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# Unveiling Optical Insights: A Focused Exploration of $x\text{Al}_2\text{O}_3$ -(50-x) $\text{P}_2\text{O}_5$ -10CaO-40K<sub>2</sub>O Phosphate Glasses Through UV-Vis Spectroscopy.

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## ABSTRACT

This study delves into the tailored optical properties of APCK<sub>x</sub> glasses, featuring a composition of  $x\text{Al}_2\text{O}_3$ -(50-x) $\text{P}_2\text{O}_5$ -10CaO-40K<sub>2</sub>O, synthesized via a conventional melt-quenching process. Through UV-Vis spectroscopy analysis, the optical characteristics are scrutinized, revealing distinct charge transfer bands around 250 nm, whose intensity amplifies with higher alumina content. These bands denote electron transfer from oxygen to aluminum atoms within the glass matrix. Significantly, these glasses maintain exceptional transparency within the 400-800 nm range, consistent with their colorless appearance. The observed reduction in optical gap energy with increasing alumina content signifies a transition from insulator to semiconductor behavior, attributable to augmented oxygen vacancies and enhanced polarizability. These versatile optical traits underscore their potential utility in various optoelectronic and semiconductor applications. The study accentuates the pivotal role of these glasses in advancing materials across diverse technological realms, highlighting their promise in driving innovations in optoelectronics and semiconductor technologies. Furthermore, the controllable tuning of optical properties opens avenues for tailored applications in photonic devices, including sensors and optical fibers. The study underscores the importance of understanding structure-property relationships in glasses, paving the way for advanced material design and innovation.

## 1. Introduction

The captivating realm of advanced materials, phosphate glasses stand as luminaries, boasting unique compositions that wield profound influence across diverse technological landscapes [1]. These glasses, with their optical versatility, have become linchpins in applications ranging from solid-state lasers to intricate optical components, shaping the trajectory of technologies like optoelectronics [2], telecommunications, and photonics [3]. The integration of rare earth ions within phosphate glasses imparts them with favorable luminescent properties, solidifying their position as exceptional candidates for laser systems and photonics applications [4,5]. Their wide bandgap and transparency across visible and near-infrared regions further solidify their relevance, paving the way for advancements in optical communication systems and optical fiber technologies [6].

Beyond their roles in active optical devices, phosphate glasses emerge as pivotal players in passive optical components, embodying excellence in transmission characteristics [7], low melting temperatures, and malleability. These qualities render them ideal candidates

for crafting optical waveguides and fibers, where their tailored composition allows for precision in fine-tuning refractive indices [8]. This, in turn, offers exact control over light propagation a critical attribute in the development of efficient optical communication systems where the performance of optical components is paramount.

As we embark on an illuminating exploration of the  $x\text{Al}_2\text{O}_3$ -(50-x) $\text{P}_2\text{O}_5$ -10CaO-40K<sub>2</sub>O glass system through the lens of UV-Vis spectroscopy, our mission transcends mere analysis. We aim to unravel the nuanced optical dimensions of these phosphate glasses, adding a compelling chapter to their storied existence. This study, building upon our extensive investigation into the structural, thermal, and chemical facets of phosphate glasses within the  $x\text{Al}_2\text{O}_3$ -(50-x) $\text{P}_2\text{O}_5$ -10CaO-40K<sub>2</sub>O system [9], takes a focused leap into the captivating realm of optical properties. By introducing alumina ( $\text{Al}_2\text{O}_3$ ) into the glass composition, we anticipate not only enhancements in structural and chemical properties but also a captivating evolution in optical behavior.

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We chose to incorporate UV-Vis spectroscopy results due to their unique ability to probe electronic transitions and absorption characteristics, providing focused insight into the optical landscape of the synthesized glasses. By isolating and elucidating the optical signatures within our glass system, we aim to complement and extend the narrative of our prior research and usher in a new perspective and depth of exploration into these technologically significant phosphate glasses.

## 2. Experimental

### 2.1. Glass preparation

In a previous study, we documented the synthesis process and characterization of phosphate glasses in great detail [9]. The high-quality reagents,  $\text{NH}_4\text{H}_2\text{PO}_4$ ,  $\text{CaCO}_3$ ,  $\text{K}_2\text{CO}_3$ , and  $\text{Al}_2\text{O}_3$ , were supplied by Sigma-Aldrich and were meticulously weighed, blended, and heated to eliminate  $\text{NH}_3$ ,  $\text{H}_2\text{O}$ , and  $\text{CO}_2$ .

