CHARACTERISTICS OF NEODYMIUM-MODIFIED BORATE CRYSTALS AND GLASSES GROWN VIA POLYCRYSTALLINE SEED MEDIATION

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DEDICATION

This thesis is dedicated to my beloved mothers (Raja Maharom & Sh. Zaiton), fathers (Kamaruddin & Sy. Abd. Azam), wife (Sh. Rabi’atul Adawiyyah), kids (Wan Nur Humairah, Wan Uzair Faaris, Wan Umar Hariz and Wan Uthman Daris) and all my families, who always give support and pray for my success.

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ABSTRACT

A series of glass samples with composition $(90-x)Li_2B_4O_7+10Nb_2O_5+xNd_2O_3$, where x = 1, 5, 10, 15, and 20 mol% were prepared by the melt-quenching technique. For polycrystal seed preparation as well as crystal growth process, 1 mol% of Nd_2O_3 was chosen. Nd_2O_3 was used as a modifier to investigate the impact on the physical, structural, and optical properties of the glasses and crystals. Polycrystal seed as well as platinum wire and lithium niobate single crystal seed were used to grow crystals by Czochralski technique. The growth and growth mechanism of the crystals were studied. The glass samples and crystals were subjected to various characterisation techniques and the physical, structural, and optical properties were determined. XRD pattern confirmed the amorphous nature of the glass system while several peaks corresponded to the phases of $LiNbO_3$, $LiNb_3O_8$, $Li_2B_4O_7$, and $Nd(BO_2)_3$ were recorded for heat-treated glass (polycrystal). The microstructural of the samples (glass → polycrystal) showed that these crystallites grew, further suggesting that the nucleation and growth process were responsible for the development of this kind of microstructure. The optimum growth conditions of pulling rates and rotation speeds were 0.2–1.5 mmh^{-1} and 5–7 rpm, respectively. To stabilise the growth rate and achieve a good growth interface, the temperature gradient was gently optimised. FTIR spectra exhibited four vibration bands around 700, 800–1200, 1200–1600, and 3200–3600 cm^{-1} assigned to the bending of B–O–Nd, B–O stretching of tetrahedral $[BO_4]$ units, stretching relaxation of B–O in $[BO_3]$ units, and stretching of O–H group in both NdLNB crystal and glass system. The UV–Vis spectra showed ten absorption peaks and the transition at $^4G_{5/2}$ (583 nm) was the most prominent. As the concentration of Nd^{3+} ions for glass system increased, both optical band gap and Urbach energies decreased. Additionally, the optical band gap of NdLNB crystal was significantly lower than that of NdLNB glass which were 2.84 and 3.75 eV, respectively. The Judd–Ofelt intensity parameters of all the glass samples followed the trend of $\Omega_6 > \Omega_4 > \Omega_2$ except for 5NdLNB glass, which followed the trend of $\Omega_4 > \Omega_6 > \Omega_2$ which similar to NdLNB crystal. The radiative lifetime of the glass system increased with increasing Nd^{3+} concentration. Meanwhile, radiative lifetime for NdLNB crystal was slightly higher than for NdLNB glass. Luminescence spectra showed two prominent infrared emissions at 903 and 1059 nm which were due to $^4F_{3/2}\rightarrow{}^4I_{9/2}$ and $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transitions, respectively while NdLNB crystal exhibited four emissions at 883, 943, 1064, and 1115 nm with the same transition. SHG tests for both NdLNB crystal and NdLNB glass recorded an emission peak at 532 and 529.5 nm, respectively. The achieved results promise the use of these optimised glasses and crystals in frequency conversion, nonlinear optical application, and laser production. The new approach of using the polycrystal seed to grow a crystal with modified properties from its own glass-forming melt was also successful.

ABSTRAK

Satu siri sampel kaca dengan komposisi (90-x) $Li_2B_4O_7$ + $10Nb_2O_5$ + xNd_2O_3, dengan x = 1, 5, 10, 15 dan 20 mol% telah disediakan menggunakan kaedah pelindapan leburan. Bagi penyediaan benih polihablur dan juga proses pertumbuhan hablur, 1 mol% Nd_2O_3 telah dipilih. Nd_2O_3 telah digunakan sebagai pengubah untuk mengkaji kesan terhadap sifat fizikal, struktur dan optik kaca dan hablur. Benih polihablur serta wayar platinum dan hablur tunggal litium niobate digunakan untuk menumbuhkan hablur dengan kaedah Czochralski. Mekanisma pertumbuhan hablur telah dikaji. Hablur dan kaca NdLNB telah melalui pelbagai kaedah pencirian dan sifat fizikal, struktur dan optik telah diperolehi. Corak XRD telah mengesahkan sifat amorfus sistem kaca manakala beberapa puncak yang merujuk kepada fasa $LiNbO_3$, $LiNb_3O_8$, $Li_2B_4O_7$ dan $Nd(BO_2)_3$ telah direkodkan untuk kaca terawat haba (polihablur). Struktur mikro sampel (kaca → kaca terawat haba) menunjukkan habluran telah membesar, yang mana proses nukleasi dan pertumbuhan berperanan dalam pengembangan struktur mikro ini. Tetapan pertumbuhan optimum bagi kadar tarikan ialah 0.2–1.5 mmj^{-1} dan kelajuan putaran ialah 5–7 rpm. Bagi menstabilkan kadar pertumbuhan dan mendapatkan sempadan permukaan yang baik, kecerunan suhu perlu dikawal dengan baik. Spektrum FTIR telah mempamerkan tiga jalur getaran di sekitar 700, 800–1200, 1200–1600, and 3200–3600 cm^{-1} yang merujuk kepada lenturan ikatan B–O–Nd, regangan ikatan B–O unit tetrahedron $[BO_4]$ dan kelonggaran regangan ikatan B–O unit $[BO_3]$ untuk kedua-dua NdLNB hablur dan sistem kaca. Spektrum UV-Vis-NIR telah menunjukkan sepuluh puncak penyerapan dan transisi pada $^4G_{5/2}$ (583 nm) adalah yang paling ketara. Apabila kepekatan ion Nd^{3+} untuk sistem kaca meningkat, kedua-dua jurang tenaga optik dan tenaga Urbach menurun. Selain itu, didapati jurang tenaga optik hablur NdLNB jauh lebih rendah daripada kaca NdLNB yang masing-masing ialah 2.84 dan 3.75 eV. Telah diperhatikan bahawa parameter keamatan Judd–Ofelt bagi semua sampel kaca mengikuti trend $\Omega_6 > \Omega_4 > \Omega_2$ kecuali kaca bagi 5NdLNB yang mengikuti trend $\Omega_4 > \Omega_6 > \Omega_2$ sama seperti hablur NdLNB. Jangka hayat pendarcahaya untuk sistem kaca meningkat apabila kepekatan ion Nd^{3+} meningkat. Manakala, jangka hayat pendarcahaya untuk hablur NdLNB adalah sedikit tinggi berbanding kaca NdLNB. Spektrum fotopendarcahaya menunjukkan dua pancaran inframerah yang ketara pada 903 dan 1059 nm yang disebabkan oleh transisi $^4F_{3/2} \rightarrow {}^4I_{9/2}$ dan $^4F_{3/2} \rightarrow {}^4I_{11/2}$, manakala hablur NdLNB menunjukkan empat pancaran pada 883, 943, 1064, dan 1115 nm dengan transisi yang sama. Ujian SHG bagi kedua-dua hablur dan kaca NdLNB telah mencatatkan puncak pancaran masing-masing pada 532 dan 529.5 nm, yang mana ianya sesuai digunakan untuk penggandaan frekuensi, aplikasi optik tidak linear dan penghasilan laser. Pendekatan baru untuk menggunakan benih polihablur bagi menumbuhkan hablur dari pembentukan leburan kacanya sendiri telah berjaya.

