sellmeier Equations (Flux Grown) and Coefficients: Cristal Laser (C. Bonnin)

Note: The following Sellmeier equations for flux-grown crystals are recommended by Sandia Nonlinear Optics (SNLO) v.7.3. These are unpublished values attributed to C. Bonnin from Cristal Laser:

$$n_a^2 = A_a + \frac{B_a}{(\lambda^2 - C_a)} - D_a\lambda^2$$

$$n_b^2 = A_b + \frac{B_b}{(\lambda^2 - C_b)} - D_b\lambda^2$$

$$n_c^2 = A_c + \frac{B_c}{(\lambda^2 - C_c)} - D_c\lambda^2$$

Sellmeier Equations Coefficients of Cristal Laser [7] (Temperature Unspecified, Assume (300 K) (C. Bonnin) (λ Expressed in Microns)

Coefficients	Units	n_a	n_b	n_c
A	Dimensionless	3.006700	3.031900	3.3134
B	μm²	0.039500	0.041520	0.056940
C	μm²	0.042510	0.045860	0.059410
D	1/μm²	0.012470	0.013370	0.016713

Spectral Range of Validity: 500-3500 nm

f. **Sellmeier Equations (Hydrothermally-Grown) and Coefficients:**

$$n_a^2 = A_a + \frac{B_a}{(\lambda^2 - C_a)} - D_a\lambda^2$$

$$n_b^2 = A_b + \frac{B_b}{(\lambda^2 - C_b)} - D_b\lambda^2$$

$$n_c^2 = A_c + \frac{B_c}{(\lambda^2 - C_c)} - D_c\lambda^2$$

Sellmeier Equations Coefficients [8] (Temperature Unspecified, Assume 300 K) (λ Expressed in Microns)

Coefficients	Units	n_a	n_b	n_c
A	Dimensionless	2.1146	2.1518	2.3136
B	μm²	0.89188	0.87862	1.00012
C	μm²	0.20861	0.21801	0.23831
D	1/μm²	0.01320	0.01327	0.01679

Spectral Range of Validity: 350-2400 nm

g. Sellmeier Equations (Hydrothermally-Grown) and Coefficients [9]:

$$n_a^2 = A_a + \frac{B_a}{(\lambda^2 - C_a)} - D_a\lambda^2$$

$$n_b^2 = A_b + \frac{B_b}{(\lambda^2 - C_b)} - D_b\lambda^2$$

$$n_c^2 = A_c + \frac{B_c}{(\lambda^2 - C_c)} - D_c\lambda^2$$

Sellmeier Equations Coefficients [9] (Temperature 303 K) (λ Expressed in Microns)

Coefficients	Units	n_a	n_b	n_c
A	Dimensionless	2.99815	3.02298	3.31105
B	μm^2	0.03995	0.04214	0.06037
C	μm^2	0.04424	0.04990	0.05261
D	$1/\mu m^2$	0.01289	0.01347	0.01652

Spectral Range of Validity: 473-1338 nm

h. Sellmeier Equations Used For OPO Calculations (Hydrothermal) [10], Modified From The Sellmeier Equations of [8]

$$n_a^2 = A_a + \frac{B_a}{(\lambda^2 - C_a)} - D_a\lambda^2$$

$$n_b^2 = A_b + \frac{B_b}{(\lambda^2 - C_b)} - D_b\lambda^2$$

$$n_c^2 = A_c + \frac{B_c}{(\lambda^2 - C_c)} - D_c\lambda^2$$

Sellmeier Equations Coefficients [10] (Temperature Unspecified, Assume 300 K) (λ Expressed in Microns)

Coefficients	Units	n_a	n_b	n_c
A	Dimensionless	3.0065	3.0333	3.3134
B	μm²	0.03901	0.04154	0.05694
C	μm²	0.04251	0.04547	0.05658
D	1/μm²	0.01327	0.01408	0.01682

Spectral Range of Validity: 439.6-3264.0 nm

i. Summary of Principal Index Values at 532 and 1064 nm Determined Using Sellmeier Equations