We used the conventional melt-quenching technique at ambient temperature. The resulting phosphate glasses were characterized by a composition denoted as  $x\text{Al}_2\text{O}_3$ -(50-x) $\text{P}_2\text{O}_5$ -10CaO-40K<sub>2</sub>O, where x varied at 2.5, 5, 7.5, 10, 12.5, and 15 mol%. These distinct glasses were designated as APCK<sub>2.5</sub>, APCK<sub>5</sub>, APCK<sub>7.5</sub>, APCK<sub>10</sub>, APCK<sub>12.5</sub>, and APCK<sub>15</sub>, respectively, adding a coherent structure to the ongoing research. The chemical composition and the samples designation are shown in Table 1.

**Table 1**  
Chemical composition of the glass/mol%.

Oxide	APCK <sub>2.5</sub>	APCK <sub>5</sub>	APCK <sub>7.5</sub>	APCK <sub>10</sub>	APCK <sub>12.5</sub>	APCK <sub>15</sub>
P <sub>2</sub> O <sub>5</sub>	47.5	45	42.5	40	37.5	35
CaO	10	10	10	10	10	10
K <sub>2</sub> O	40	40	40	40	40	40
Al <sub>2</sub> O <sub>3</sub>	2.5	5	7.5	10	12.5	15

## 3. Results and discussion

In an earlier conducted inquiry [9], we extensively studied the structural, thermal, and the chemical characteristics of glasses denoted as APCK<sub>x</sub> (x = 2.5, 5, 7.5, 10, 12.5, 15mol%) with a composition of  $x\text{Al}_2\text{O}_3$ -(50-x) $\text{P}_2\text{O}_5$ -10CaO-40K<sub>2</sub>O. X-ray diffraction (XRD) revealed a consistent amorphous nature across all compositions. Concurrently, density measurements and molar volume calculations demonstrated that increasing alumina content led to higher density, attributed to the substitution of lower-density P<sub>2</sub>O<sub>5</sub> with denser Al<sub>2</sub>O<sub>3</sub>. This substitution resulted in a more compact glass network, as indicated by a decrease in molar volume. Differential scanning calorimetry (DSC) unveiled an enhanced trend in both glass transition temperature ( $T_g$ ) and onset crystallization temperature ( $T_x$ ) values with increasing Al<sub>2</sub>O<sub>3</sub> content, indicating improved glass structure compactness facilitated by Al<sup>3+</sup> incorporation. Fourier transform infrared spectroscopy (FTIR) and Raman analyses provided further insights, highlighting characteristic bands and the formation of P-O-Al bonds, contributing to a more reticulated and rigid glass network.

### 2.2. Optical characterization using UV-Vis spectroscopy

The focus of the research was on studying the optical properties of phosphate glasses. The team used UV-Vis spectroscopy to analyze the absorption and transmission characteristics of the glasses, which provided valuable insights into their optical behavior within the spectrum of interest. It's worth noting that this study is a continuation of a prior comprehensive characterization that involved various techniques, such as X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, scanning electron microscopy with energy-dispersive X-ray spectroscopy (MEB/EDX), density and molar volume measurements, differential scanning calorimetry (DSC), and chemical studies [9].

While the current study focuses on UV-Vis spectroscopy, the choice of this technique was informed by our prior investigations, ensuring a cohesive understanding of the material properties. The integrated approach between the current and previous works contributes to a more holistic characterization of the phosphate glasses.

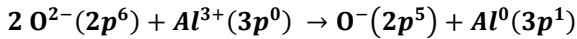
The optical spectra in our investigation were acquired using a JASCO V-670 spectrophotometer and an integrating sphere. This setup allowed us to analyze absorption over a wide spectrum, from 100 nm (ultraviolet) to 1800 nm (Visible and NIR). The sample is a few millimeters thick polished glass.

Scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) confirmed the amorphous nature and uniform elemental distribution within the glass system. In tandem, chemical durability studies underscored the profound impact of increasing Al<sub>2</sub>O<sub>3</sub> content on the glass's resistance to leaching in deionized water, HCl, and NaOH solutions. The dissolution rates exhibited a consistent decrease with higher Al<sub>2</sub>O<sub>3</sub> content, attributed to the substitution of easily hydrolyzable P-O-P bonds by more hydration-resistant P-O-Al bonds. This enhanced chemical stability was further validated by observed variations in pH during immersion, offering a comprehensive understanding of the intricate interplay between composition and properties in the APCK<sub>x</sub> glass system.

Continuing our exploration of the multifaceted properties of APCK<sub>x</sub> glasses, we now focus on the optical study through UV-Vis spectroscopy. Having extensively characterized these glasses earlier. We now turn our attention to understanding the intricate relationship between their composition and the optical behavior.

### 3.1. Absorbance and transmittance spectra

Figure 1 showcases the UV transmittance and absorbance spectra in the wavelength range of 190-800 nm of APCK<sub>x</sub> glasses (x=2.5, 5, 7.5, 10, 12.5, and 15 mol%), revealing a conspicuous absorption band in the vicinity of 250 nm. Notably, this absorption band's intensity demonstrates an upward trend with increasing Al<sub>2</sub>O<sub>3</sub> content, coinciding with a nuanced shift towards longer wavelengths. This unique optical behavior finds its rationale in a potential charge transfer between oxygen and aluminum ions as follows:



This is also indicative of amorphous materials with transition metal impurities [10], underscores the complex optical behavior of these glasses.

Interestingly, the optical spectra of the APCK<sub>x</sub> glass system also disclose a noteworthy absence of detectable signals within the 400-800 nm range. This spectral transparency reinforces their overall colorless appearance and aligns seamlessly with the aesthetic neutrality of the glass system.

### 3.2. Absorption ( $\alpha$ ) and extinction ( $K$ ) coefficients

Using the absorbance values obtained experimentally, we calculated the absorption coefficients  $\alpha$  and extinction  $k$  of the glasses studied employing the following relations:

$$\alpha = \frac{1}{d} \ln\left(\frac{100}{T}\right); A = -\log(T); K = \frac{\alpha\lambda}{4\pi}$$

With  $d$ : the thickness of the sample;  $T$ : transmittance; and  $A$ : absorbance.

In Figure 2, a compelling narrative unfolds as the absorption and extinction coefficients dynamically vary with wavelength across the spectrum of the APCK<sub>x</sub> glass samples under investigation. A notable trend surfaces: both coefficients exhibit a proportional increase with the growing Al<sub>2</sub>O<sub>3</sub> content. Beyond this intriguing correlation, the extinction coefficient discloses a fascinating detail an indication that long-wavelength rays undergo a subtle energy loss when traversing through the glasses. However, this energy loss becomes notably minimized with the escalating concentration of Al<sub>2</sub>O<sub>3</sub>. This phenomenon hints at a nuanced interplay between aluminum content and energy absorption characteristics.

Observing this trend, it becomes evident that the synthesis of our glass system undergoes a transformative shift with increasing aluminum content. The rise in absorption and extinction factors is likely attributed to the heightened influx of Al ions into the glass matrix. These aluminum ions, with energy levels harmonizing with wavelengths in the UV-Vis spectrum, contribute to an augmented absorption phenomenon. This nuanced relationship between aluminum content and energy absorption not only enriches our understanding of the optical properties of APCK<sub>x</sub> glasses but also unveils the intricacies of energy dynamics within the synthesized glass matrix