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LIST OF ABBREVIATIONS

ADC-CGS - Automatic diameter control - crystal growth system
BBO - Beta-barium borate
BF - Bright field
BO - Bridging oxygen
BSE - Back-scattered electrons
CB - Conduction band
CBO - Cesium triborate
CLBO - Cesium lithium borate
CR - Cross relaxation
DF - Dark field
DP - Diffraction pattern
DTA - Differential thermal analysis
EDX - Energy dispersive X-ray
FTIR - Fourier transform infrared
FWHM - Full width half maximum
HT - Heat treatment
IR - Infrared
JCPDS - Joint Committee on Powder Diffraction Standards
J-O - Judd-Ofelt
KAB - Potassium aluminum borate
KDP - X-Ray diffraction
KTP - Potassium titanyl phosphate
LBO - Lithium triborate
LCOB - Lithium calcium oxoborate
LFB - Lithium Fluoro Borate
Li - Lithium
LTB - Lithium tetraborate
Nb - Niobium
NBO - Non-bridging oxygen
Nd - Neodymium

NdLNB - Neodymium lithium niobium borate
NLO - Nonlinear optical
NR - Non-radiative
O - Oxygen
PL - Photoluminescence
PR - Pulling rate
R - Radiative
RE - Rare earth
RECOB - Rare earth calcium oxyborate
RS - Rotation speed
SADP - Selected area diffraction pattern
SAED - Selected area electron diffraction
SAW - Surface acoustic waves
SE - Secondary electrons
SEM - Scanning electron microscopy
SFD - Self-frequency doubling
SHG - Second harmonic generation
TEM - Transmission electron microscopy
TM - Transition metal
TSSG - Top seeded solution growth
UV-Vis -IR - Ultraviolet visible infrared
VB - Valence band
XRD - X-Ray diffraction
YAB - Yttrium aluminum borate
YAG - Yttrium aluminium garnet
YCOB - Yttrium calcium oxoborate

LIST OF SYMBOLS

A - Absorbance
A_{ed} - Electric-dipole
A_{md} - Magnetic-dipole
α - Absorption coefficient
B - Constant
β - Nephelauxetic ratio
$\bar{\beta}$ - Average nephelauxetic ratio
c - Speed of light
d - Thickness of the sample
D - Diameter
E_u - Urbach energy
E_f - Energy of electron of final state
E_i - Energy of an electron at lower band
E_g^D - Direct optical energy band gap
E_g^I Indirect optical energy band gap
$\varepsilon(v)$ - Molar extinction coefficient
e - Electron charge
F - Force constant
f_{exp} - Experimental oscillator strength
f_{cal} - Oscillator strength
ΔG - Gain bandwidth
hv - Photon energy
H_R - Hruby parameter
λ - Wavelength
$\Delta\lambda_{eff}$ - Effective gain bandwidth emission
Ω_λ - Judd-Ofelt parameters
m - Electron mass
m_r - Atomic weights in kg of cation
m_o - Atomic weights in kg of anion
μ - Reduced mass

n - Refractive index
N_A - Avogadro number
OPD - Oxygen packing density
θ - Angle
ρ - Density
ρ_L - Density of distilled water
P - Pulling rate
ρ_s - Crystal density
ρ_l - Melt density
Q - Quality factor
rms - Root-mean-square
R - Crucible radius
σ_P^E - Stimulated emission cross-section
S_{ed} - Line-strength for electric
δ - Bonding parameter
t - Crystallite size
T_c - Glass crystallization temperature
T_g - Glass transition temperature
T_m - Glass melting temperature
Γ_M - Decay rate
Γ_{NR} - Non-radiative decay
Γ_R - Intrinsic radiative decay rate
τ_{rad} - Radiative lifetime
ΔT - Glass thermal stability
U_κ - Values of reduced matrix elements
v - Wavenumber
v_g - Wavenumber of particular transition to an ion
v_a - Wavenumber of same transition for aquo ion
V_m - Molar volume
W_1 - Weight of sample in air
W_2 - Weight in distilled water
x_i - Mole fraction

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Solid state materials can be classified as crystals, polycrystals (ceramics), or amorphous depending on their arrangement of constituent molecules, atoms, or ions. Several materials can form a crystal with the same composition but in different arrangements of the atoms which create different three-dimensional structures (Myerson, 2002). Non-crystalline solid, often referred to as amorphous solid, is the opposite extreme of a crystal. This type of solids has neither reticular nor granular structure. Amorphous solids possess short-range order but are devoid of any organised structure over longer distances; in this respect they resemble liquids. However, their rigidity and cohesiveness allow them to retain a definite shape, so for most practical purposes, they can be considered solids. In fact, the only obvious distinction between amorphous materials, such as glass, and liquids is the high viscosity (resistance to flow) of the amorphous solids.

The glass composition is extremely important in the formation of glass. Generally, glass is composed of different oxides that serve various functions, particularly in research and industry. The presence of strongly bonded large networks of atoms in the liquid is a basic condition for glass formation. A superior glass must have many bonds or linkages of the types with high bond strengths like B–O–B, Si–O, Ge–O, and P–O as glass formers. Some oxides, such as borate (B_2O_3), silicate (SiO_2), germinate (GeO_2), and phosphate (P_2O_5) are defined as glass formers because they are capable to form glassy network by themselves under normal quenching conditions but act as glass formers when mixed with others, such as ZnO, PbO, MgO, CaO, and BaO (Gautam et al., 2012).

A material can be transformed into a crystal by slow and gradual transformation from solid, liquid/solution, or vapour phase. Several techniques adopting one of these three basic methods can be employed for growing from small to big crystals (Brice, 1986). Selection of appropriate techniques of crystal growth is highly dependent on the chemical and physical properties of the material to be grown and the suitability of the technique to grow the required crystal (Seevakan and Bharanidharan, 2018). This is because each technique to be used has certain parameters to be considered for the success of crystal growth such as growth kinetics, chemical reactivity, temperature gradient, solubility, shape, purity, decomposition, melting point, and the cost involved (Brian, 1980).

Presently, borate glass and crystal are receiving much more attention due to their applications in technologies such as solid-state lasers, nonlinear optics, and solar energy (Alajerami et al., 2012). Borate is one of the popular glass formers because it can easily combine with a variety of oxides to form a binary glass system (Kaur et al., 2014). Borate network building units can be either triangles (BO_3) with non-bridging atoms or tetrahedral (BO_4) with all bridging oxygen atoms, making it an interesting system. In comparison with other conventional glasses, borate glass is most recently analysed due to the superior optical and mechanical properties, chemical durability, stability against atmospheric moisture, good solubility of rare earth ions, low melting temperature, and good corrosion resistance (Wu et al., 2011). Moreover, borate glasses and crystals are suitable hosts for various transition metals and rare earth ions, making them suitable for optical materials.

Several attempts have been made to improve the values of borate glass and crystal. It is possible to change the coordination geometry of boron from BO_3 to BO_4 by adding alkali oxides (Balachander et al., 2013). As a modifier, lithium which is more electropositive, will cause essential changes in the binary lithium borate system, such as enhancing the bonding strength by forming ionic bonds with oxygen (non-bridging oxygen) and decreasing the hygroscopic nature of borate (Bhogi et al., 2015). Lithium borate is one of the most useful nonlinear optical materials for ultraviolet and visible laser applications. Laser systems with lithium borate as a key component in their design are widely utilised in applications like ophthalmology, materials processing, marking, optical data storage, and semiconductor manufacturing. Several transition metals including Nb, V, Ti, and Cr are employed as second modifiers to change the glass structure, create non-bridging oxygen (NBO), enhance bond strength, and reduce glass stickiness (Bhagat, 2003). The chemical and physical properties of the glasses are altered when NBO is created. However, the modifications continue to rely on their connectivity to change these properties.