References	n_a	n_b	n_c	T(K)
		532 nm		
[7]	1.77972	1.78974	1.88767	300
[6]	1.77795	1.78870	1.88865	293
[8]	1.77899	1.78997	1.88680	300
[9]	1.77811	1.78883	1.88902	303
[9]	1.77818	1.78883	1.88902	303
		1064 nm		
[7]	1.74035	1.74785	1.82963	300
[6]	1.73793	1.74547	1.82967	293
[8]	1.73988	1.74754	1.82963	300
[9]	1.73791	1.74547	1.82983	303
[9]	1.73788	1.74547	1.82983	303

j. Linear Loss Coefficients at 532 nm and 1064 nm For Flux-grown KTP

References	Condition	Absorption Coefficient (cm^{-1})	Temperature (K)
	532 nm		
[11]	E||X	0.009-0.036	273
[11]	E||Y	0.011-0.024	273
[11]	E||Z	0.019-0.039	273
	1064 nm		
[12]	Propagation Along a	0.0002	273

[12]	Propagation Along b	0.0005	273
[12]	Propagation Along c	0.0004	273

k. Linear Loss Coefficients at 532 nm For Hydrothermal Growth

References	Conditions	Absorption Coefficient (cm^{-1})	Temperature (K)
[11]	E‖X	0.017	273
[11]	E‖Y	0.025	273
[11]	E‖Z	0.040	273

l. Intensity Dependent Nonlinear Coefficient at 1064.2 nm

References	γ (cm^2/W) (x 10^{-15})	Conditions
[13]	1.4	X-Y Plane
[14]	1.4	[110] Direction
[14]	1.8	[010] Direction
[14]	2.1	[100] Direction

m. Optical Damage Thresholds: Bare Hydrothermal KTP Surfaces

References	Wavelength (nm)	Intensity (GW/cm^2)	Pulse Width (ns)	Conditions
[15]	526.0	30.0	0.03	
[15]	526.0	30.0	0.03	10 Hz
[15]	1064.2	2.0-3.0	11.0	10 Hz

n. Optical Damage Threshold: Bare Flux-Grown KTP Surfaces

Wavelength (nm)	Intensity (GW/cm2)	Pulse Width (ns)	Conditions
532.1	1.4-2.2	8.0	2 Hz
1064.2	1.5-2.2	11.0	2 Hz

o. Optical Damage Thresholds: Bulk, Flux-Grown KTP

References	Wavelength (nm)	Intensity (GW/cm^2)	Pulse Width (ns)	Conditions
[15]	523.5	> 8.0	0.0035	50 Hz
[15]	526.0	10.0	0.03	10 Hz
[15]	532.1	2.0-3.2	8.0	2 Hz
[15]	532.1	> 1.8	0.06	5 Hz

[15]	1064.2	> 3.3	30.0	
[15]	1064.2	2.4-3.5	11.0	2 Hz
[15]	1064.2	0.9-1.0	10.0	

p. Gray-Tracking Thresholds, Flux-Grown KTP, CW

References	Wavelength (nm)	Intensity (kW/cm^2)	Pulse Width	Conditions
[15]	514.50	26.0	CW	E⊥C, θ=90°,φ=23.4°
[15]	514.50	130.0	CW	E⊥C, θ=90°,φ=23.4°

q. Gray-Tracking Thresholds, Flux-Grown KTP, Pulsed

References	Wavelength (nm)	Intensity (GW/cm^2)	Pulse Width (FWHM) (ns)	Conditions
[15]	532.1	0.015	75	6.3 kHz, θ=90°,φ=23.1°
[15]	532.1	0.125	75	1.0 kHz, θ=90°,φ=23.1°
[15]	532.1	0.045	25	10.0 Hz, θ=90°,φ=23.0°
[15]	532.1	0.05-0.10	20	20.0 Hz, θ=90°,φ=23.0°
[15]	532.1	0.080	10	10.0 Hz, θ=90°,φ=23.0°
[15]	532.1	> 0.10	1.0	3.7 kHz, θ=90°,φ=26.0°
[15]	532.1	2.0	0.026	10.0 Hz, θ=55°,φ=0.0°

