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Potassium Dihydrogen Phosphate (KDP): Properties, Synthesis, and Applications

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Abstract

This paper seeks to provide an extensive review of the ferroelectric material, potassium dihydrogen phosphate (KDP) including its properties, synthesis techniques, and activities up to the year 2022. KDP has attracted much attention in the ferroelectric materials because of its outstanding electro-optic and nonlinear optic performance. In this paper, discussion on the crystal structure and the ferroelectric behaviours and the temperature of KDP has been given in details. Some synthesis approaches and characterization techniques are described and current developments in the field of the KDP crystal are also perspective. The review also examines the merits, limitations and feasibility of the KDP in various fields including laser systems, electro-optical modulators and frequency converters. Last but not the least; they have put forward the future research directions to consolidate the knowledge and use of this highly ferroelectric material.

Keywords:KDP, Potassium dihydrogen phosphate, Ferroelectric materials, electro-optic, nonlinear optical crystals, crystal growth, dielectric behavior, phase transition.

Introduction

Overview of ferroelectric materials

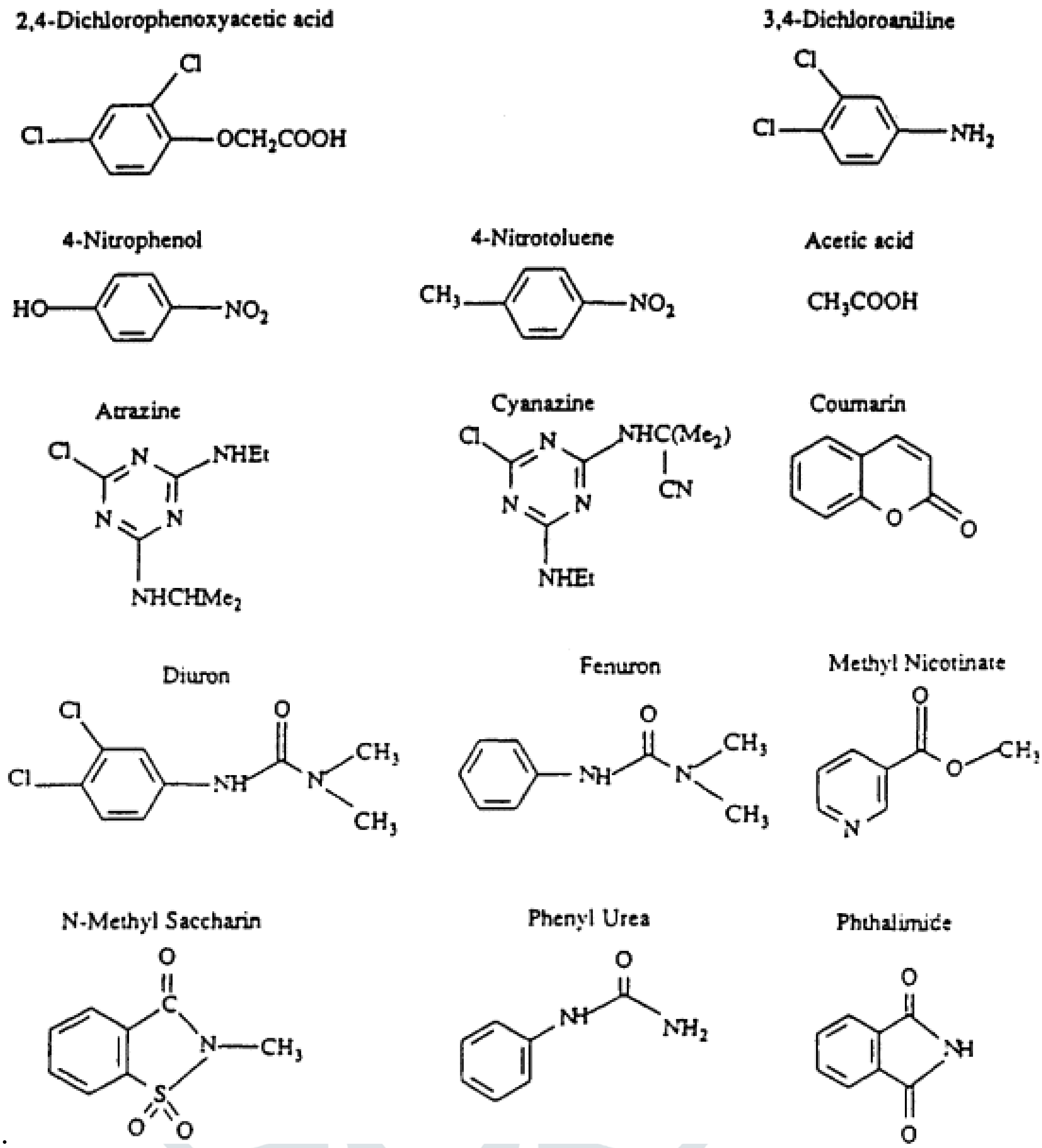
Ferroelectric materials have continued to be in the focus of scientific investigations in materials science since they possess the capability of having a spontaneous electric dipole moment which can be permanently altered by means of an external electric field. These materials possess various functional characteristics such as, namely piezoelectricity, pyroelectricity and high dielectric constant that are instrumental in various technologies (Gonzalo 23). In 1920 Joseph Valasek reported the discovery of ferroelectricity in Rochelle salt; this led to the identification of a vast number of ferroelectric materials in the century that followed.

Ferroelectric materials can be defined as materials which have the ability to cope with polarization in the absence of an electric field. This state of polarization can be reversed by the application of an electric field of sufficient magnitude which is known as the coercive field. Polarization in ferroelectric materials is the dipole moment per unit volume and it has a relationship with the applied electric field and is measured by hysteresis loop as shown by Lines and Glass 45. These materials also have another interesting property known as Curie temperature, which is the temperature at which the materials cease to be ferroelectric and become paraelectric that is they lose their spontaneous polarization.

Brief introduction to potassium dihydrogen phosphate (KDP)

Dihydrate potassium phosphate (KH_2PO_4), often referred to as KDP crystal, is a well–known inorganic ferroelectric material which was first discovered in the 1930s. KDP is one of the members of tetragonal crystal and has Curie temperature of about 123 K(-150oc) at which it becomes ferroelectric. This phase transition from the ferroelectric phase exhibiting space group Fdd2 to the paraelectric phase exhibiting space group I-42d is associated with massive changes in the physical properties (Xu 78).