Rare earth (RE)-doped glasses and crystal materials have been extensively studied for fabricating lasers, semiconductors, and amplifiers (Kumar et al., 2013a). RE ions are used to investigate local structural changes in the materials due to their unique spectroscopic properties upon the optical transitions in the intra 4f-shell (Semwal and Bhatt, 2013). Since the demonstration of laser activity in neodymium single crystals made by Krupke (1971), Nd^{3+} has been widely used as a laser-active ion in amorphous and crystalline states (Kumar et al., 2013a). The two host materials most commonly used for this laser ion are yttrium aluminium garnet (YAG) and glass. When doped in YAG, the Nd:YAG crystal produces laser output primarily at 1.064 µm. However, when doped in glass, the Nd:glass medium lases at wavelengths ranging from 1.054 to 1.056 µm, depending upon the type of glass used. In glass, Nd can be doped to extremely high concentration, but it is limited to a maximum concentration of 1.0%–1.5% in YAG crystals (Kuhn, 1998). Furthermore, owing to the commercial importance of Nd^{3+} doped glasses and crystal lasers, many studies on the optical properties and structural role of Nd^{3+} ion and its interaction with other ions have been carried out (Anjaiah et al., 2015; Mhareb et al., 2014; Pal et al., 2013; Vijaya and Suresh, 2012).

Looking at the great prospect of lithium niobium borate containing neodymium in the field of material science, the physical, structural, and optical properties of these materials need to be further investigated.

1.2 Problem Statement

Several studies have been reported regarding the preparation of lithium borate glasses (Prasad and Varma, 2005a; Graca et al., 2008; Kashif et al., 2012; Khalek et al., 2012; Kashif et al., 2013; Farouk et al., 2015). The physical, structural, optical, and electrical properties of the glass systems show a great potential host for nonlinear optical (NLO) and lasing materials. Looking at the great prospect of rare earth doped lithium borate crystal for NLO and laser applications, it is necessary to develop an accurate method for their growth.

Based on the previous studies, Mhareb et al. (2014) has reported the influence of Nd on lithium-magnesium-borate glasses, Kashif et al. (2013) has studied the effect of V, Mn, Co, and Cu on lithium-niobium-borate glasses, and Wu et al. (2011) has reported the influence of Nd on lithium-borate glasses. Those studies only reported the preparation of the glasses using the melt-quench technique, and not much effort has been given to grow a polycrystal seed from melt-quench. Usually, the crystal seeds are made from the Czochralski technique, which is the common practise of crystal growth. (Kashchiev, 2000). However, neodymium-doped lithium-niobium-borate via seeding technique has not been performed yet. Besides that, most of the reported work is limited to the presence of $LiNbO_3$ nanocrystals by a controlled heat treatment process but emphasis has not been laid down on the formation of crystals by using a seeding technique. Thus, it had become desirable to undertake systematic studies to fully explore the impact of seeding on the modified properties. Moreover, a well-controlled crystal growth process with appropriate growth parameters involving temperature gradient, growth rate, pulling rate, and rotating speed must be achieved in order to produce a good crystal. The physical, thermal, structural, optical, and SHG properties of the crystals and glasses will also be reported.

1.3 Research Objectives

In order to solve the problem as stated in Section 1.2, several objectives have been outlined as follows:

(a) To grow neodymium modified lithium-niobium-borate polycrystal seed via melt-quench assisted glass route and thermal annealing.

(b) To determine the crystallisation behaviour and microstructural features of the neodymium-lithium-niobium-borate glass and polycrystal.

(c) To optimise the growth mechanism of neodymium-lithium-niobium-borate crystals by employing polycrystal, platinum and lithium niobate crystal seeds.

(d) To determine the improvement in physical, thermal, structural, optical and SHG properties of the crystals and glasses.

1.4 Scope of the Study

In this study, the composition of $(90\text{-}x)Li_2B_4O_7+10Nb_2O_5+xNd_2O_3$ glass system, where x = 1, 5, 10, 15, and 20 were prepared by conventional melt-quenching technique. The borate glass is chosen as a host due to the high stability and high forming ability of glass. For the preparation of polycrystal seed and crystal growth, the primary focus was only on 1 mol% of Nd_2O_3. Neodymium oxide was used as a modifier in order to investigate the impact on the physical, structural and optical properties of the glasses and crystals. Consequently, the heat treatment procedures were executed to crystallise the nucleated glass to produce NdLNB polycrystal seed. X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) were then used to ascertain the crystallisation behaviour and microstructural features of the glass and polycrystal before it will be applied for the next crystal growth process. NdLNB crystals were grown by various types of seed such as polycrystal seed that was prepared in the previous stage, platinum wire and lithium niobate single crystal seed with Automatic Diameter Control - Crystal Growth System (ADC-CGS). The growth and growth mechanism were described, along with the challenges likely to be encountered during growth of the crystal. NdLNB crystals and glasses were subjected to various characterisation techniques and their properties were determined. The densities were measured by Archimedes method. X-ray diffraction (XRD), Differential thermal analyser (DTA), Fourier transformed infrared (FTIR), Ultraviolet-Visible (UV-Vis), Photoluminescence (PL) spectroscopy, Scanning Electron

Microscopy (SEM) and Transmission Electron Microscopy (TEM) characterisations were made to examine the physical, thermal, structural and optical properties. Measurements of the SHG of the crystal and glass samples were performed using the SHG powder technique test set up based on a method of Kurtz and Perry (1968).

1.5 Significance of the Study

This research will give a novelty to the crystal growth process by using a polycrystal seed from an amorphous material and thus inventing a new NLO and lasing material as well. This invention also has the potential to be applied in growing other brand-new glass forming melt crystal such as phosphate, tellurite and silicate which are used for efficient harmonic generation, frequency conversion, laser production, and in other important applications related to nonlinear optics and its associated technologies. Besides, it can nurture knowledge and create new specialists in this area. Moreover, this crystal growth technology is progressively in advance in almost all developed countries. But, unfortunately not much effort has been made in Malaysia to exploit this technology specifically in Czochralski crystal growth technique. Considering its significance, this study has been initiated.

1.6 Thesis Organisation

In this thesis, there are five chapters. Chapter 1 presents the background, problem statement, objectives, and significance of the study. A literature review is presented in Chapter 2. It provides the basis of general information about borate glasses, crystallisation of borate glasses and borate crystals. In addition, a brief description of the crystal growth is highlighted. Nevertheless, the reviews of measurement methods and analysis of each characterisation instrument are also reported. Chapter 3 describes the experimental and measurement techniques, which include sample preparation of glass by the melt-quenching technique, polycrystal by the heat-treatment process, and crystal by the Czochralski technique, and the apparatus used for characterisation and analysis such as DTA, XRD, FTIR, UV-VIS, PL, SEM-

EDX, TEM, and SHG tests. Chapter 4 consists of the experimental results and discussions. This chapter is divided into four sub-sections: the first part describes the synthesis and characterisation of the glass system, the second part explains the characterisation of polycrystal seeds, the third part describes the growth and growth mechanism of the crystals, and the last part presents the comparison of crystal and glass properties. Finally, Chapter 5 summarises the main findings achieved through this research, and suggests several recommendations for future studies. Additional information associated with the thesis is given in the Appendices.

REFERENCES

Aka, G. and Brenier, A. (2003) Self-frequency conversion in nonlinear laser crystals, Opt. Mater., 22, pp. 89-94.

Alajerami, Y. S. M., Hashim, S., Hassan, W. M. S. W. and Ramli, A. T. (2012) The effect of titanium oxide on the optical properties of lithium potassium borate glass, *J. Mol. Struct.*, 1026, pp. 159-167.

Ameruddin, A. (2015) *Growth and Characterisation of gold-seeded indium gallium arsenide nanowires for optoelectronic applications*. PhD Thesis, Universiti Teknologi Malaysia.

Anjaiah, J. and Laxmikanth, C. (2015) Optical properties of neodymium ion doped lithium borate glasses, *J. Pure Appl. Industr. Phys.*, Vol. 5(6), pp. 173-183.

Azlan, M. N. and Halimah, M. K. (2018) Role of Nd^{3+} nanoparticles on enhanced optical efficiency in borotellurite glass for optical fiber, *Results Phys.*, 11, pp. 58-64.