III. Second Harmonic Generation (SHG) Nonlinear Properties:

a. Second-Order Nonlinear Coefficients Matrix

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix}$$

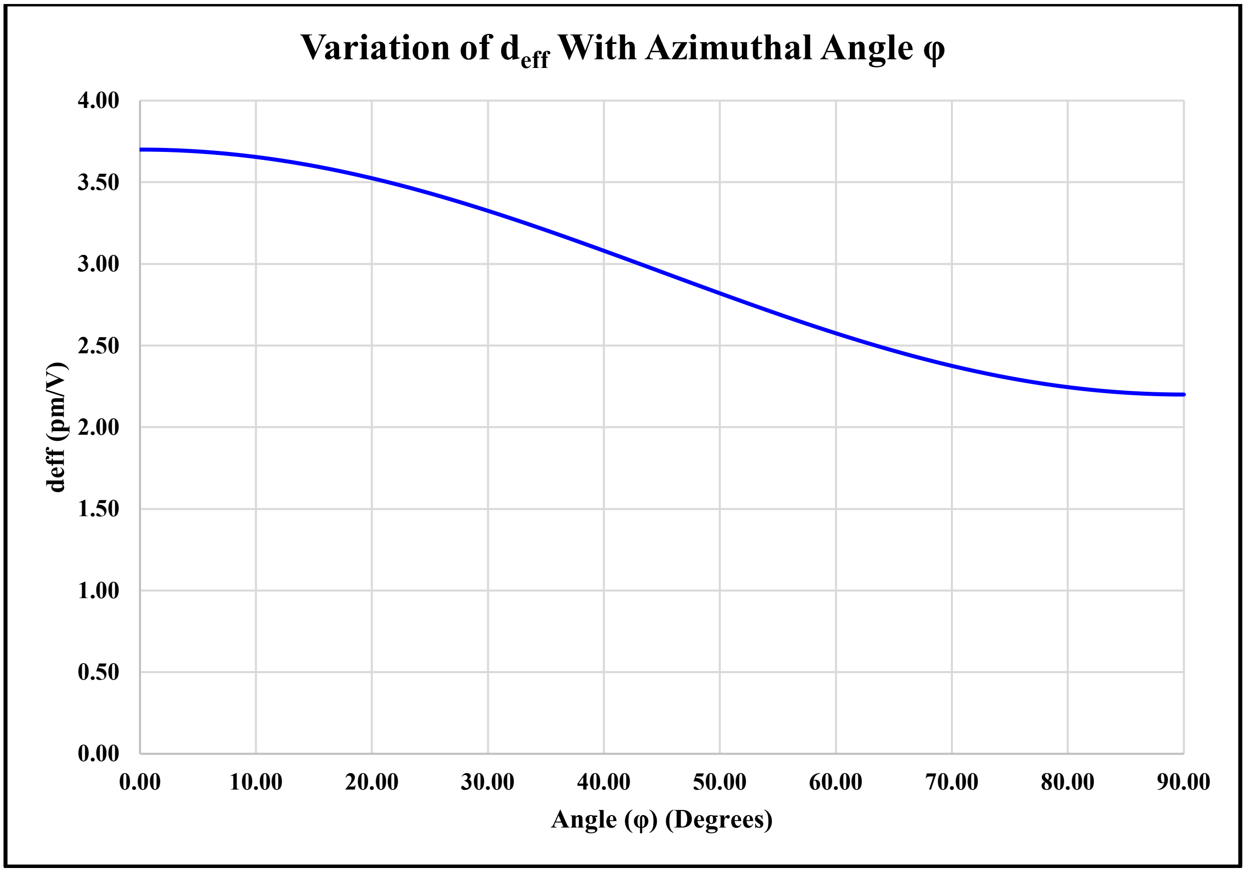
b. Absolute Values of KTP Second-Order Nonlinear Coefficients [15]

Nonlinear Coefficients	Values (pm/V)
d_{15}	1.90
d_{24}	3.70
d_{31}	2.20
d_{32}	3.70
d_{33}	14.60

c. Effective Second-Order KTP Nonlinear Coefficient Calculation in X-Y Plane

For KTP Type II Phase-Matching in the X-Y plane, we have [15]:

$$d_{eff} = d_{eoe} = d_{oee} = d_{31} \cdot \sin(\varphi)^2 + d_{32} \cdot \cos(\varphi)^2$$



d. Calculated Values of Type II SHG Phase-Matching Angles (eoe) For θ=90º

References	SHG Wavelengths (nm)	Phase Matching Angle (φ)	Temperature (K)
[7]	1064.2 => 532.10	23.50	300
[6]	1064.2 => 532.10	23.70	293
	Average:	23.60	
	Hydrothermal Calculations		
[8]	1064.2 => 532.10	26.00	300
[9]	1064.2 => 532.10	24.40	303
[9]	1064.2 => 532.10	24.30	303
	Average:	24.90	