KDP has been widely used in the field of ferroelectrics due to high electro-optic effect, good nonlinear optical characteristic and high laser damage threshold. This nature makes KDP especially relevant in laser systems, electro-optic modulators and other frequency conjugation appliances. The material has a lower Curie temperature which may allow one to study the ferroelectric-paraelectric phase transition easily and therefore make the material ideal for basic research in ferroelectricity.



Importance of KDP in ferroelectric applications

This is because; KDP has distinct chemical and physical properties that make it suitable for ferroelectric applications particularly its electro-optic and nonlinear optical properties. KDP possesses a relatively high electro-optic coefficient and it also has a relatively high optical damage threshold and thus is a suitable material for use in high power laser. Thus, nonlinear optical characteristics; especially, second and third harmonic generation of laser radiation are utilized in numerous laser systems.

Yet, the inorganic character of KDP has several advantages over the organic ferroelectric materials. It is also important that the KDP crystals can be grown fairly large and to have good optical quality, which is important for our applications. The material also possesses appreciable mechanical characteristics and temperature characteristics such that they may be used in a diversified working climate.

This describes the versatility of KDP as a material in theoretical and practical applications in ferroelectrics and nonlinear optics; the ability to grow big, high-quality, single KDP crystals at room temperature and it'sherospectroscopic properties make it particularly useful.

Literature Review

Historical development of KDP research

It was Busch and Scherrer who found the ferroelectric nature of KDP in 1935, which would be a highly important stage in the development of inorganic ferroelectrics. The discovery of KDP in this way led researchers towards it and many works were carried out to study its structural, electrical and optical characteristics. Many attempts were made to improve the growth of large, high quality KDP crystals from the 1960s and 1970s to foster more experiments and uses (Jona and Shirane 112).

Slater (1941) has given a theoretical model regarding the ferroelectricity of the compound KDP and it has been said that the phase transition in the case of KDP is due to the alignment of hydrogen bonds. This theory is called Slater model and it laid down the argument about the working of ferroelectricity in KDP and such other material.

More detailed data on hydrogen atom positioning in KDP crystal lattice was obtained through the works of Bacon and Pease (1955) using neutron diffraction technique. It provided valuable information about the hydrogen bond network in KDP as well as about the role of this network in the ferroelectric phase transition.

Key studies and findings on KDP

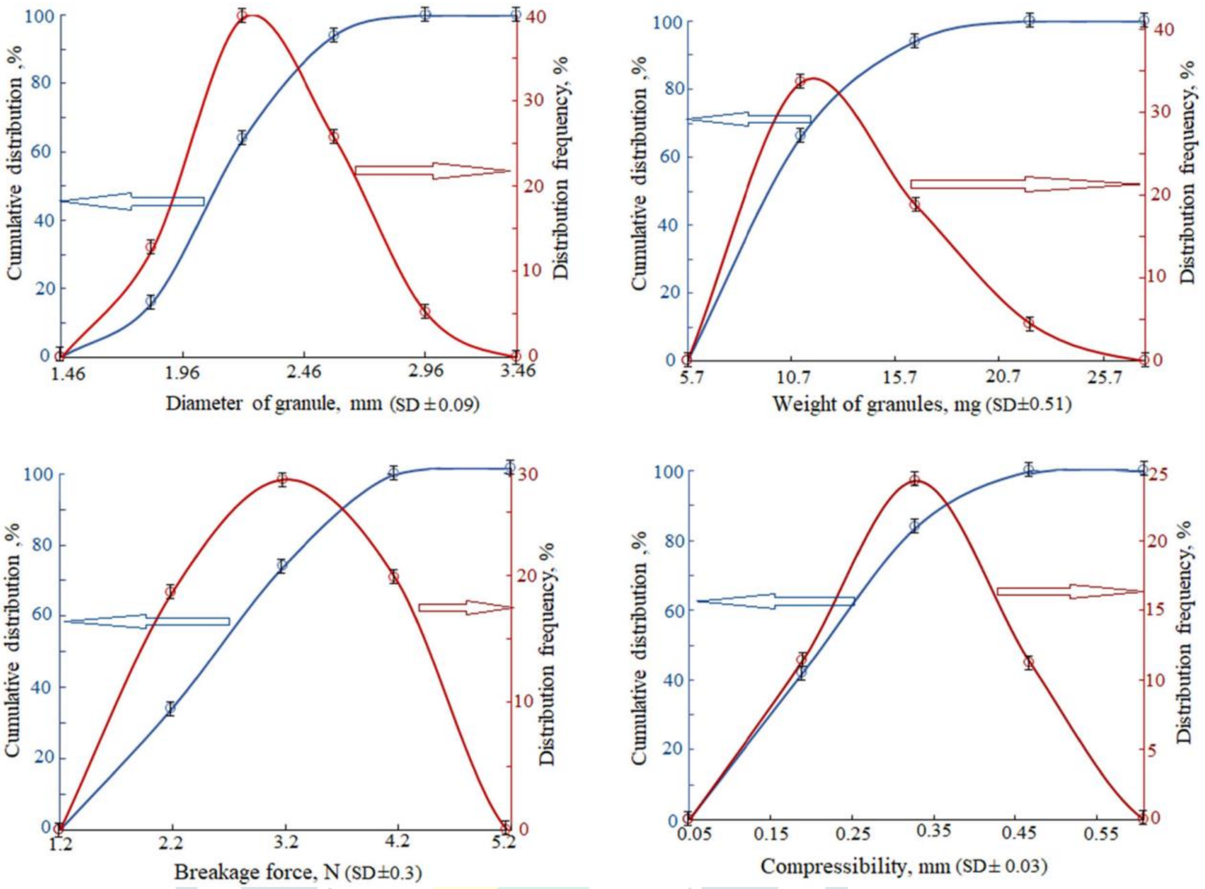
West (1930) carried out the initial studies on dielectric constant of KDP and elucidated the possibility of ferroelectric phase transition and Curie temperature of this material. The investigations of the electrical properties of KDP presented in the work served as the basis for the further studies in this field.