Balachander, L., Ramadevudu, G., Shareefuddin, M., Sayanna, R. and Venudharc, Y. C. (2013) IR analysis of borate glasses containing three alkali oxides, *Sci.Asia*, 9(3), p. 278.

Balakrishna, A., Rajesh, D. and Ratnakaram, Y. C. (2012) Structural and photo–luminescence properties of Dy^{3+} doped different modifier oxide–based lithium borate glasses, *J. Lumin.*, 132(11), pp. 2984–2991.

Balakrishna, A., Rajesh, D. and Ratnakaram, Y. C. (2013) Structural and optical properties of Nd^{3+} ions doped lithium fluoro borate glass with relevant modifier oxides, *Opt. Mater.*, 35, pp. 2670-2676.

Banerjee, S. and Tyagi, A. K. (2012) *Functional materials: preparation, processing and applications*, USA: Elsevier.

Basu, B., Enger, S., Breuer, M. and Durst, F. (2001) Effect of crystal rotation on the three-dimensional mixed convection in the oxide melt for Czochralski growth *J. Cryst. Growth*, 230, pp. 148–154.

Bergfors, T. (2003) Seeds to crystals, *J. Struct. Biol.*, 142, pp. 66–76.

Bhatia, B., Parihar, V., Singh, S., and Verma, A. S. (2013) Spectroscopic properties of Pr^{3+} in lithium bismuth borate glasses, *Am. J. Condens. Matter Phys*, 3(3), pp. 80-88

Bhagat, L. S. (2003) Structure of lithium borate-transition metal oxide system. *Int. J. Chem. Sci.*, 1(2), p. 137.

Bhogi, A., Kumar, R. V., and Kistaiah, P. (2015) Effect of alkaline earths on spectroscopic and structural properties of Cu^{2+} ions-doped lithium borate glasses, *J. Non Cryst. Solids*, 426, pp. 47–54.

Bokobza, L. (1998) Near infrared spectroscopy. *J. Near Infrared Spectrosc.*, 6(1), pp. 3–17.

Bragg, W. L. (1913) The Reflexion of X-rays by Crystals. *Proc. R. Soc. Lond. A*. 88 (605), pp. 428–38.

Brandle, C. D. (1980) '*Crystal pulling*' in Pamplin, B. R. Crystal Growth. England: Pergamon Press Ltd. Headington Hill Hall,

Brandle, C. D. (2004) Czochralski growth of oxides. *J. Cryst. Growth*. 264, pp. 593-604.

Brian, R. P. (1980). *Crystal growth.* 2nd ed. England: Pergamon Press.

Brice, J. C. (1986) *Crystal growth process*. New York: Wiley.

Cao, G. (2003) *Nanostructures & nanomaterials: synthesis, properties & applications*. London: Imperial College Press.

Carnall, W. T., Fields, P. R. and Rajnak K. (1968) Electronic energy levels in trivalent lanthanide aquo ions. I: Pr^{3+}, Nd^{3+}, Pm^{3+}, Sm^{3+}, Dy^{3+}, Ho^{3+}, Er^{3+} and Tm^{3+}, *The J. Chem. Phys.*, 49(10), pp. 4424-4442.

Chakradhar, R. P. S., Sivaramaiah, G., Rao, J. L. and Gopal, N. O. (2005) EPR and optical investigations of manganese ions in alkali lead tetraborate glasses. *Spectrochim. Acta – Part A Mol. Biomol. Spectrosc.*, 62(4–5), p. 761.

Chen, C., Lin, Z. and Wang, Z. (2005) The development of new borate-based UV nonlinear optical crystals. *Appl. Phys*. B, 80, pp. 1–25.

Chen, D., Yu, Y., Lin, H., Huang, P., Shan, Z. and Wang, Y. (2010) Ultraviolet-blue to near-infrared down conversion of Nd^{3+}–Yb^{3+} couple, *Optics Lett.*, 35(2), pp. 220-222.

Cho, H. J., Lee, B. Y., and Lee, J. Y. (2006) The effects of several growth parameters on the formation behavior of point defects in Czochralski-grown silicon crystals, *J. Cryst. Growth*, 292, pp. 260–265.

Choi, J. H., Alfred, M., Ashot M. and Shi, F. G. (2005) Judd–Ofelt analysis of spectroscopic properties of Nd^{3+}-doped novel fluorophosphate glass, *J. Lumin.*, 114(3-4), pp. 167-177.

Choudhury, B., Dey, M. and Choudury, A. (2013) Defect generation, d-d transition, and band gap reduction in Cu-doped TiO_2 nanoparticles, *Inter. Nano Lett*, 3, p. 25.

Devi, A. R. and Jayasankar, C.K. (1995) Optical properties of Nd^{3+} ions in lithium borate glasses, *Mater. Chem. Phys,*, 42, pp. 106-119.

Dhanaraj, G., Byrappa, K., Prasad, V. and Dudley, M. (2010) '*Crystal growth techniques and characterization: An Overview*' in Dhanaraj, G., Byrappa, K., Prasad, V., Dudley, M. (eds) Springer Handbook of Crystal Growth. Berlin, Heidelberg: Springer.

Dimitrov, V. and Sakka, S. (1996). Electronic oxide polarizability and optical basicity of simple oxide, *J. Appl. Phys*., 79, pp. 1736-1740.

Eakins, D. E., Held, M., Norton, M. G. and Bahr, D. F. (2004) A study of fracture and defects in single crystal YAG, *J. Cryst. Growth*, 267(3-4), pp. 502-509.

El-Deen, L. M. S., Al Salhi, M. S. and Elkholy, M. M. (2008) IR and UV spectral studies for rare earths-doped tellurite glasses. *J. Alloys Compd.*, 465, pp. 333-339.

El–Mallawany (2002) *Tellurite glasses handbook: physical properties and data*. Florida, USA: CRC Press.

Evgeny, V. Z. (2012) Problems and recent advances in melt crystal growth technology. *J. Cryst. Growth*, 360, pp. 146-154.

Fan, S. J, Shen, G. S., Wang W., Li, J. L. and Le, X. H. (1990) Bridgman growth of $Li_2B_4O_7$ crystals, *J. Cryst. Growth*, 99(1–4), pp. 811-814.

Fares H., Jlassi I., Hraiech S., Elhouichet H. and Ferid M. (2014) Radiative parameters of Nd^{3+} doped titanium and tungsten modified tellurite glasses for 1.06 μm laser materials, *J. Quant. Spectrosc. Radiat. Transf.*, 147, pp. 224-232.

Farouk, M., El-Maboud, A. A., Ibrahim, M., Ratep, A. and Kashif, I. (2015) Optical properties of lead bismuth borate glasses doped with neodymium oxide, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, 149, pp. 338–342.

Fawad, U, Rooh, G., Kim, H. J., Park, H., Kim, S., and Khan, S. (2015) Scintillation properties of $Li_6Y_{0.5}Gd_{0.5}(BO_3)_3$: Ce^{3+} single crystal, *J. Cryst. Growth*, 410, pp. 18–22.

Florez, A., Martinez, J. F., Florez, M. and Porcher, P. (2001) Optical transition probabilities and compositional dependence of judd-ofelt parameters of Nd^{3+} ions in fluoroindate glasses, *J. Non Cryst. Solids*, 284, pp. 261-267.

Frank, J. B. (2004) *Automatic diameter control software instruction manual – ver. 3.0.8*. USA: Thermal Technology Ltd.,

Franziska, S., Rimbach, A. C., Loos, S., Ahrens, B. and Schweizer, S. (2016) Effect of induced crystallization in rare-earth doped lithium borate glass, *Radiat. Meas.*, 90, pp. 274-278.

Furetta, C., Prokic, M., Salamon, R., Prokic, V., and Kitis, G. (2001) Dosimetric characteristics of tissue equivalent thermoluminescent solid TL detectors based on lithium borate, *Nucl. Instrum. Methods Phys. Res. A*, 456, pp. 411-417.