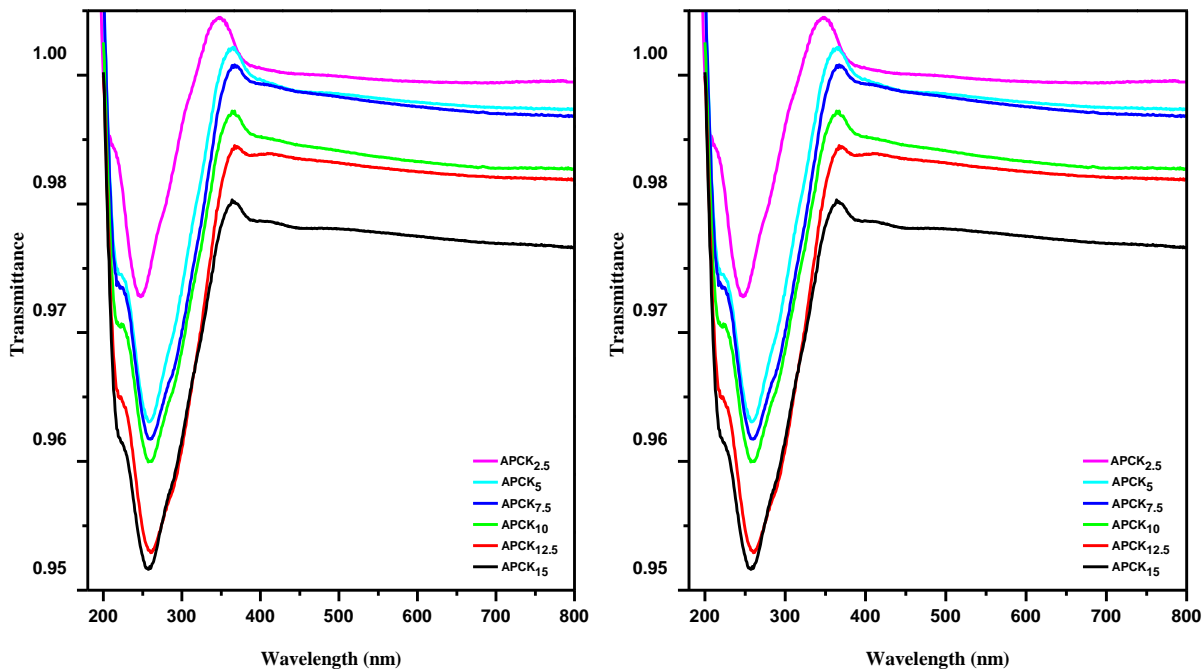


Fig. 1. Absorbance and transmittance spectra of  $x\text{Al}_2\text{O}_3-(50-x)\text{P}_2\text{O}_5-10\text{CaO}-40\text{K}_2\text{O}$  glass system, ( $x=2.5, 5, 7.5, 10, 12.5, 15$  mol%).