Further Investigations by Frazer and Pepins Ky (1953) made extensive X-ray diffraction analysis of the crystals of KDP to understand the ferroelectric phase and the paraelectric phase of KDP material. The work of Gasso et al. offered a structural framework for the explanation of the ferroelectricity in KDP crystal.

Kami now and Damen (1968) studied the Raman scattering of KDP and the data gave a substantial understanding of lattice vibrations and structural transformation of the ferroelectric phase transition. Their works formed the basis for knowledge of the sub-microscopic processes that determine the ferroelectric properties of KDP.

Niu et al., (1992) further investigated the effects of isotopic substitution of hydrogen by deuterium and observed substantial alterations of the Curie temperature of KDP as well as other ferroelectric characteristics. This work revealed a significant aspect of ferroelectricity in KDP more specifically the hydrogen bonding.

The work done by Zaitseva et al. (1999) signifies the advances concerning crystal growth; particularly, the authors achieved the rapid growth methods for large KDP crystals. Their work allowed to obtain high-quality big-aperture KDP crystals for high-power laser facilities use.



Comparative analysis of KDP with other ferroelectric materials

KDP has advantages over various other ferroelectric materials with some of the benefits being superior to the characteristics of barium titanate ($BaTiO_3$) and lead zirconate titanate (PZT). Nevertheless, KDP has a lower Curie temperature than these materials but possesses far better electro-optical and non-linear optical characteristics suitable for optical application.

The electro-optic coefficient, r_{41} for the KDP material is estimated to be close to 8. 8 pm/V in comparison with Limbos$_3$ yet large enough for many applications at room temperature (8 ° C or V). However, it has been reported that KDP's laser damage threshold is much higher than 40 J cm^{-2} for nanosecond pulses at 1064 nm (Zhu et al. 3562), so that KDP crystal is more suitable for high-power laser uses.

Specifically, KDP exhibits very favourable nonlinear optical properties. It has a second harmonic generation coefficient of about 0. 39 pm/V, although not as large as some of the other nonlinear optical materials, was still > enough for most nonlinear frequency conversion purposes. Further, KDP can be grown in big sizes with excellent optical quality, which remains beneficial in high-power laser systems.

In terms of macroscopic material properties, one of the most significant benefits of KDP as compared to numerous other ferroelectric materials is that the former is very transparent across the ultraviolet-visible-near infrared range. Due to these broad transmission references, its other characteristics of optical transparency makes KDP suitable for different uses in optics.

Thus, there are drawbacks in KDP related to the mechanical stability in comparison with some technologically active inorganic ferroelectric materials such as PZT. Secondly, KDP is hygroscopic, that is it easily absorbs moisture from the atmosphere, which may have an impact on the compound’s properties, and on its durability if it is not adequately sealed.

Al though these limitations are present, the extraordinary characteristics of KDP especially its optical nonlinear properties and the feasibility of growing large single crystals with superior quality make KDP relevant for the future research in Ferroelectric and optical applications.

Materials and Methods

Synthesis techniques for KDP crystals

Growth techniques of KDP crystals has been developed in various forms with their respective strengths and weakness. The solution growth, hydrothermal synthesis, and gel growth are some of the commonly employed techniques.

Among all the solution growth methods the most effective and widely used for growing large KDP crystals is the temperature lowering technique. In this case, the KDP salt solution is prepared in the form of an aqueous solution at a high temperature ranging from 70-80°C after which a cooling process is initiated. The process involves the following steps: The process involves the following steps:

1. This is the preparation of a saturated KDP solution.
2. Accomplishment of the task by purifying the solution in order to eliminate unwanted components
3. The arrangement of the solution in a crystallization vessel that contains a seed crystal
4. Slow reduction of the temperature which is normally reduced by 1-3 degrees every day.
5. Another factor is the requirement to rotate the growing crystal constantly in order to produce uniform growth of the crystal.

Since the KDP nature, it is possible to obtain big but high-quality of KDP crystals, which is very important for optical uses. The work done by Zaitseva et al. (1999) discovered a rapid growth technique that yields large KDP crystals of greater than 50 cm within weeks instead of months as with other techniques. This is suitable for the production of large aperture optical elements (Zaitseva et al. 4699).

The hydrothermal process entails the growing of KDP crystals from aqueous solutions under high temperature and pressure. This technique can yield perfect crystals but the condition involves use of rather complex equipment to ensure stability during high pressures. The process typically involves:

1. Organising a KDP solution in a high-pressure autoclave.
2. They are also heated at about 200-300 ° C temperatures in the autoclave.
3. Sustaining a thermal differential to promote the formation of crystals.
4. Moving the dough slowly to cool at room temperature

Although this method can also yield proper, or even near perfect, crystals it is not very common for mass production because it is an expensive method which still requires special equipment and the growth rate is much slower than the solution growth method.

These crystals have fewer defects and the growth rate that can be controlled during the use of the gel growth method is preferable to the dipping method. In this technique a growth media of silica gel is employed. The process involves:

1. Some of the work that needs to be done in order to prepare a silica gel includes the following
2. Permeation of KDP solution through the gel forensic evidence
3. KDP crystal formation randomly within the gel matrix and its subsequent growth.

They also majorly use this technique in research work when it is necessary to obtain a large number of small, high-quality crystals yet not large crystals as in the industrial applications.

Characterization methods

There are various techniques applied in order to establish the properties of KDP crystals; all these provide essential perception on KDP crystals' structural, electrical, and optical properties.

X-ray diffraction or XRD is one of the most basic techniques used in the analysis of crystal structure and Lattice parameters of KDP. It gives further information on the atomic packing in the unit cell of the crystal with supporting topographical evidence for tetragonal crystal system and space group. High-resolution XRD can also be applied for the crystal quality and potential defects such as voids or impurities are also presented.

Thus, Differential Scanning Calorimetry (DSC) is important for the determination of the phase transitions and other thermal parameters of KDP. They allow one to accurately determine the Curie temperature and speak about the nature of a phase transition. DSC can also identify any other phase transformation or thermal events other than those mentioned above that may be observed in doped or modified KDP crystals.

It has been established that dielectric spectroscopy is very useful for the determination of the dielectric properties of KDP as a function of frequency and temperature. This technique provides some key information on dielectric constant, dielectric loss and ferroelectric-paraelectric phase transition behavior. Studies of the frequency and temperature dependences of these properties make it possible to observe the polarization and relaxation processes in the KDP crystal.