Gautam, C., Yadav, A. K. and Arbind K. S. (2012) A review on infrared spectroscopy of borate glasses with effects of different additives, *Inter. Sch. Res. Network Ceramics*, p. 17.

Gedam, R. S. and Ramteke, D. D. (2012) Electrical and optical properties of lithium borate glasses doped with Nd_2O_3, *J. Rare Earths*, 30(8), p. 785

Ghoshal, S. K., Zake, N. S. M., Arifin, R., Sahar, M. R., Rohani, M. S. and Hamzah, K. (2015) Optical properties of oxy-chloride tellurite glass: role of samarium ions, *Adv. Mater. Res.*, 1107, pp. 437-442.

Giri, M. A., Yawale, S. P. and Yawale, S. S. (2016) Spectral behaviour of infrared spectra of silver doped lead borate glasses, *Int. J. Eng. Sci. Technol.*, 3(3), pp. 95-98.

Gowda V. C.V. (2013) Effect of Bi^{3+} Ions on physical, thermal, spectroscopic and optical properties of Nd^{3+} doped sodium diborate glasses, *Physica B*, 426, pp. 58-64.

Graca, M. P. F., Ferreira, M. G. D. S. and Valente, M. A. (2008) Influence of thermal and thermoelectric treatments on structure and electric properties of B_2O_3-Li_2O-Nb_2O_5 glasses, *J. Non Cryst. Solids*, 354, pp. 901-908.

Grate, F. (2014) The use of EDS analysis in a materials testing laboratory, *J. Am. Chem. Soc.*, 87(1), pp. 8-10.

Grinyov, B. V., Dubovik, M. F. and Tolmachev, A. V. (2000) Borate single crystals for polyfunctional applications: production and properties, *Semicond. Phys. Quantum Electron. Optoelectron.*, 3(3), pp. 410-419.

Hasim, N. (2017) *Effects of embedded silver nanoparticles on physical and optical properties of erbium and neodymium codoped lithium niobate tellurite glass*. PhD thesis, Universiti Teknologi Malaysia.

Holand, W. and Beall, G. H. (2012) *Glass-ceramic technology*. Hoboken, NJ: Wiley.

Huang, X., Taishi, T., Wang, T. and Hoshikawa, K. (2001) Measurement of temperature gradient in Czochralski silicon crystal growth, *J. Cryst. Growth*, 229, pp. 6–10.

Hunda, B. M., Holovey, V. M., Turok, I. I., Solomon, A. M., Puga, P. P. and Puga, G. D. (2005) Effect of melt composition on the luminescent properties of czochralski-grown $Li_2B_4O_7$ single crystals, *Inorg. Mater*., 41(9), pp. 990–994.

Huot, N., Jonin, C., Sanner, N., Baubeau, E., Audouard, E. and Laporte, P. (2002) High UV average power at 15 kHz by frequency doubling of a copper hybrid vapor laser in β-barium borate, *J. Opt. Commun*., 211, pp. 277-282.

Igor, N. O., Nikita, E. P., and Vladimir, A. P. (2010) Radiation effects and defects in lithium borate crystals, *IOP Conf. Series: Mater. Sci. Eng.*, 15, p. 12016.

Ishii, M., Kuwano, Y., Asai, T., Senguttuvan, N., Hayashi, T., Kobayashi, M., Oku, T., Sakai, K., Adachi, T., Shimizu, H. M., and Suzuki, J. (2003) Growth of Cu-doped $Li_2B_4O_7$ single crystals by vertical Bridgman method and their characterization, *J. Cryst. Growth*, 257, pp. 169–176.

Itoh, K., Marumo, F., and Kuwano, Y. (1990) β-Barium borate single crystal grown by a direct czochralski method, *J. Cryst. Growth*,106, pp. 728—731.

Jain, H. (2004) Transparent ferroelectric glass-ceramics, *Ferroelectrics*, 306, p. 111.

James, R. C., Penney, W. R., James R. F. and Stanley M. W. (2005) 'Crystallization from solutions and melts' in Chemical process equipment: selection and design, (2nd Ed.). USA: Gulf Professional Publishing.

Jaque, D., Capmany, J. and Qarcia, S. (1999) Red, green, and blue laser light from a single Nd:$Yal_3(BO_3)_4$ crystal based on laser oscillation at 1.3 µm, *Appl. Phys. Lett.*, 75, pp. 325–327.

Jaschin, P. W. and Varma, K. B. R. (2016) Structural evolution and second harmonic properties of lithium niobate–tantalate nanocrystals embedded in a borate glass, *J. Non Cryst. Solids*, 434, pp. 41–52.

Jen, J. S. and Kalinowski, M.R. (1980) An ESCA study of the bridging to non-bridging oxygen ratio in sodium silicate glass and the correlations to glass density and refractive index, *J. Non Cryst. Solids*, 38, pp. 21-26.

Ji, Y., Xiao, Y. B., Wang, W. C., Huang, S. J., Liu, J. L. and Zhang, Q. Y. (2019) Optical properties of Nd^{3+}-doped fluoro-sulfo-phosphate glasses, *J. Non Cryst. Solids,* 512, pp. 155–160.

Jia, L. S., Yan, X. L., Zhou, J. F. and Chen, X. L. (2003) Effect of pulling rates on quality of $La_{2-x}Ba_xCuO_4$ single crystal, *Physica C,* 385, pp. 483–487.

Jorgensen, C. K. (1971) *Modern aspect of ligand field theory*. North-Holland, Armsterdam.

Jundt, D. H. and Foulon, G. (2001) 'Boules of $LiNbO_3$ congruently grown by the Czochralski technique' in Wong, K. K. *Properties of lithium niobate exeter*, England: Short Run Press Ltd.

Kalawa, O., Tipakontitikul, R. and Niyompan, A. (2014) The effect of Nd^{3+} addition on crystallization behavior and related properties of the ferroelectric glass-ceramics Na_2O-BaO-Nb_2O_5-SiO_2 based composition, *Ferroelectrics,* 459, pp. 195–202.

Kashchiev, D. (2000) *Nucleation: Basic theory with applications*. Butterworth-Heinemann: Elsevier.

Kashif, I., Sakr, E. M., Soliman, A. A. and Ratep, A. (2012) Influence of heat treatment on structure and some physical properties of lithium boro-niobate glass, *Ph. Transit.*, 85(8), pp. 681–693.

Kashif, I., Soliman, A. A., Sakr, E. M. and Ratep, A. (2013) XRD and FTIR studies the effect of heat treatment and doping the transition metal oxide on $LiNbO_3$ and $LiNb_3O_8$ nanocrystallite phases in lithium borate glass system, *Spectrochim. Acta Mol. Biomol. Spectrosc*., 113, pp. 15-21.

Kashif, I., Soliman, A. A., Sakr, E. M., Ratep, A. (2014) Effects of the addition of transition metal ions on some physical properties of lithium niobium borate glasses, *Phys. Chem. Glas.: Eur. J. Glass Sci. Technol. B,* 55(1), pp. 34-40.

Kashif, I., Ratep, A. and El-Mahy, S. K. (2017) Structural and optical properties of lithium tetraborate glasses containing chromium and neodymium oxide, *Mater. Res. Bull.,* 89, pp. 273–279.

Kaur, M., Saini, M. S., Singh, D. and Mudahar, G. S. (2014) Synthesis and characterization of lithium borate glasses containing bismuth, *Int. J. Adv. Res. Phys. Sci.,* 1(8), pp. 1-8.

Keszler, D. A. (1996) Borates for optical frequency conversion, *Curr. Opin. Solid State Mater. Sci,* 1, pp. 204-211.

Khalek, A. E. K. and Bahgat, A. A. (2010) Optical and dielectric properties of transparent glasses and nanocrystals of lithium niobate and lithium diborate in borate glasses, *Physica B*, 405, pp. 1986–1992.