Notes:

1. **For hydrothermal growth, the value of [8] seems to be an outlier, although it is used for hydrothermal grown KTP in the SNLO program.**
2. **Taking the average of the [9] values and the experimental APS value yields a more accurate value of 24.31 degrees.**
3. **The values of [9] are at odds with the phase-matching angle of 26 degrees mentioned in the paper. This is due to the erroneous calculation of the principal index value n_z in Table 3 of the publication.**

e. Measured Values of Type II SHG Phase-Matching Angles (eoe) For θ=90°

References	SHG Wavelengths (nm)	Phase-Matching Angle (φ)	Temperature (K)
	Flux Measurements		
[15]	1064.1 => 532.05	23.5	293
[15]	1064.1 => 532.05	23.6	293
[15]	1064.2 => 532.10	23.0	293
[15]	1064.2 => 532.10	23.2	293
[15]	1064.2 => 532.10	23.3	293
[15]	1064.2 => 532.10	24.1	293
[15]	1064.2 => 532.10	24.7	293
[15]	1064.2 => 532.10	25.0	293
[15]	1064.2 => 532.10	25.2	293
[15]	1064.2 => 532.10	25.3	293
	Hydrothermal Measurements		
[15]	1053.0 => 526.5	34.0	293
[15]	1062.0 => 531.0	25.0	293
[15]	1064.2 => 532.10	26.0	293
[16]	1064.2 => 532.10	24.23	295

f. Walk-Off Angles and Wave Mismatch Sensitivities For Flux-Grown KTP, Type II SHG Phase-Matching (eoe) For X-Y Plane, θ=90° and Temperature of 293 K [15]

SHG Wavelengths (nm)	Phase-Matching Angle (Deg)	Internal Angle Δφ (Deg)	Internal Angle Δθ (Deg)	ΔT (Deg)	Δv (cm^{-1})
1058.2 => 592.1		0.43	2.01		
1062.0 => 531.0	25.0	0.49	2.23	25.0	4.9

1064.2 => 532.1	**23.0**	**0.53**		**20.0**	
1064.2 => 532.1	**23.0**			**23.3**	
1064.2 => 532.1	**23.2**	**0.58**	**1.82**	**24.0**	
1064.2 => 532.1	**23.3**	**0.43**		**20.0**	**4.0**
1064.2 => 532.1	**25.0**				**6.2**
1064.2 => 532.1	**25.2**			**25.0**	
1064.2 => 532.1	**25.2**	**0.42**		**17.5**	
1064.2 => 532.1	**25.2**	**0.52**	**2.52**	**25.7**	

IV. Optical Parametric Oscillator (OPO) and Optical Parametric Amplifier (OPA) Nonlinear Properties:

a. OPO Energy Balance Equation

$$hc\bar{\nu}_p = hc\bar{\nu}_s + hc\bar{\nu}_i \text{, or}$$

$$\frac{1}{\lambda_P} = \frac{1}{\lambda_S} + \frac{1}{\lambda_i}$$

Here, h is Planck's constant, c the speed of light, and $\bar{\nu}_p$, $\bar{\nu}_s$, and $\bar{\nu}_i$ are the wavenumbers for the pump, signal, and idler waves respectively. Also, λ_p, λ_s, and λ_i are the wavelengths of the pump, signal, and idler waves.

b. Phase-Matching Equation in X-Z plane (φ=0) is Equivalent to Type II Phase-Matching in a Positive Uniaxial Crystal:

$$\frac{n_P^o}{\lambda_P} = \frac{n_s^o}{\lambda_s} + \frac{n_i^e}{\lambda_i}$$

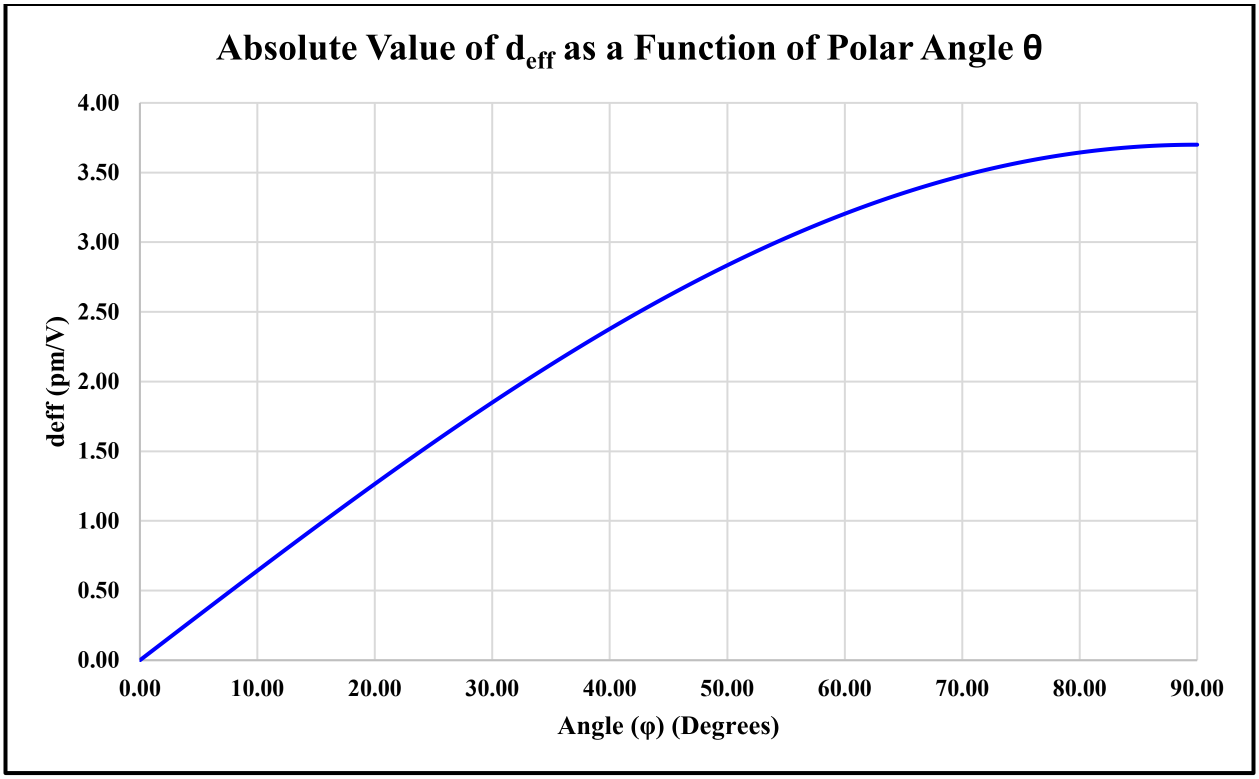
n_P^o, and n_s^o are the ordinary indices of refraction for the pump and signal waves (both with E parallel to the y-axis), and n_i^e is the extraordinary index for the idler wave (E parallel to the z-axis).

c. KHP Second-Order Nonlinear Coefficient d_{eff} for OPO's, φ=0°, θ Variable [17]

From Table 21 of [17], we find

$$d_{eff} = -d_{32} \cdot \sin(\theta)$$

From III. b. of this data sheet, and the above equation, we show d_{eff} as a function of the polar angle θ in the plot below:



The nonlinear coefficient takes the absolute value of 3.7 pm/V for θ = 90°, and zero for θ = 0°.

d. KTP Usage in Single-Resonant Type II OPO's

KTP plays an important role in modern eye-safe laser rangefinders operating near 1550 nm, as a wavelength shifting device from the 1064 nm laser transition in Nd:YAG to the eye-safe region around 1550 nm. While many designs abound using KTP, a particularly well-developed one uses non-critical phase-matched (NCPM) KTP with the following parameters:

Crystal Angle θ (Degrees)	Crystal Angle φ (Degrees)	Propagation Axis	Typical Crystal Length (mm)
90.0	0.00	Along Z-Axis	15-20

e. Pump, Signal, and Idler Polarizations:

Wave	Example Wavelengths (nm)	Polarization Direction	Polarization Type (e or o)
Pump	1064.0	E || Y	o
Signal	1571.0	E || Y	o
Idler	3297.0	E || Z	e