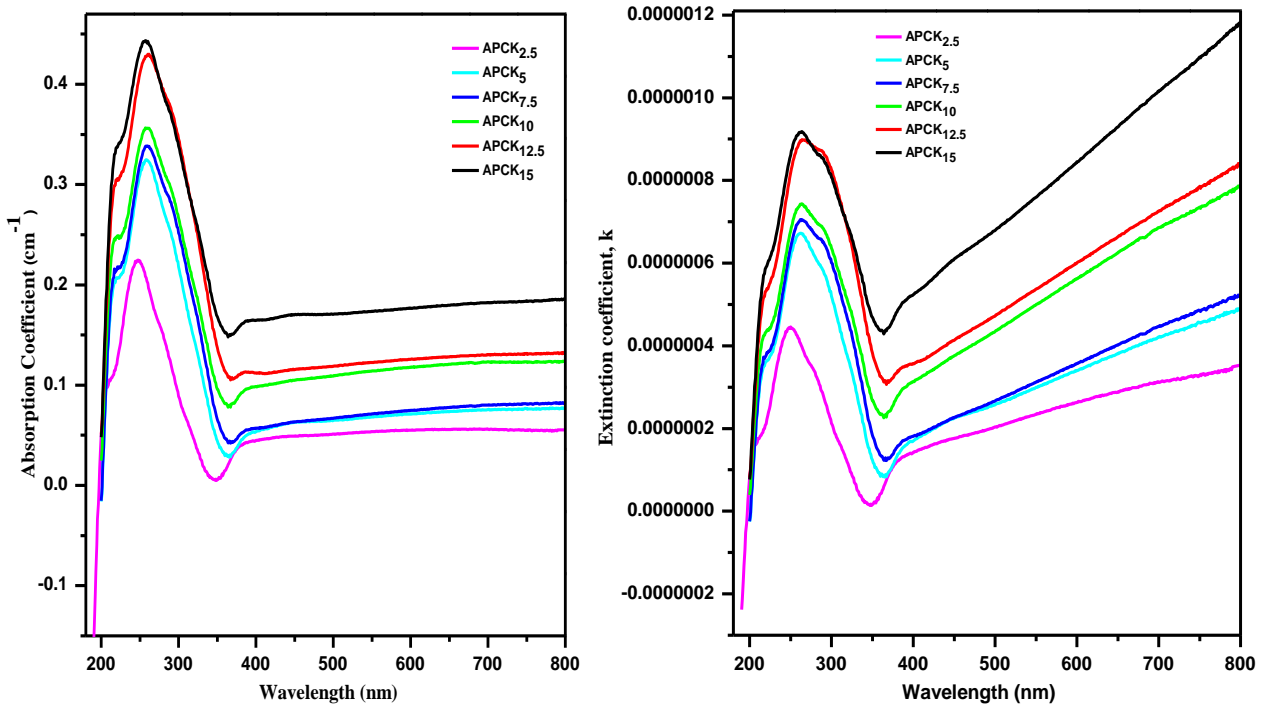


Fig. 2. Variation of the absorption and extinction coefficient as a function of the wavelength for glasses of composition  $x\text{Al}_2\text{O}_3-(50-x)\text{P}_2\text{O}_5-10\text{CaO}-40\text{K}_2\text{O}$  ( $x=2.5,5,7.5,10,12.5,15$  mol%).

### 3.3. Optical gap

Using the law of Tauc [11,12], the absorption coefficient has enabled calculating the optical gap energy of various glassy materials. This law is expressed in several ways depending on whether the electronic transitions are done directly or indirectly.

$$(\alpha h\nu)^{1/2} = A(h\nu - E_g) \quad \text{Indirect gap}$$

$$(\alpha h\nu)^2 = A(h\nu - E_g) \quad \text{Direct gap}$$

Figure 3 provides a detailed insight into the optical characteristics of the studied samples, revealing both indirect and direct optical gap values obtained through extrapolation of the linear portions of the curves  $(\alpha h\nu)^{1/2}$  and  $(\alpha h\nu)^2$  versus  $(h\nu)$  for zero absorption. The ensuing compilation of direct and indirect optical gap values in Table 2 establishes a foundation for understanding the vitreous samples' semiconductor properties.

Upon meticulous analysis of the figures, a discernible pattern emerges the optical gap energy experiences a

consistent decrease with the escalating concentration of aluminum. This intriguing trend signifies a noteworthy enhancement in the semiconductor character of our glasses. Notably, the reduction in band gap energy, transitioning from 3.73 to 3.13 eV (indirect  $E_g$ ) and 3.93 to 3.41 eV (direct  $E_g$ ) with increasing alumina concentration in the phosphate glass system, underscores a substantial shift from an insulator to a semiconductor behavior. This narrowing of the band gap becomes indicative of a profound alteration in the electronic structure, a transformation induced by the incorporation of alumina into the glass matrix. While the materials may not precisely align with conventional semiconductor characteristics, the observed trend towards lower band gap energies strongly suggests a substantial shift towards semiconductor behavior, emphasizing the impactful role of alumina in shaping the electronic properties of the synthesized glasses.

Table 1  
The indirect and direct  $E_g$  values of the APCK<sub>x</sub> studied glasses

Samples	APCK <sub>2.5</sub>	APCK <sub>5</sub>	APCK <sub>7.5</sub>	APCK <sub>10</sub>	APCK <sub>12.5</sub>	APCK <sub>15</sub>
$E_g$ indirect (eV)	3.73	3.44	3.37	3.27	3.20	3.13
$E_g$ direct (eV)	3.93	3.76	3.67	3.62	3.50	3.41