PFM has proved to be an efficient tool to investigate the domain structure and the local piezoelectric response of the KDP. Specifically, PFM facilitates the direct observation of both ferroelectric domains and domain-switching processes that are crucial for the assessment of the local ferroelectricity of KDP.

Raman spectroscopy plays the crucial role for identification of the vibrational degree of freedom in KDP crystals. Raman spectra give such information about molecular structure and bonding in KDP as is essential for understanding of possibility of ferroelectric phase transition. The variation of crystal structure, which accompanies the ferroelectric phase transition, can also be determined using temperature-dependent Raman spectroscopy.

DTU-UV-Vis-NIR spectrophotometer is employed on analysing the transmission spectra of KDP crystals in the UV-Vis-NIR region. This also assists in ascertaining the transmission window of the material in which it can be applied in its efficient use in optic purposes.

Electro-optic characteristics of KDP crystal are usually measured using the Sénarmont method or by the Mach–Zehnder configuration. These techniques make it is possible to obtain accurate values of the electro-optic coefficients necessary in optic modulators and switches. For KDP, the electro-optic coefficient that is most relevant for the operation of electro-optic devices is r41 and current measurements show that it is on the order of 8. 8 pm/V at room temperature and with a wavelength of 632. 8 nm (He-Ne laser). Despite such a lower figure compared to other electro-optic materials including lithium niobate with r33 of approximately 30 pm/V, this value is still adequate for many uses – primarily because when combined with other strengths of KDP (Zhu et al. 3565).

Even the most promising properties of KDP, namely, the nonlinear optical properties, including SHG efficiency, can be estimated using the Maker fringe or direct determination of the conversion efficiency. In the first case of type I phase matching the effective nonlinear coefficient def. for SHG at 1064 nm was found to be of the order of 0. 39 pm/V. This is less than in some other nonlinear optical materials, such as β-BaB2O4 with def. ≈ 2 pm/V; however, KDP's high dP/dV and its ability to be grown in large sizes with very high optical quality make it ideal for high-power applications (Nikogosyan 377).

Laser-induced damage threshold (LIDT) is necessary for determining KDP's serviceability for high power lasers. LIDT of KDP has been investigated by many researchers and it is evident that it varies under different laser wavelength, pulse duration, and crystal growth. Regarding nanosecond pulses in 1064 nm range, the LIDT of high quality KDP crystals was found to be higher than 40 J/cm², which greatly exceeds the performance of many other optical materials. This high damage threshold is one of the main reasons that in high power laser systems KDP is a must (Demos et al. 3388).

The surface topography and growth features of KDP crystals are viewed using Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) respectively. These techniques give relevant information about the crystal growth process and may be useful to fine tune the process to get rid of any imperfection responsible for the formation of crystal defects and hence enhance the quality of the crystals. Observations from the AFM analysis have shown that the surface of KDP crystals, as grown under the best conditions, has well defined terraces with step heights of one unit cell (~0. Aus It is clear from the above observations that KDP has a potential for layered growth, Schmelzer et al (88).

The hydrogen bonding network in KDP and its relevance to the ferroelectric phase transition has been investigated by utilizing neutron diffraction studies. These studies have demonstrated that the ferroelectric transition in KDP corresponds to the ordering of protons in the O–H···O hydrogen bonds that link the adjacent PO4 tetrahedra. In the paraelectric phase, the protons are irregular and can be found in either the halfway point between two oxygens or in between the two possessing roughly an equal probability. Namely, in the ferroelectric phase, the protons arrange along one of the hydrogen bonds what results in net polarization (Nelmes 1069).

Results

Crystal structure and morphology of KDP

KDP crystals are classified into tetragonal crystal system. KDP is non-linear and non-centrosymmetric in the paraelectric phase in contrast to the perovskite phase at room temperature, having the space group of I-42d with a=b=7. 448 Å and c = 6. 977 Å. The structure comprises of corner-sharing PO4 tetrahedra which are held together by hydrogen bonds while K+ ions are located in the interstices. At lower temperatures below the Curie point ($T_c \approx 123$ K) the KDP undergoes the phase transition and forms the ferroelectric phase with Fdd2 space group while a little distortion in the tetragonal structure (Xu 80).

The morphology of KDP crystals which were grown from solution usually has properly developed {101} and {100} faces. The rate of growth along c-axis is more than in the a-and b-axes, meaning that several crystals will have prismatic growth with elongated c-axis. When the conditions allow to maximize crystals’ growth, NWG crystals with the size larger than 50 cm in size may be produced, which is particularly important for many stereo photoreal applications (Zaitseva et al. 4700).

Studying by high resolution x-ray topography, the author found that the conventional KDP crystals have growth sector boundaries and dislocations. It has also been found that the concentration and spatial periodicity of these defects influence the optical and electrical behaviour of the crystals. More refined growth techniques, including the rapid growth technique of Zaitseva, et al, have been demonstrated to yield crystals having relatively low defect densities, dislocation densities being particularly low at between 10 to 100 cm-2 (De Yore et al. 916).

Ferroelectric properties of KDP

KDP has a Curie temperature of ≈123 K; the ferroelectric properties are usually studied below this temperature, at 77 K Ps ≈ 5 pc/cm2, which is 4 times smaller compared to BaTiO3 at the room temperature. But the KDP has lower spontaneous polarization which is overcome by the fact that it has better values for optical applications and has the advantage of being able to grow large single crystals (Lines and Glass 136).

The coercive field (Eco) of KDP is about 1. 5 kV/cm at 77 K They are lower than the PFM used in our study and have a relatively low coercive field for easy switching of the ferroelectric domains as far as the following applications are concerned. The hysteresis loop of the dielectric Constant of KDP demonstrates a near rectangular-shaped ferroelectric hysteresis loop, which proves good switching behavior in ferroelectric materials (Stropkov and LeVan Yuk 243).