V. Mechanical Properties:

a. **Measured Mass Density ρ (Average) [4]: 3.005 gr/cm^3**

b. **Calculated Mass Density ρ : 3.05 gr/cm^3**

c. **Molecular Weight w_m [4]: 197.934 gr/mole**

d. **Mohs Hardness [4]: 5**

e. **Knoop Hardness [4]: 702**

f. **Vickers Hardness (Average) [4]: 548.5**

g. **Young's Modulus E: 142 GPa = 1.448 x 10^6 kg/cm^2 [18]**

VI. Thermal Properties:

a. **Curie Temperature θ_C: 1211 K [15]**

b. **Melting Temperature (With Some Decomposition) (Average) [4]: 1422 K**

c. **Specific Heat Capacity:**

References	Specific Heat Capacity (J/(gr-K))
[14]	0.688
[14]	0.727
[14]	0.729
Average:	0.715

d. **Thermal Conductivity Matrix and Coefficient Values k (W/(cm-K) at 295 K [4]:**

$$k = \begin{bmatrix} k_a & 0 & 0 \\ 0 & k_b & 0 \\ 0 & 0 & k_c \end{bmatrix}$$

k Values Table

k Coefficients	k Values (W/(cm-K))	References
k_a	0.020	[1]
k_b	0.030	[1]
k_c	0.033	[1]

e. Thermal Expansion Matrix and Coefficient Values α (1/K) at 295 K [4]:

$$\alpha = \begin{bmatrix} \alpha_a & 0 & 0 \\ 0 & \alpha_b & 0 \\ 0 & 0 & \alpha_c \end{bmatrix}$$

α Values Table

α Coefficients	α Values (1/K) (10^{-6})	References
α_a	11.0	[1]
α_b	9.0	[1]
α_c	0.6	[1]

VII. References:

[1] J. D. Bierlein and H. Vanherzeele, J. Opt. Soc. Am. B, 6, 622-633 (1989).

[2] D. R. Lovett, *Tensor Properties of Crystals*, Adam Hilger (1990).

[3] A. Authier, *International Tables For Crystallography*, Volume D, *Physical Properties of Crystals*, Kluwer Academic Publishers (2003).

[4] D. N. Nikogosyan, *Properties of Optical and Laser-Related Materials*, John Wiley & Sons Ltd. (1998).

[5] W. Wiechmann, S. Kubota, T. Fukui, H. Masuda, Opt. Lett. 18, 1208-1210 (1993).

[6] K. Kato and E. Takota, Appl. Opt. 41, 5040-5044 (2002).

[7] C. Bonnin, Cristal Laser, and SNLO (www.as-photonics.com/snlo).

[8] H. Vanherzeele, J. D. Bierlein, and F. C. Zumsteg, Appl. Opt. 27, 3314-3316 (1988).

[9] C.-L. Zhang, Z.-G. Hu, L.-X. Huang, W.-N. Zhou, Z. Lu, G. Zhang, Y.-C. Liu, Y.-B. Zou, F.-H. Lu, H.-D. Hou, S.-J. Qin, H.X. Zhang, and L. Bai, J. Crystal Growth 310, 2010-2014 (2008).

[10] K. Kato, IEEE J. Quant. Electron. 27, 1137-1140 (1991)

[11] G. Hansson, H. Karlsson, S. Wang, and F. Laurell, Appl. Opt. 27, 5058-5069 (2000).

[12] D. J. Gettemy, W.C. Harker, G. Lindholm, and N. P. Barnes, IEEE J. Quant. Electron. 24, 2231-2237 (1988).

[13] R. Adair, L.L. Chase, and S.A. Payne, Phys. Rev. B 39, 3337-3350 (1989).

[14] R. DeSalvo, M. Sheik-Bahae, A.A. Said, D.J. Hagen, and E.W. Van Stryland, Opt. Lett. 18, 194-196 (1993).

[15] D. N. Nikogosyan, *Nonlinear Optical Materials A Complete Survey*, Springer (2005)

[16] Type II eoe phase-matching angle φ measured at Advanced Photonic Sciences (2019)

[17] R. L. Sutherland, *Handbook of Nonlinear Optics*, Second Edition, Marcel-Decker (2003).

[18] N.V. Stus, S.N. Dub, D.A. Stratiychuk, and V.V. Lisnyak, J. of Alloys and Compounds 366, L13-L15 (2004).