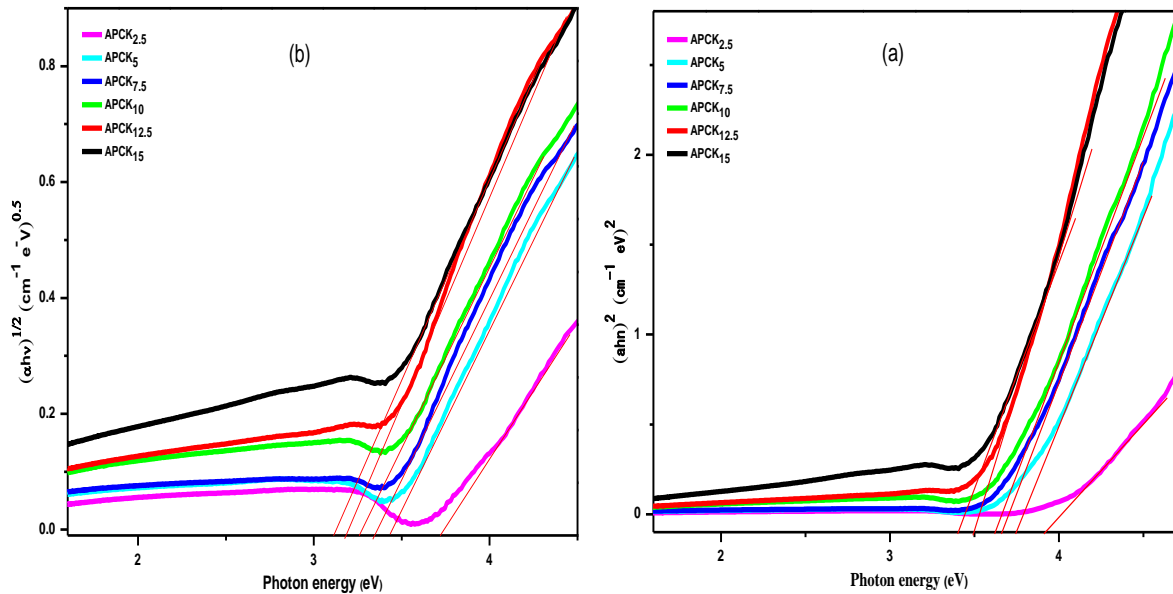


Fig. 3. Determination of the direct optical gap energy (a) and the indirect optical gap energy (b) of APCK<sub>x</sub> glass system.

### 3.4. Versatile applications for APCK<sub>x</sub> glass system

The synthesized  $x\text{Al}_2\text{O}_3-(50-x)\text{P}_2\text{O}_5-10\text{CaO}-40\text{K}_2\text{O}$  glasses, with their finely tuned optical properties, hold promising applications across diverse technological domains. The transparency exhibited in the UV-Vis range, coupled with the controllable absorption bands centered around 250 nm, positions these glasses as excellent candidates for optoelectronic applications [13,14]. The ability to modulate absorption and extinction coefficients, especially for long-wavelength rays, signifies potential use in optical coatings [15], where tailored energy absorption is crucial. The transition from insulator to semiconductor behavior, as indicated by the decreasing optical gap energy with increasing alumina concentration, opens avenues for semiconductor device applications [16,17]. This includes sensors that could benefit from the enhanced electronic structure brought about by alumina addition. Moreover, the complete transparency in the visible range aligns seamlessly with applications in optics [18,19], such as lenses or windows for optical instruments. The chemical durability observed in acidic, basic, and neutral solutions enhances the suitability of these glasses for environments where resistance to leaching is paramount, such as in sensor technologies exposed to various environmental conditions [20,21]. Altogether, the synthesized glasses exhibit versatile optical characteristics, offering a platform for applications in optoelectronics, sensors, optical coatings, and beyond.

## 4. Conclusion

The UV-Vis spectroscopy results for the  $x\text{Al}_2\text{O}_3-(50-x)\text{P}_2\text{O}_5-10\text{CaO}-40\text{K}_2\text{O}$  glasses underscore their tailored optical properties. The observed charge transfer bands and transparency within specific wavelength ranges are consistent with the glass's colorless appearance. The

decrease in optical gap energy with increasing alumina content, indicative of a transition from insulator to semiconductor behavior, aligns with the findings from our previous work. This evolution in electronic structure, coupled with the tunable optical characteristics, enhances the glasses' versatility for applications in optoelectronics and semiconductor devices. The seamless correlation with prior investigations further validates the significance of these tailored glasses in advancing materials for technological applications.