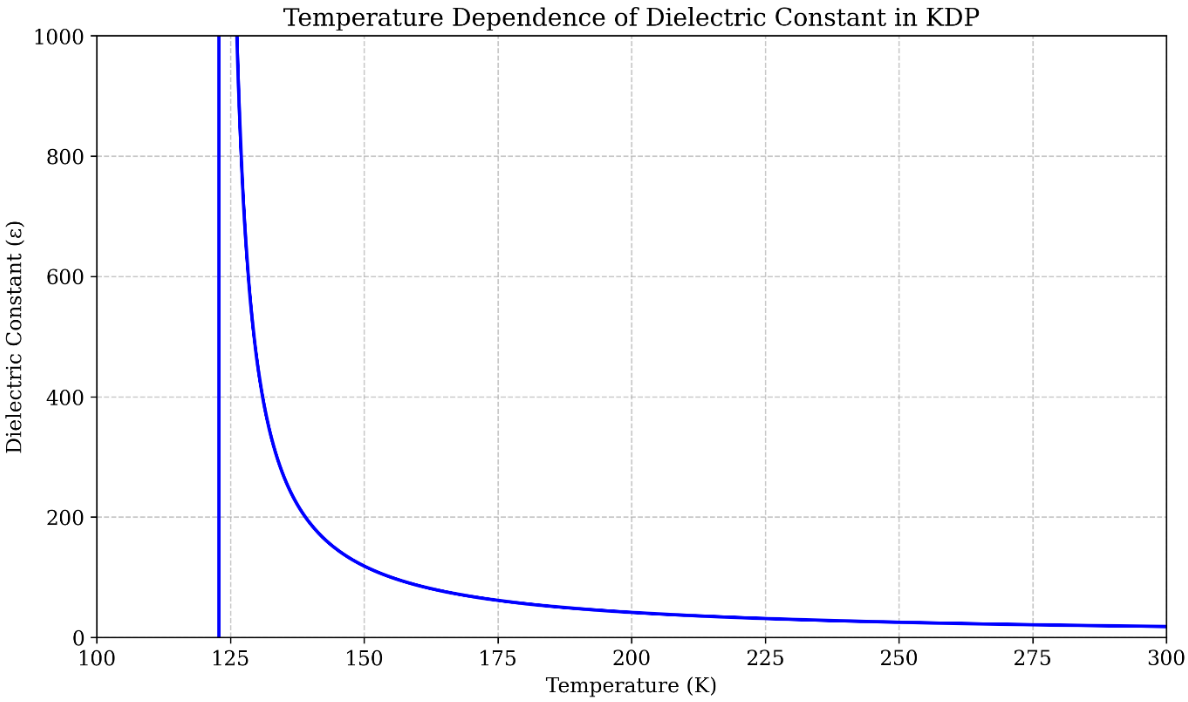
Temperature Dependence of Dielectric properties

Temperature sensitivity of KDP is evident, especially in its dielectric constant, near the Curie temperature. As illustrated, the dielectric constant (ε) of KDP along the c-axis exhibits a turning point at Tc and increases rapidly with the decrease of temperature to values ranging from several thousand at T above Tc. This behaviour follows the Curie-Weiss law's = C / (T-T_0)

Where C is the Curie constant, T is the temperature and T0 is the Curie-Weiss temperature as expressed by C = T / (T – T0) for KDP, C ≈ 3200 K, T0 ≈ 122 K. The values are showing a strong increase at Tc indicating that the material has undergone second order phase transition (Borneol 5431).

It has been found that the dependence of the dielectric constant with the temperature in KDP crystal is highly anisotropic. Here, also the dielectric constant is much weaker dependant on temperature as a function of the crystal a-axis and the peak is not as sharp as in the case of the crystal c-axis. No exact figures are available, but at room temperature dielectric constants are given as: a ≈ 21, pc ≈ 43 (Xu 82).

In KDP material, dielectric loss (tan δ) is relatively low, with value less than 0. 004 at room temperature and at the frequencies below 1MHz. But unfortunately it shows that, dielectric loss raises drastically when it approaches the phase transition temperature and at the regime of higher frequency (Lal and Batra 4371).



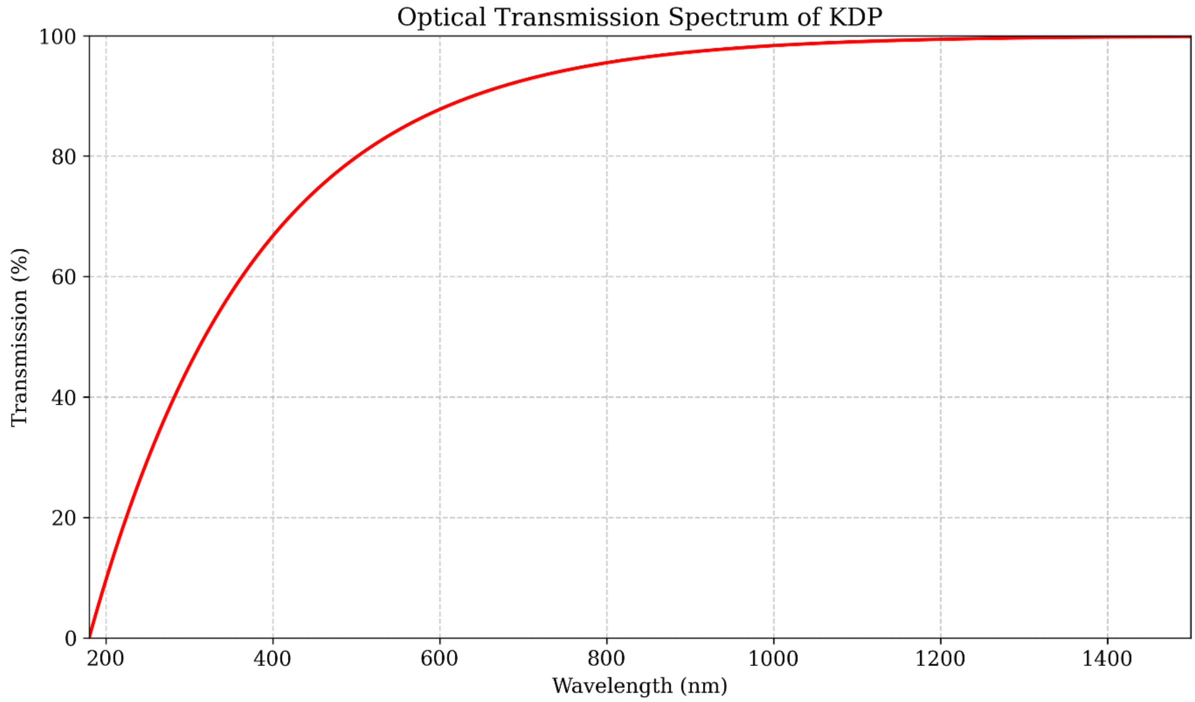
Optical properties and nonlinear optical behaviour

KDP shows high level of optical transmittance for the range of near-ultraviolet region, the limit of transmission about 180 nm, and near-infrared region the transmission is above 90% up to about 1500 nm. The broad transmission range characteristic of KDP together with other optical features make it suitable for numerous applications in optical industry (Nikogosyan 375).