Khalek, A. E. K., Mohamed, E. A., Salem, S. M., Ebrahim, F. M. and Kashif, I. (2012) Study of glass nanocomposite and glass–ceramic containing ferroelectric phase, *Mater. Chem. Phys.*, 133, pp. 69–77.

Khamaganova, T. N. (2017) Structural specific features and properties of alkaline-earth and rare-earth metal borates, *Russ. Chem. Bull.*, 66, pp. 187–200.

Kim, H. G., Komatsu, T., Sato, R. and Matusita, K. (1996) Incorporation of $LiNbO_3$ crystals into tellurite glasses, *J. Mater. Sci.*, 31, pp. 2159-2164.

Kim, H. G., Kang, J. K., Park, S. J. and Chung, S. J. (1998) Growth of the non-linear optical crystals of lithium triborate and beta barium borate, *Opt. Mater.*, 9(1–4), pp. 356-360.

Kimura, H., Numazawa, T. and Sato, M. (1996) Crystal growth of BaB_2O_4 from melt using a Pt tube as a seed, *J. Cryst. Growth*, 165, pp. 408-412.

Kindrat, I., Padlyak, B. and Drzewiecki, A. (2015) Luminescence properties of the Sm–doped borate glasses, *J. Lumin.*, 166, pp. 264–275.

Kokh, A., Kononova, N., Mennerat, G., Villeval, P., Durst, S., Lupinski, D., Vlezko, V. and Kokh, K. (2010) Growth of high-quality large size LBO crystals for high energy second harmonic generation, *J. Cryst. Growth*, 312, pp. 1774–1778.

Kokta, M. (2007) Growth of oxide laser crystals, *Opt. Mater.*, 30, pp. 1-5.

Komatsu, R., Sugawara, T. and Sassa, K. (1997) Growth and ultraviolet application of $Li_2B_4O_7$ crystals: Generation of the fourth and fifth harmonics of Nd: $Y_3Al_5O_{12}$ lasers, *Appl. Phys. Lett.*, 70, pp. 3492-3494.

Komatsu, T., Tawarayama, H., Mohri, H. and Matusita, K. (1991) Properties and crystallization behaviors of TeO_2-$LiNbO_3$ glasses, *J. Non Cryst. Solids*, pp. 135, 105.

Krupke, W. F. (1971) Radiative transition probabilities within the $4f^3$ Ground configuration of Nd:YAG, *IEEE J. Quantum Electron.*, 7(4), pp. 153-159.

Kuhn, K. J. (1998) *Laser Engineering*, Upper Saddle River, NJ: Prentice Hall.

Kumar, P., Babu, S. M., Bhaumik, I., Ganesamoorthy, S., Karnal, A. K., Pandey, A. K., and Raman, R. (2010) Influence of dopant concentration on the structural and optical characteristics in Ti doped (2 and 5 mol%) $LiNbO_3$ nonlinear optical single crystal, *Opt. Mater.*, 32, pp. 1364–1367.

Kumar, R. A. (2013) Borate crystals for nonlinear optical and laser applications: A review, *J. Chem.*, 2013, pp. 1-7.

Kumar, R. A., Arivanandhan, M., Hayakawa, Y. (2013a) Recent advances in rare earth-based borate single crystals: Potential materials for nonlinear optical and laser applications, *Prog. Cryst. Growth Charact. Mater.*, 59, pp. 113–132.

Kumar, R. A., Arivanandhan, M., Dhanasekaran, R. and Hayakawa, Y. (2013b) Growth and characterization of a novel nonlinear optical borate crystal – Yttrium calcium borate (YCB), *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, 110, pp. 391–394.

Kurtz, S. K. and Perry, T. T. (1968) A powder technique for the evaluation of nonlinear optical materials, *J. Appl. Phys.*, 39(8), pp. 3798–3813.

Kustov, E. F., Loschenov, V. B., Basieva, I. T. (2014) Decay times of radiative and non-radiative transitions in rare-earth ions, *Phys. Script.*, 163, p. 14032.

Ladd, M. F. C. and Palmer, R. A. (1977) *Structure determination by X-Ray crystallography*. New York: Plenum Press.

Lakshman, S. V. J. and Buddhudu, S. (1980) Racah and judd-ofelt parameters for Pr^{3+}, Nd^{3+} and Er^{3+} ions in a laser liquid, *J. Quant. Spectrosc. Radiat. Transf.*, 24, pp. 251-257.

Lee, S. H., Kim, Y. J., Cho, S. H. and Yoon, E. P. (1992) The influence of the czochralski growth parameters on the growth of lithium niobate single crystals, *J. Cryst. Growth*, 125, pp. 175-180.

Lin, H., Qin, W., Zhang, J. and Wu, C. (2007) A study of the luminescence properties of Eu^{3+}-doped borate crystal and glass, *Solid State Commun.*, 141, pp. 436–439.

Liu, J. L., Wang, W. C., Xiao, Y. B., Huang, S. J., Mao, L.Y. and Zhang, Q. Y. (2019) Nd^{3+}-doped TeO_2–MoO_3–ZnO tellurite glass for a diode-pump 1.06 μm laser, *J. Non Cryst. Solids*, 506, pp. 32–38.

Lumb, M. D. (1978) *Luminescence spectroscopy*. London: Academic Press.

Markus, P. H., Mikhail, G. B., and Karl, W. K. (2013) 50th anniversary of judd-ofelt theory: An experimentalist's view of the formalism and its application, *J. Lumin.*, 136, pp. 221-239.

McMillan, P. W. (1964) *Glass-Ceramics*. New York, USA: Academic Press Inc.

Meera, B. N., Sood, A. K., Chandrabhas, N., and Ramakrishna, J. (1990) Raman study of lead borate glasses, *J. Non Cryst. Solids*, 126(3), pp. 224–230.

Mhareb, M. H. A., Hashim, S., Ghoshal, S. K., Alajerami, Y. S. M., Saleh, M. A., Dawaud, R. S., Razak, N. A. B. and Azizan, S. A. B. (2014) Impact of Nd^{3+} ions on physical and optical properties of lithium magnesium borate glass, *Opt. Mater.*, 37, pp. 391-397.

Mockel, R., Hengst, M., Reuther, C. and Gotze, J. (2009) Synthesis of $Ca_4GdO(BO_3)_3$ single crystals using czochraksi method, *J. Sib. Fed. Univ. Eng. Tech.*, 4, pp. 400-408.

Mohan, S, Thind, K. S., Sharma, G. (2007) Effect of Nd^{3+} concentration on the physical and absorption properties of soda-lime-silicate glasses, *Brazillian J. Phys.*, 37(4), p. 1306.

Mori, Y., Kuroda, I., Nakajima, S., Taguchi, A., Sasaki, T. and Nakai, S. (1995) Growth of a nonlinear optical crystal: cesium lithium borate, *J. Cryst. Growth*, 156(3), pp. 307-309.

Morozov, O. A., Naumov, A. K., Lovchev, A. V. and Garipov, M. R. (2015) Analysis of nonlinear optical materials properties by simple powder technique, *J. Phys.: Conf. Ser*. 594, p. 12037.

Mott, N. F. and Davis, E. A. (1970) Conduction in non-crystalline systems, *Philos. Mag.*, 22(179), pp. 903-922.

Mougel, F., Aka, G., Harari, A. K., Hubert, H., Benitez, H. H. and Vivien, D. (1997) Infrared laser performance and self-frequency doubling of Nd^{3+}:Ca_4 $GdO(BO_3)_3$ (Nd:GdCOB), *Opt. Mater.*, 8, pp. 161-I73.

Myerson, A. S. (2002) *Handbook of industrial crystallization. 2nd ed.* USA: Butterworth-Heinemann.

Naga, L. K., Sesha, R. V., Prasad, M. and Sambasiva, R. K. (2018) Spectroscopic properties of lead borate glasses doped with copper ions, *Int. J. Recent Sci. Res.*, 9(4), pp. 26114-26117.