## References

- [1] K. Mohammedsleh Katubi, B. Basha, S.J. Alsufyani, Z. Alrowaili, C. Sriwunkum, M.M. Alnairi, M. Al-Buriah, Radiation attenuation and optical properties of  $\text{P}_2\text{O}_5$ -based glass system, *J. Radiat. Res. Appl. Sci.* 16 (2023) 1687–8507. <https://doi.org/10.1016/j.jrras.2023.100688>.
- [2] O.I. Sallam, M.I.A. Abdel Maksoud, S.M. Kassem, A.S. Awed, N.A. Elalaily, Enhanced linear and nonlinear optical properties of erbium/ytterbium lead phosphate glass by gamma irradiation for optoelectronics applications, *Appl. Phys. A Mater. Sci. Process.* 128 (2022) 1–14. <https://doi.org/10.1007/S00339-022-05965-4/FIGURES/13>.
- [3] M. Kuwik, J. Pisarska, W.A. Pisarski, Influence of Oxide Glass Modifiers on the Structural and Spectroscopic Properties of Phosphate Glasses for Visible and Near-Infrared Photonic Applications, *Mater.* 2020, Vol. 13, Page 4746. 13 (2020) 4746. <https://doi.org/10.3390/MA13214746>.
- [4] C. Basavapoornima, K. Linganna, C.R. Kesavulu, S. Ju, B.H. Kim, W.T. Han, C.K. Jayasankar,