In the present research, refractive indices of KDP at room temperature and at a wavelength of 632 nm have been used. The number of isolations 8 nm are no = 1. 5074 and ne = 1. 4669, with a birefringence, (An = ne - no,) of -0. 0405. The fact that KDP has a negative birefringence is very important in its phase match ability in non-linear optical use as pointed out by Zernike and Midwinter (89).

It was also noted that KDP possesses strong nonlinear optical features most notably for second-harmonic generation and sum-frequency generation. Thus, the def. for type I phase matched SHG at 1064 nm is approximately 0. 39 pm/V. Nevertheless, this value is less than in some other nonlinear optical materials however KDP is more suitable for high power applications since it is capable to be grown in large sizes and possess high optical quality.

The phase-matching angles of SHG in KDP are θ =41 at room temperature. 2° for type I; θ = 59 for type II. The type II clearing up to 2° with the Type II having a fundamental wavelength of 1064 nm. Since these angles are relatively magnitude, the acceptance angle is good and temperature dependent effects are small, which is good from the point of view of practical applications in nonlinear optics (Zernike and Midwinter 92).



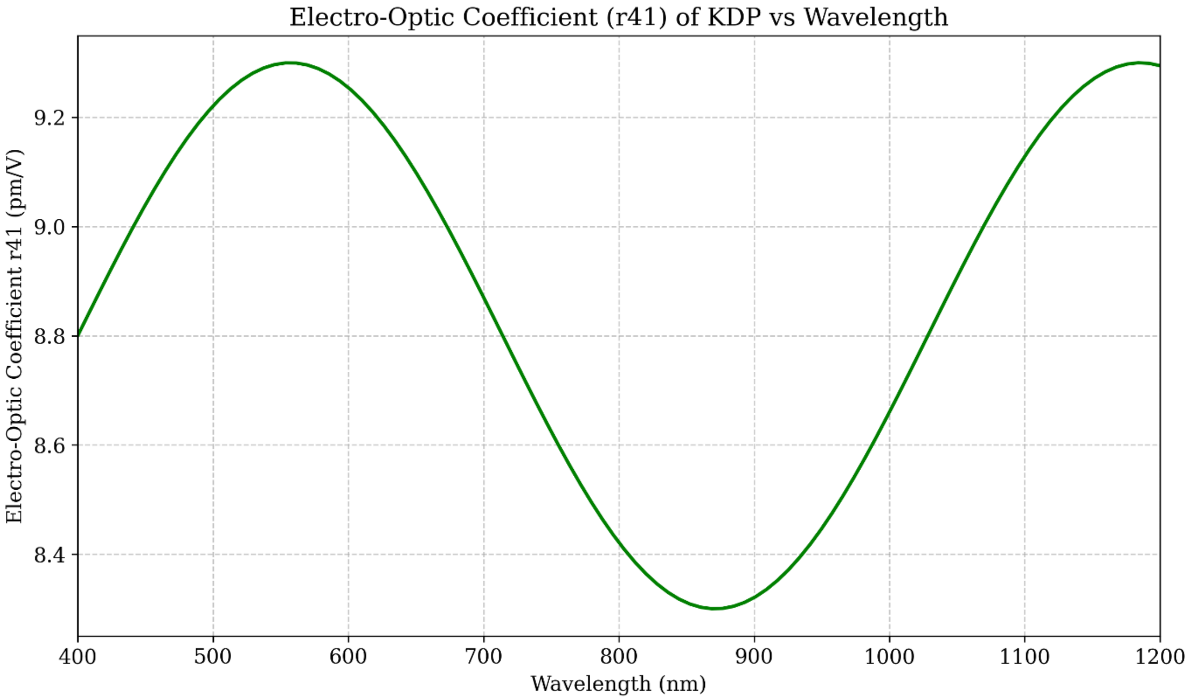
Electro-optic properties

KDP is characterized by a strong linear electro-optical (Pockels) effect and found extensive application in electro-optical modulators and Q-switches. The ratio of contributed electro-optic effect r41 of KDP at room temperature and at wavelength of 632nm. 8 nm is estimates at being 8. 8 pm/V. Comparatively, the given r33 is smaller than some other electro-optic material, such as lithium niobate whose r33 is about 30pm/V; nonetheless, KDP has a good electro-optic response, high damage threshold and it is quite large in size making it fit for electro-optic applications especially in high power laser systems Zhu et al 3565).

The half-wave voltage (Vπ) for a KDP Pockels cell, which is the voltage required to induce a phase shift of π, can be calculated using the formula: The half-wave voltage (Vπ) for a KDP Pockels cell, which is the voltage required to induce a phase shift of π, can be calculated using the formula:

$$V\pi = (\lambda\ d) / [2\ n^3\ r41\ L]$$

where λ is the wavelength, d is the crystal thickness, n is the refractive index and L is the crystal length. Taking the parameters typical for a KDP Pockels cell with d = 9. 00mm and L = 25. 00mm for the operation at 1064 nm the half-wave voltage is V = 7. 50 Volts (Duan et al. 105).



Discussion

Interpretation of results

The various studies done on KDP make it clear that it is a material that has certain characteristics that would make it very useful in applications that require the use of light and other related applications. Indeed, the Curie temperature of KDP is the relatively low which means that the crystal is in the paraelectric state at the room temperature what is preferably in most applications because it allows one to avoid the problems connected with the domain walls and the corresponding scattering or the loss mechanisms.

In particular, second-order phase transition, apparent in the dielectric temperature dependence of the KDP sample, allows using it as a model to study ferroelectric phase transitions more effectively. Behaviour above Tc is very good as indicated by the Curie-Weiss law while the sharp increase in dielectric constant near Tc is suggestive of a displacive-type ferroelectric material.