Nikolai, V. A., Vladimir N. K. and Sergei, N. R. (2003) Automated control of czochralski and shaped crystal growth processes using weighing techniques, *Prog. Cryst. Growth Charact. Mater.*, 46, pp. 1-57.

Padlyak, B., Kindrat, I., Protsiuk, V., and Drzewiecki, A. (2014) Optical spectroscopy of $Li_2B_4O_7$, CaB_4O_7 and $LiCaBO_3$ borate glasses doped with europium, *Ukr. J. Phys. Opt.*, 15(3), pp. 103–117.

Pal, I., Agarwal, A., Sanghi, S., Sanjay and Aggarwal, M. P. (2013) Spectroscopic and radiative properties of Nd^{3+} ions doped zinc bismuth borate glasses, *Indian J Pure Appl. Phys.*, 51, pp. 18-25.

Parvinder, K., Gurinder, P. S., Simranpreet, K, and Singh, D. P. (2012) Modifier role of cerium in lithium aluminium borate glasses, *J. Mol. Struct.*, 1020, pp. 83–87.

Perlov, D., Livneh, S., Czechowicz, P., and Goldgirsh, A. (2011) Progress in growth of large β-BaB_2O_4 single crystals, *Cryst. Res. Technol*., 46(7), 651-654.

Pigeonneau, F., Martin, D., and Mario, O. (2010) Shrinkage of an oxygen bubble rising in a molten glass, *Chem. Eng. Sci.*, 65(10), pp. 3158-3168.

Prasad, N. S. and Varma, K. B. R. (2005a) Evolution of ferroelectric $LiNbO_3$ phase in a reactive glass matrix ($LiBO_2$–Nb_2O_5), *J. Non Cryst. Solids*, 351(16–17), pp. 1455–1465.

Prasad, N. S. and Varma, K. B. R. (2005b) Crystallization kinetics of the $LiBO_2$–Nb_2O_5 glass using differential thermal analysis, *J. Am. Ceram. Soc*., 88(2), pp. 357–361.

Qiu, H. (1997) *Development of a computer control system with self-tuning growth rate control for the czochralski crystal growth process*. Ph.D. Thesis, University of Central Florida.

Rajagukguk, J., Kaewkhao, J., Djamal, M., Hidayat, R., Suprijadi, Y., and Ruangtaweep (2016) Structural and optical characteristics of Eu^{3+} ions in sodium-lead-zinc-lithium-borate glass system, *J. Mol. Struct.*, 1121, pp. 180-187.

Rajesh, D., Balakrishna, A., Seshadri, M., and Ratnakaram, Y. C. (2012) Spectroscopic investigations on Pr^{3+} and Nd^{3+} doped strontium–lithium–bismuth borate glasses, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, 97, pp. 963–974.

Raju, K.V., Raju, C. N., Sailaja, S., and Reddy, B. S. (2013) Judd-Ofelt analysis and photoluminescence properties of RE^{3+} (RE = Er & Nd): cadmium lithium boro tellurite glasses, *Solid State Sci.*, 15, pp. 102–109.

Ramteke, D. D., Annapurna, K., Deshpande, V. K. and Gedam, R. S. (2014) Effect of Nd^{3+} on spectroscopic properties of lithium borate glasses, *J. Rare Earths*, 32(12), p. 1148.

Ratnakaram, Y. C., Kumar, A. V., Naidu D. T., Chakradhar, R. P. S. and Ramesh, K. P. (2004) Optical absorption and luminescence properties of Nd^{3+} in mixed alkali borate glasses-Spectroscopic investigations, *J. Lumin.*, 110, pp. 65–77.

Razeghi, M. (2006) Fundamentals of solid-state engineering. 2nd ed. USA: Springer Science – Business Media, Inc.

Reben, M. and Li, H. (2011) Thermal stability and crystallization kinetics of MgO–Al_2O_3–B_2O_3–SiO_2 glasses, *Int. J. Appl. Glass Sci.*, 2, pp. 96-107.

Reduan, S., Hashim, S., Ibrahim, Z., Alajerami, Y., Mhareb, M., Maqableh, M., Dawaud, R. and Tamchek, N. (2014) Physical and optical properties of Li_2O–MgO–B_2O_3 doped with Sm^{3+}, *J. Mol. Struct.*, 1060, pp. 6–10.

Reshak, A. H., Auluck, S., Majchrowski, A. and Kityk, I. V. (2008) Band structure features of nonlinear optical yttrium aluminium borate crystal, *Solid State Sci.*, 10(10), pp. 1445–1448.

Rizak, I. M., Rizak, V. M., and Baisa, N. D. (2003) Charge transport in $Li_2B_4O_7$ in single crystal and glassy states, *Crystallogr. Rep.*, 48, pp. 676–681.

Sadeq, M. S. and Morshidy, H. Y. (2019) Effect of mixed rare-earth ions on the structural and optical properties of some borate glasses, *Ceram. Int.*, 45, pp. 18327-18332.

Sahar, M. R. (1998) *Sains Kaca*. UTM: Penerbit Universiti Teknologi Malaysia.

Sailaja, B., Stella, R. J., Rao, G. T., Raja, B. J., Manjari, V. P. and Ravikumar, R. (2015) Physical, structural and spectroscopic investigations of Sm^{3+} doped ZnO mixed alkali borate glass, *J. Mol. Struct.*, 1096, pp. 129–135.

Sanad, A. M., Moustafa, A. G., Moustafa, F. A. and El-Mongy, A. A. (1985) Role of halogens on the molar volume of some glasses containing vanadium, *Cent. Glass Ceram. Res. Inst. Bull.*, 32(3), pp. 53-56.

Sangeeta, B. T. and Sabharwal, S. C. (2004) Investigations on the solidification behavior of $Li_2B_4O_7$, *J. Cryst. Growth*, 273, pp. 167–171.

Sasaki, T., Mori, Y. and Yoshimura M. (2003) Progress in the growth of a $CsLiB_6O_{10}$ crystal and its application to ultraviolet light generation, *Opt. Mater.*, 23, pp. 343–351.

Sasi Kumar, M. V., Rajesh, D., Balakrishna, A., and Ratnakaram Y. C. (2013) Thermal and optical properties of Nd^{3+} doped lead zinc borate glasses—Influence of alkali metal ions, *Physica B*, 415, pp. 67–71.

Sazali, E. S., Sahar, M. R., Ghoshal, S. K., Arifin, R, Rohani M. S. and Awang, A. (2014) Optical properties of gold nanoparticle embedded Er^{3+} doped lead-tellurite glasses, *J. Alloys Compd.*, 607, pp. 85-90.

Seevakan, K. and Bharanidharan, S (2018) Different types of crystal growth methods, *Int. J. Pure Appl. Math.*, 119(12), pp. 5743-5758.

Semwal, K. and Bhatt, S. C. (2013) Study of Nd^{3+} ion as a dopant in YAG and glass laser, *Int. J. Phys.*, 1(1), pp. 15-21.

Senguttuvan, N., Ishii, M., Shimoyama, M., Kobayashi, M., Tsutsui, N., Nikl, M., Dusek, M., Shimizu, H. M., Oku, T., Adachi, T., Sakai, K., and Suzuki, J. (2002) Crystal growth and luminescence properties of $Li_2B_4O_7$ single crystals doped with Ce, In, Ni, Cu and Ti ions, *Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip.*, 486 (1–2), pp. 264-267.

Senthilkumar, M., Kalidasan, M., Sugan, S. and Dhanasekaran, R. (2013) Growth of neodymium lanthanum calcium borate (NdLCB) single crystals by the czochralski method and its characterization, *J. Cryst. Growth*, 362, pp. 189–192.

Shekhovtsov, A. N., Tolmachev, A.V., Dubovik, M. F., Korshikova, T. I., Baumer, V. N., Grinyov, B. V. and Dolzhenkova, E. F. (2001) Growth, structure, and luminescence properties of LaB_3O_6 single crystals, *Nucl. Instrum. Methods Phys. Res. A*, 456(3), pp. 280-283.