- Spectroscopic and pump power dependent upconversion studies of Er<sup>3+</sup>-doped lead phosphate glasses for photonic applications, *J. Alloys Compd.* 699 (2017) 959–968. <https://doi.org/10.1016/J.JALLCOM.2016.12.199>.
- [5] D. Bayoudhi, C. Bouzidi, E. Matei, M. Secu, A. Catalin Galca, Optical characterization of Sm<sup>3+</sup> doped phosphate glasses for potential orange laser applications, *J. Lumin.* 265 (2024) 120204. <https://doi.org/10.1016/J.JLUMIN.2023.120204>.
- [6] J.L. Clabel H., G. Lozano C., I.C. Pinto, R.F. Falci, V.A.G. Rivera, Y. Messaddeq, E. Marega, Overall Aspects of Glasses for Photonic Devices, (2023) 1–52. [https://doi.org/10.1007/978-3-031-20266-7\\_1](https://doi.org/10.1007/978-3-031-20266-7_1).
- [7] D. Ehrhart, P. Ebeling, U. Natura, UV Transmission and radiation-induced defects in phosphate and fluoride-phosphate glasses, *J. Non. Cryst. Solids.* 263–264 (2000) 240–250. [https://doi.org/10.1016/S0022-3093\(99\)00681-X](https://doi.org/10.1016/S0022-3093(99)00681-X).
- [8] S.H. Mussavi Rizi, N.G. Boetti, D. Pugliese, D. Janner, Phosphate glass-based microstructured optical fibers with hole and core for biomedical applications, *Opt. Mater. (Amst).* 131 (2022) 112644. <https://doi.org/10.1016/J.OPTMAT.2022.112644>.
- [9] Y. Alaoui, M. Laourayed, A. Er-rafi, M. Hammi, M. El Moudane, M. Boudalia, Z. Sekkat, I. Warad, A. Guenbour, A. Bellaouchou, A. Zarrouk, Effect of alumina insertion on structural properties, thermal stability, and chemical durability of potassium calcium based-phosphate glasses, *Inorg. Chem. Commun.* 142 (2022) 109632. <https://doi.org/10.1016/J.INOCHE.2022.109632>.
- [10] F.H. ElBatal, Y.M. Hamdy, S.Y. Marzouk, UV-visible and infrared absorption spectra of transition metals-doped lead phosphate glasses and the effect of gamma irradiation, *J. Non. Cryst. Solids.* 355 (2009) 2439–2447. <https://doi.org/10.1016/J.JNONCRY SOL.2009.08.044>
- [11] A. Dolgonos, T.O. Mason, K.R. Poepelmeier, Direct optical band gap measurement in polycrystalline semiconductors: A critical look at the Tauc method, *J. Solid State Chem.* 240 (2016) 43–48. <https://doi.org/10.1016/J.JSSC.2016.05.010>.
- [12] P. Makuła, M. Pacia, W. Macyk, How To Correctly Determine the Band Gap Energy of Modified Semiconductor Photocatalysts Based on UV-Vis Spectra, *J. Phys. Chem. Lett.* 9 (2018) 68146817. [https://doi.org/10.1021/ACS.JPCLETT.8B02892/SUPPL\\_FILE/JZ8B02892\\_LIVESLIDES.MP4](https://doi.org/10.1021/ACS.JPCLETT.8B02892/SUPPL_FILE/JZ8B02892_LIVESLIDES.MP4).
- [13] H.C. HAFNER, N.J. KREIDL, R.A. WEIDEL, Optical and Physical Properties of Some Calcium Aluminate Glasses, *J. Am. Ceram. Soc.* 41 (1958) 315–323. <https://doi.org/10.1111/J.1151-2916.1958.TB12923.X>.
- [14] G. Jagan Mohini, N. Krishnamacharyulu, G. Sahaya Baskaran, P. Venkateswara Rao, N. Veeraiah, Studies on influence of aluminium ions on the bioactivity of B<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-P<sub>2</sub>O<sub>5</sub>-Na<sub>2</sub>O-CaO glass system by means of spectroscopic studies, *Appl. Surf. Sci.* 287 (2013) 46–53. <https://doi.org/10.1016/J.APSUSC.2013.09.055>.
- [15] B.W. Stuart, M. Gimeno-Fabra, J. Segal, I. Ahmed, D.M. Grant, Degradation and Characterization of Resorbable Phosphate-Based Glass Thin-Film Coatings Applied by Radio-Frequency Magnetron Sputtering, *ACS Appl. Mater. Interfaces.* 7 (2015) 27362–27372. [https://doi.org/10.1021/ACSAMI.5B08957/ASSET/IMAGES/MEDIUM/AM-2015-08957M\\_0011.GIF](https://doi.org/10.1021/ACSAMI.5B08957/ASSET/IMAGES/MEDIUM/AM-2015-08957M_0011.GIF).
- [16] M. Arshad, N.U. Saqib, G. Rooh, N. Chanithima, F. Zaman, M. Asif, H.J. Kim, S. Kothan, S. ul Haq, J. Kaewkhao, Spectroscopic and photoluminescence properties of praseodymium doped potassium aluminum phosphate (P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O-Al<sub>2</sub>O<sub>3</sub>) glasses for optoelectronics applications., *J. Non. Cryst. Solids.* 586 (2022) 121570. <https://doi.org/10.1016/J.JNONCRY SOL.2022.121570>.
- [17] M.S. Al-Assiri, S.A. Salem, M.M. El-Desoky, Effect of iron doping on the characterization and transport properties of calcium phosphate glassy semiconductors, *J. Phys. Chem. Solids.* 67 (2006) 1873–1881. <https://doi.org/10.1016/J.JPCS.2006.04.015>.
- [18] A. Shearer, B. Hauke, M. Montazerian, J.C. Mauro, A critical review of infrared transparent oxide glasses, *Opt. Mater. X.* 20 (2023) 100258. <https://doi.org/10.1016/J.OMX.2023.100258>.
- [19] R. Frerichs, New Optical Glasses with Good Transparency in the Infrared\*, *J. Opt. Soc. Am.* 43 (1953) 1153. <https://doi.org/10.1364/JOSA.43.001153>.
- [20] R. Narro-García, J.J. Leal, E. Rodríguez, Effect of Al<sub>2</sub>O<sub>3</sub> concentration on fluorescence intensity ratio of Er<sup>3+</sup>/Yb<sup>3+</sup> co-doped tellurite glasses for optical temperature sensors under 375 nm and 980 nm excitation, *J. Lumin.* 244 (2022) 118745. <https://doi.org/10.1016/J.JLUMIN.2022.118745>.
- [21] M. Elisa, S.M. Iordache, A.M. Iordache, I.C. Vasiliu, C.E.A. Grigorescu, B.A. Sava, L. Boroica, A. V. Filip, M.C. Dinca, C. Bartha, N. de Acha, C.E. Aguado, Peculiarities of the structural and optical properties of rare-earth-doped phosphate glasses for temperature sensing applications, *J. Non. Cryst. Solids.* 556 (2021) 120569. <https://doi.org/10.1016/J.JNONCRY SOL.2020.120569>.