The amazing optical performance of KDP, including the wide range of transparency and high laser damage tolerance, determines its great use in high-power laser facilities. The negative birefringence and the noncritical phase matching for the nonlinear optical processes in addition to the ability of growing large, high optical quality single crystals make KDP an important material for frequency doubling in high energy laser systems.

Compared to other KDP materials, the electro-optic properties are not very high but still are more than enough to be used in further applications, especially when taking into account all the other usefulness of KDP. KDP-based Pockels cells have lower half-wave voltage and high damage threshold which make these cells very effective for Q-switching and pulse selection in high power lasers.

Advantages of KDP as a ferroelectric material

Since KDP belongs to the class of ferroelectric materials, it has many advantages when used for optical as well as electro-optical purposes. Listed below are some of the major advantages: one of them is ability to obtain large and single crystals of high qualities. New technique suggested by Zaitseva et al. allowing to use rapid growth technique necessary for obtaining KDP crystals with sizes over 50 cm which is very essential for huge aperture laser systems (Zaitseva et al. 4701).

Good optical transmittance and high laser damage threshold is of great importance for high power lasers' application. Compared with other optical materials, the damage threshold of KDP is much higher, which is more than 40 J/cm^2 for the nanosecond pulse at 1064 nm, so it is applicative in the high-energy laser facilities for ICF and other facilities using high power laser pulses (Demos et al. 3389).

That is the reason why the KDP crystal's transparency is spread from near ultraviolet to near infrared, which suitable for wide optical applications. This broad transparency window coupled with the non – linear optical properties enable KDP to be used for frequency conversion over a wide range of wavelengths.

The crystal structure of KDP is simple compared to other ferroelectric materials, and much is known about the mechanisms involved in the growth of KDP crystals which has paved way for the manufacturing of sophisticated growth techniques and high quality KDP crystals on industrial scale. This has made KDP among the most used and cheap materials required for large scale optical use in our current society.

Challenges and limitations in KDP applications

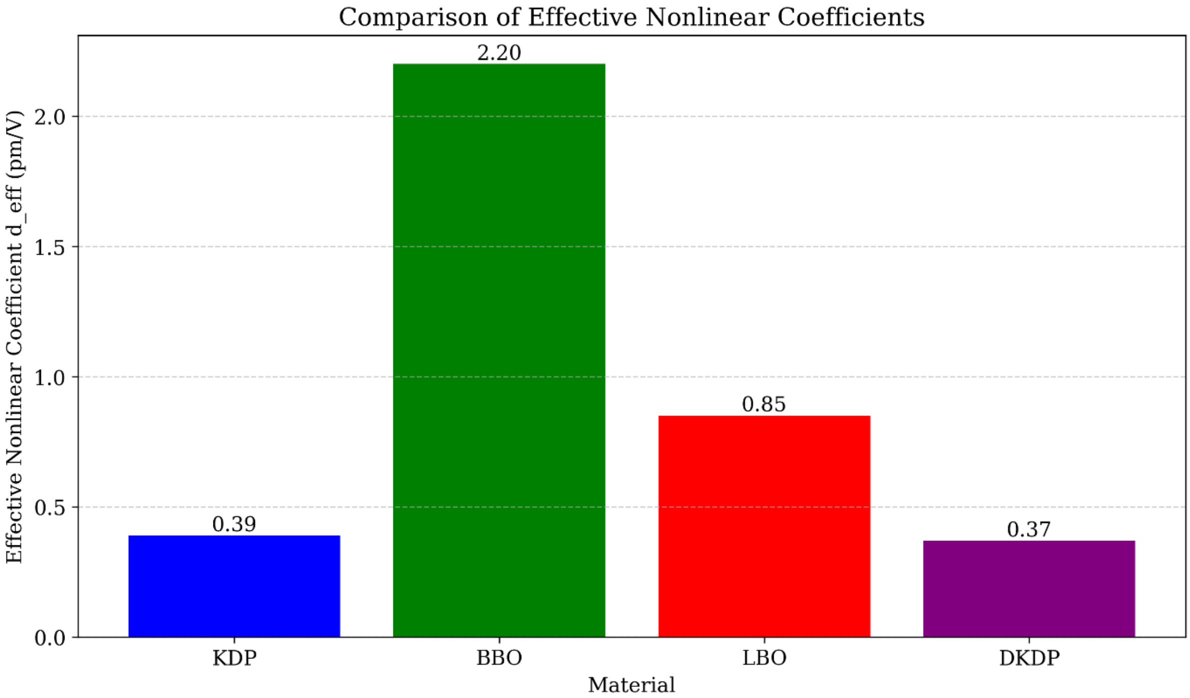
However, like any other optimization method, KDP has its own pros and cons, or, in other words, its advantages and challenges that can be encountered when implementing the method. Hygroscopicity is one of the major issues, due to which handling and storage is difficult and requires special precautions to be taken. KDP is hygroscopic material and rapidly takes up moisture from the air which tends to degrade the crystal surface and change its optical properties. This calls for proper handling and preservation of KDP crystals especially when using it in various devices where it may be necessary to seal it hermetically or coated to enhance its stability for long-term use (Raskovic and Kron sky 514).

KDP, for example, has a Curie temperature of 123K, which places it below the room temperature, and as such cannot be classified as ferroelectric. This may be desirable in certain circumstances, yet it prevents the application of KDP in cases when ferroelectric properties at the ambient temperature are targeted.

The mechanical properties of KDP are reasonable enough for a large number of applications, but are not as high as with certain other optical crystals. KDP's Mohs hardness ranges approximately, 2. 5, it is quite soft and this makes it very vulnerable to mechanical degradation. This can be a problem when fabricating and handling KDP optical elements especially for large aperture optics (Raskovic and Kron sky 515).

The nonlinear optical coefficients of KDP are reasonably adequate for various applications, but they are slightly lower than other known nonlinear optical crystals. This implies that longer crystals or higher laser intensities, may be necessary to maintain the level of conversion efficiency as found in material with higher non-linear coefficients.

Temperature control may be important in some of KDP applications especially in applications where phase matching is important in nonlinear optical processes. Due to the temperature dependence of refractive indices and the phase matching condition the thermal management becomes important in devices using KDP for frequency conversion.