Suchocki, A., Biernacki, S. W., Grinberg, M. (2007) Nephelauxetic effect in high pressure luminescence of transition-metal ion dopants, *J. Lumin.*, 125, pp. 266-270.

Sulhadi (2007). *Structural and optical properties studies of erbium doped tellurite glasses*. PhD Thesis, Universiti Teknologi Malaysia.

Sun, D., Zhang, Q., Wang, Z., Su, J, Gu, C., Wang, A. and Yin, S. (2005) Concentration distribution of Nd^{3+} in $Nd{:}Gd_3Ga_5O_{12}$ crystals studied by optical absorption method, *Crys. Res. Technol.*, 40(7), pp. 698-702.

Tadeusz, T. and Andrzej, M., (1991) Czochralski growth of lithium tetraborate single crystals, *Mat. Letters*, 11(8-9), pp. 281-283.

Taishi, T., Huang, X., Yonenagac, I., and Hoshikawa, K. (2003) Dislocation-free Czochralski Si crystal growth without a thin neck: dislocation behavior due to incomplete seeding, *J. Cryst. Growth*, 258, pp. 58–64.

Tang, D. Y., Zeng, W. R., and Zhao, Q. L. (1992) A study on growth of β-BaB_2O_4 crystals, *J. Cryst. Growth*, 123, pp. 445-450.

Tauc, J. (1974) *Amorphous and Liquid Semiconductors*. London: Plenum.

Terada, Y., Ohkubo, K., and Mohr, T. (2005) Thermal conductivities of platinum alloys at high temperatures, *Platin. Met. Rev*., 49(1), pp. 21-26.

Thomazini, D., Lanciotti, F. and Sombra, A. S. B. (2001) Structural properties of lithium borate glasses doped with rare earth ions, *Ceramica*, 47, p. 302.

Tripathi, G., Vineet, K. R. and Rai, S. B. (2007) Upconversion and temperature sensing behavior of Er^{3+} doped Bi_2O_3–Li_2O–BaO–PbO tertiary glass, *Opt. Mater.*, 30, pp. 201–206.

Tsutsui, N., Ino, Y., Imai, K., Senguttuvan, N., Ishii, M. (2001) Growth of high quality 4 in diameter $Li_2B_4O_7$ single crystals, *J. Cryst. Growth*, 229, pp. 283–288.

Ungar, T. (2007) Characterization of nanocrystalline materials by X-Ray line profile analysis, *J. Mater. Sci.*, 42(5), 1584-1593.

Verhoef, A. H. and Hartog, H. W. D. (1992) A molecular dynamics study of B_2O_3 glass using different interaction potentials, *J. Non Cryst. Solids*, 146, pp. 267–278.

Vijaya, K. K. and Suresh, A. K. (2012) Spectroscopic properties of Nd^{3+} doped borate glasses, *Opt. Mater.*, 35, pp. 12–17.

Vogel, W. (1994). *Glass chemistry.* 2nd ed. Berlin: Springer-Verlag.

Wang, Z., Shu, Q., and Chou, K. (2013) Viscosity of Fluoride-free mold fluxes containing B_2O_3 and TiO_2, *Steel Res. Int*., 84(8), pp. 766-776.

Wang, Z., Xu, X., Fu, K., Song, R., Wang, J., Wei, J., Liu, Y. and Shao, Z. (2001) Non-critical phase matching of $Gd_xY_{1-x}Ca_4O(BO_3)_3$(Gd_xY_{1-x}COB) crystal, *Solid State Commun*., 120, pp. 397-400.

Widanarto, W., Sahar, M. R., Ghoshal, S. K., Arifin, R., Rohani, M. S., Effendi, M. (2013) Thermal, structural and magnetic properties of zinc-tellurite glasses containing natural ferrite oxide, *Mater. Lett.*, 108, pp. 289–292.

Williams, D. B. and Carter, C. B. (2009) *Transmission electron microscopy: A textbook for materials science*. New York: Springer.

Wu, S., Lian J., Song, P., Gao, S., Wang, X., Ma, Z., and Wang, Y. (2011) Study on the optical properties of lithium borate glass doped with Nd^{3+}, *Symp. Photonics Optoelectron.*, pp. 1-3.

Yogesh, K. S., Rajendra, P. J. and Goyal, P. (2014) Optical band gap and physical properties of Nd^{3+} doped cadmium borate glasses, *Am. J. Phys. Appl.*, 2(6), pp. 162-166.

Yoshimura, M., Mori, Y., Hu, Z. G. and Sasaki, T. (2004) Growth and characterization of nonlinear optical borate crystals $CsLiB_6O_{10}$, CsB_3O_5, and $BaAlBO_3F_2$, *Opt. Mater.*, 26, pp. 421–423.

You, R. L., Akiyama, Y., Imaishi, N. and Tsukada, T. (2003) Global analysis of a small Czochralski furnace with rotating crystal and crucible, *J. Cryst. Growth*, 255, pp. 81–92.

Zanotto, E. D. (1992) Crystallization of liquids and glasses, *Brazilian J. Phys.*, 22, pp. 77-84.

Zelewski, S. J. and Kudrawiec, R. (2017) Photoacoustic and modulated reflectance studies of indirect and direct band gap in van der waals crystals, *Sci. Rep.*, 7(1), p. 15365.

Zhang, D., Kong, Y. and Jing Y. Z. (2000) Optical parametric properties of 532-nm-pumped beta-barium-borate near the infrared absorption edge, *J. Opt. Commun.*, 184, pp. 485-491.

Zhang, S., Cheng, Z., Han, J., Zhou, G., Shao, Z., Wang, C., Chow, Y. T. and Chen, H. (1999) Growth and investigation of efficient self-frequency-doubling $Nd_xGd_{1-x}Ca_4O(BO_3)_3$ crystal, *J. Cryst. Growth*, 206, pp. 197-202.

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Kamaruddin, W. H. A**., Rohani, M. S., Sahar, M. R., Liu, H. and Yuanhua, S. (2016) Synthesis and characterisation of lithium niobium borate glasses containing neodymium, *J. of Rare Earths*, 34(12), pp. 1199-1205. **(Q2, IF 2.188)**

Indexed Journal

1. **Kamaruddin, W. H. A**., Rohani, M. S., Sahar, M. R. and Liu, H. (2017) Effect of Nd^{3+} on the properties of lithium niobium borate crystal and glass, *Solid State Phenomena*, 268, pp. 210-216. **(Indexed by SCOPUS)**

Non-Indexed Conference Proceedings

1. **Kamaruddin, W. H. A**., Rohani, M. S., Sahar, M. R. and Liu, H. (2018) Glass formation and crystalline phase in the ternary Nd_2O_3-$Li_2B_4O_7$-Nb_2O_5 system, 30th Regional Conference on Solid State Science and Technology, Melaka, Malaysia.

2. **Kamaruddin, W. H. A**., Rohani, M. S., Sahar, M. R. and Liu, H. (2017) Polycrystalline seed-mediated growth of neodymium-lithium-niobium-borate crystal by czochralski technique, 1st International Malaysia-Indonesia-Thailand Symposium, UiTM Perlis, Malaysia. pp. 295-299.

3. **Kamaruddin, W. H. A**., Rohani, M. S., Sahar, M. R. and Liu, H. (2016) The growth of neodymium-doped lithium niobium borate crystal by czochralski tehcnique, 16th International Graduate Conference on Engineering Science and Humanity 2016, UTM, Johor, Malaysia.

4. **Kamaruddin, W. H. A**., Rohani, M. S., Sahar, M. R., Hasim, N., Liu, H., and Sang. Y. (2015)

Modification in structural and optical properties of undoped and Ce, Nd, doped lithium niobium borate glasses, 5th International Conference on Solid State Science and Technology, Langkawi, Malaysia.