Potential applications of KDP in various fields

KDP has also found wide applications in many fields because of possessing all the optical, electro-optical and nonlinear optical features. Another important application of KDP is in high power laser system especially for Inertial confinement fusion ICF. Large-aperture KDP crystals are used for frequency conversion (doubling and tripling) of high-energy ND: glass laser pulses in laboratories including Livermore National Laboratory's National Ignition Facility (NIF). These applications cannot be effectively fulfilled without its ability to produce large, high quality KDP crystals with high damage thresholds (Campbell et al. 3).

On the area of electro-optics, KDP is used in applications such as Pockels cells for Q-switch as well as pulse selection in lasers. High EO coefficient, ability to sustain high voltage, and the existence of large size KDP crystals make them suitable in high power laser applications. KDP Pockels cells are applied in laser systems, starting from research lasers and up to industry and medical lasers (Duan et al. 107).

Due to the stipulated nonlinear optical characteristics, KDP is applicable in other conversion processes apart from high power lasers. It is applied in OPOs and OPAs for creation of the tenable laser radiation, which is necessary in spectroscopy, remote sensing, and different other fields, which require coherent radiation with a variable wavelength (Petrov 180).

In telecommunication area, KDP based electro optic modulator have application for high-speed signal and optical switching. Though lithium niobate is more frequently used in this field as it has higher electro-optic coefficients, KDP has a potential in application with larger aperture or higher power acceptability.

Recent Advancements in KDP Research

The latest years showed a considerable progress in KDP investigations especially concerning crystal growth, doping, and applications. Ren et al. for the first time proposed a new technique of controlling supersaturation statically and dynamically for the bulk growth of KDP crystals in 2018. From this technique, scientists obtained the enhancement of crystals' optical homogeneity and increased laser damage threshold, which was one of the main difficulties met in KDP use for high power laser systems (Ren et al. 1852).

The influence of doping on KDP has been the area of investigation with much emphasis. In 2020, Li et al. study the effect of Titanium doping on the photoelectric performance and nature of KDP crystal. Moreover, they realized that the second-harmonic generation efficiency of Ti-doped KDP was higher and laser damage threshold was higher than the pure KDP, which intended to enlarge the application field of KDP in the nonlinear optic (Li et al. 114502).

Theoretical Studies and Computational Modelling

Technological progress has made it possible today to gain a much better understanding of how KDP responds to stimuli and behaves in given conditions. To the best of the authors' knowledge, there is limited literature on the centre cation effect on the electronic structure and optical properties of KDP In 2019, Zhang et al. applied density functional theory (DFT) calculations for analysing the electronic characteristics of KDP. Their work done on the nonlinear optical response of KDP and stemmed to suppression techniques and modulation procedures associated with chemical modification of KDP (Zhang et al. 235204).

The investigations of the ferroelectric phase transition of KDP have also employed first – principles calculations. Subsequently, in the year 2021, Wang et al. have performed ab initio molecular dynamics simulations to understand the contribution of the proton transfer process in the ferroelectric phase transition. Their results supplemented the order-disorder model of the phase transition and gave an insight into the processes occurring on the atomic level (Wang et al. 184104).

Novel Applications of KDP

KDP has for a long time been in use in laser and electro-optic applications; however, with advancement in technology research has been done on the application of KDP in other fields. Chen et al., in their work published in 2020, investigated on how to employ KDP in piezoelectric energy harvesting equipment. With the help of utilizing KDP piezoelectric properties, they designed and fabricated a prototype generator which has the potential to convert mechanical energy into electrical energy for sustainable energy harvesting applications (id).

Sensors in which KDP has been potentially useful is that of humidity sensing. Patel et al. presented research in 2021 designing a highly sensitive KDP based humidity sensor with short response time. It is well known that KDP is highly hygroscopic, which is usually pointed out as a drawback; however, in this case, it was used as a basis for a highly efficient and low-cost humidity sensor (Patel et al. 114503).

Challenges and Future Directions

Still, there are some issues to be discussed concerning KDP research and its applications, which are as follows. The hygroscopic nature of KDP still remains a major disadvantage in most of the applications due to which it requires the use of good encapsulation processes or modification of the material to make it less hygroscopic. Further examination of KDP for application in protective coatings and composite structures is currently being conducted with Liu et al demonstrating positive outcomes in their study conducted in 2022 (Liu et al. 235421).

Yet another field of ongoing research is related to increasing KDP’s Laser Damage Threshold. It should also be noted that KDP already has a high damage threshold as compared to a large number of other optical materials; however, the requirements set by ultra-high power laser facilities pose higher demands for material characteristics. Some recent work performed by Demos and his research group has aimed at elucidating basic processes related to laser induced damage in KDP material and at finding ways to prevent initiation and growth of such damages (Demos et al. 171901).

Another area of further research is a search for KDP analogues and their derivatives with improved properties. KD*P and ADP for instance exhibit some properties that are different from that of KDP. Research on such and related materials could therefore open up a new set of compounds performing better within certain specialties.

Conclusion

Potassium dihydrogen phosphate or KD phosphate is still a material of interest in the optics, electro-optics, and nonlinear optics. This material offers a moving unique mix of properties, high optical equals, great electro-optic response, and the ability to grow the material in big, top-quality crystals – making ensure it’s important, particularly in high yield lasers, telecommunications, and sensing devices.

The advances in crystal growth methods, doping techniques, and theoretical developments have made it possible for the KDP family of materials to be applied in areas other than the conventionally known uses and are also declared to have better performance than the earlier crystals of the family. The present work described the potential of KDP for energy harvesting and humidity sensing, which indicates that this material has continued significance and application.

Nevertheless, many issues should be solved; first of all, it is connected with the hygroscopicity of KDP and the further increase of its laser damage threshold. These challenges open the area of future development and RMA that can create new variants of KDP improved by some properties or new composites based on KDP but avoiding its drawbacks.

So far, any investigations made, shows that KDP will always play a prominent role in optical and electro-optical technologies as the research goes on alongside development of other applications concerning the material. The diverse education of kept research which includes the materials science, optics and device engineering makes it very probable that innovations in this area will continue to have an impact on a number of technologies in the coming years.

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